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Quantum Computing Architecture: Implementing Qubits

Abstract: This paper will cover basic concepts of quantum computing, various applications in different fields and the mechanism behind them, and analyze previous research performed on quantum computing architectures and attempt to observe previous implementations of qubits within those architectures. It will report findings regarding the most effective methods of implementing qubits in quantum architectures, and how to minimize all errors and deficiencies and improve the overall system of quantum computing. Our major finding is that even large qubit circuits can be made resilient to error by adding a modest number of extra qubits.

Introduction and Background

Definition : Quantum computers seem to have a significant impact on business.Various quantum algorithms were developed since quantum computing was proposed in the 1980s and

Governments have been increasing the funding for quantum computing research and development not only for the advancement of computing technology but also for their national security. Normal computer architecture designs represent and store information using bits, which are normally grouped in a cluster of 8 bits, which represent numbers between 0 and 255. Bits and Qubits are the building blocks of quantum computing.

Quantum computing uses a microscopic object (e.g., electron, photon, ion) as the medium to store and transfer digital information. One-bit information (i.e., zero or one) can be encoded using two orthogonal states of a microscopic object. This quantum two-state system is called a quantum bit (or qubit). A quantum computer solves a problem by setting qubits in initial states and then manipulating the states so that an expected result appears on the qubits. In order to design such a quantum circuit, quantum mechanics is used to describe the states since those microscopic objects do not follow the rules of classical physics. The state of a qubit can be written as a vector $|\psi\rangle$. $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle, \{\alpha, \beta \in \mathbb{C}\}$ where α and β are complex numbers $\mathbb{C}$, called probability amplitude, and satisfy $|\alpha|$ 2 + $|\beta|$^2 = 1. $|\alpha|$^2 is the probability of getting the state $|0\rangle$ as the result of the measurement on the qubit $|\psi\rangle$ while $|\beta\rangle$ 2 is the probability of getting $|1\rangle$.

Quantum computers perform operations on qubits which can be in superposition of state which is additional and these are the same as bits used by classical or digital computers. In comparison with classical computers a quantum register with 2 qubits can store 4 numbers in superposition simultaneously where a classical register with 2 bits stores only 2 numbers and a 300 qubit register holds more numbers than the total number of atoms in the universe. This leads to storage of infinite information at the time of computation but we can't get at it. The problem occurs at the time of reading out an output in a superposition state holding so many different values.

One major drawback of this design, however, is that bits can only physically be in a single state at a time. While bits represent binary values, that is digits from 0 to 1, they strictly represent either an active or inactive state, or more simply put, on or off. Due to this architecture, there is a limit to the certain capabilities these binary systems can perform. This limitation has led to the advancement of research and studies in the field of Quantum Computing, which effectively solves the issue of bits being limited to a hard state. Quantum computing uses qubits to represent and store information. Qubits are so interesting and revolutionary, because they can directly perform any actions that bits can, however they possess the ability to be in multiple states at any time, and can perform unlimited numbers of information processing all simultaneously. This allows them to take advantage of mechanics such as superposition and quantum entanglement, allowing them to be in multiple states at a single point in time.

Applications: Quantum Computations As mentioned earlier, one of the significant advantages of quantum computation is the ability of massively parallel computation. By using a quantum superposition state, 2 n inputs can be stored in n qubits simultaneously. Since universal quantum gates allow us to design an arbitrary quantum circuit, the n qubits can be used as the input for a quantum circuit, which performs an arbitrary computation.The measurement result is one of 2 n possible output states with the probability 1/2 n . Therefore, a quantum circuit needs to be designed to manipulate the probability amplitudes of the qubits so that an expected result can be found by the measurement with the probability higher than 1/2 n .

Challenges : While this does seem to be an extraordinary capability, it is extremely difficult to implement and maintain qubits. Because they are very unstable and sensitive, there are many regulations and specifications involved that must be perfectly maintained in order to be able to take advantage of qubits. These range from maintaining a constant temperature of absolutely zero degrees, and must have no interference at all, and they are extremely complicated to implement due to their operations working on a nano scale. The modern challenge with implementing quantum computer architecture involves actively working on solutions and regulations in order to have qubits run and operate at the most efficient level possible. In our research towards finding a solution for this problem, we found that Quantum error correction has been done before on smaller arrays of qubits, and on other types of qubit than the superconducting transmon qubits that Sycamore uses .An error-correcting unit with measure and data qubits constitutes one 'logical qubit', the building block for implementing and executing quantum algorithms. Yet, significant hurdles remain to achieving practically useful logical qubits.Quantum error correction is done by adding 'measure' qubits to the original data qubits. In one error-correction cycle, the measure qubits compare various combinations of data qubits, then the values of these measure qubits can be read out, after which they are reset. This allows the detection of error events in the data qubits without actually detecting their individual values In fact , the key achievement of the Google team was showing that the probability of errors decreased exponentially when using more qubits. That means even large qubit circuits can be made resilient to error by adding a modest number of extra qubits. This paper covers the basic concepts of quantum computing, various applications, different factors that affect the efficiency of the qubits and different ways to minimize the error. The main finding being that for error correction to be successful, the data qubits must have a minimum level of stability, which also depends on the configuration. This minimum has been reached for a long chain of qubits on the Sycamore processor, but not yet for a large surface configuration. The modern challenge with implementing quantum computer architecture involves actively working on solutions and regulations in order to have qubits run and operate at the most efficient level possible. In our research towards finding a solution for this problem, we found that Quantum error correction has been done before on smaller arrays of qubits, and on other types of qubit than the superconducting transmon qubits that Sycamore uses .An error-correcting unit with measure and data qubits constitutes one 'logical qubit', the building block for implementing and executing quantum algorithms. Yet, significant hurdles remain to achieving practically useful logical qubits.

Analysis

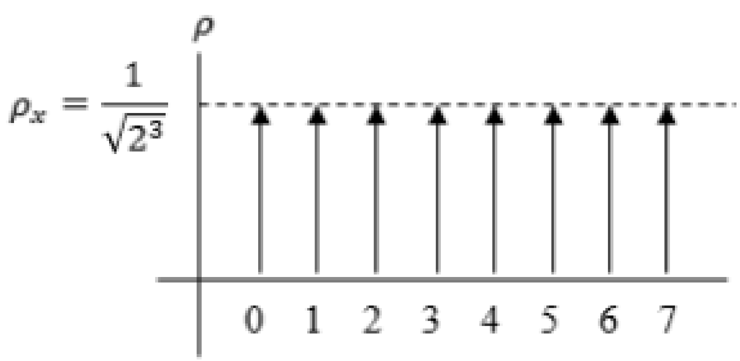
Quantum Computing is used for various applications . Some of them that were studied for this paper are as mentioned below :

Grover's algorithm : This database search algorithm is designed to find an item in an unordered list. For example, it can be used for speeding up brute force key search on symmetric key encryption such as AES (Bernstein, 2010). It is known that this algorithm requires $O(\sqrt{N})$ operations to search an unsorted array consisting N elements, which requires $O(N)$ operations for classical algorithms (Grover, 1996). The idea of Grover's algorithm is the following. When the number xa that satisfies $f(xa) = 1$ needs to be found in a large unsorted database, the qubits are set to be in a superposition state of all possible ID numbers $\{x = 0,1,2,\dots, N - 1\}$ as the initial state. To simplify the expression, the decimal notation is used for n-qubit. For example,$|1\rangle|0\rangle|0\rangle$ is written as $|4\rangle$. The initial state (Below Figure) can be written as where the initial values of ϱx are $1/\sqrt{2}\ n$ when $N = 2\ n$.

Thus, $\sum \varrho x\ N-1\ 2\ x=0 = 1$. $|\psi\rangle = \sum \varrho x\ |x\rangle\ N-1\ x=0 = \varrho 0\ |0\rangle + \varrho 1\ |1\rangle + \varrho 2\ |2\rangle + \cdots \varrho N-1\ |N - 1\rangle$.

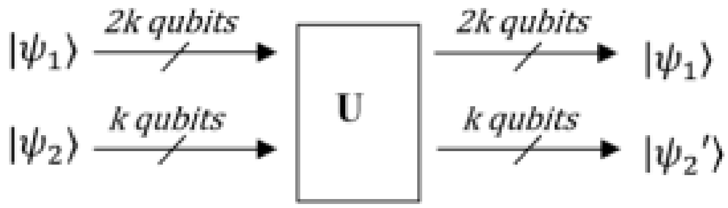
Here $\varrho x = 1/\sqrt{2}\ n$ when $N = 2\ n$.

Thus, $\sum \varrho x$^2 (x=0 to x= N-1) = 1



This figure demonstrates initial values for N=8.

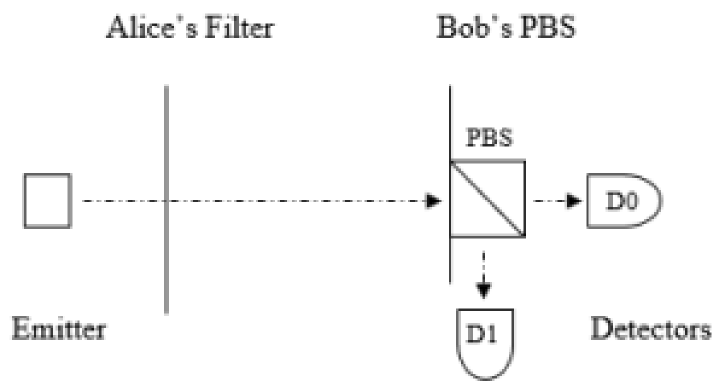
Shor's Algorithm : In 1994, Peter Shor showed that a quantum computer could be used to factor a large integer in polynomial time (Shor, 1994). His algorithm attracted a great deal of attention from security agencies since, if a quantum computer is developed, it can break the RSA encryption algorithms (Van Meter & Horsman, 2013), which is the most widely used public-key encryption algorithm. Shor's algorithm consists of classical parts and quantum parts.



Quantum circuit U

When the integer N is large (e.g., 200 digits), finding the period of $fa,N(m)$ is very time-consuming with a classical computer (if possible.) Thus, a quantum superposition state is used to find the period by computing $fa,N(m)$ for m = 0 to, at least, m = N 2 . In *Grover's algorithm* : In this algorithm, only one set of qubits in the superposition state is manipulated to increase the probability of finding the targeted index by measurement on the qubits. In Shor's algorithm, two sets of qubits are used: $|\psi 1\rangle$ for the input m and $|\psi 2\rangle$ for the output of $fa,N(m)$ in (20). The number of qubits for $|\psi 2\rangle$ is k = log N since $fa,N(m)$ is always less than N while the number of qubits for $|\psi 1\rangle$ is, at least, log N 2 = 2k (Yanofsky & Mannucci, 2008). The initial state of the qubits for m is $a\ r - 1 \equiv 0\ mod\ N$ (23) $(a\ r/2 - 1)(a\ r/2 + 1) \equiv 0\ mod\ N$ (24) $|\psi 1\rangle = \sum pm|m\rangle$ = p0 $|0\rangle$ + p1 $|1\rangle$ + p2 $|2\rangle$ + ⋯ + pN^2−1 $|N$^ 2 − 1$\rangle$. Here the initial values of pm are 1/√2 2k . The initial state of the qubits for $fa,N(m)$ is $|\psi 1\rangle$ and $|\psi 2\rangle$ are placed into a quantum circuit which computes $fa,N(m)$ as shown in figure above.

Quantum Key Distribution Quantum cryptography (Gisin, Ribordy, Tittel, & Zbinden, 2002) : It is currently one of the most practical applications of quantum information science. The most wellknown quantum cryptography is the quantum key distribution (QKD) protocol (Bennett & Brassard, 1984), which has been implemented and commercially available for more than a decade. The OKD with the one-time pad can provide theoretically unbreakable end-to-end security by utilizing quantum mechanical properties in a classical cryptographic protocol. Here “unbreakable” means that the security of the cryptography does not rely on the complexity of the algorithm but a physical property that prevents decryptions without the key. The one-time pad is classical cryptography known to be a perfect encryption scheme (Schneier, 1996). The protocol is simple as follows. A sender, called Alice, generates n-bit random number K as a one-time shared key and delivers it to a receiver, called Bob, before the communication. $K = \{ki = 0,1 \mid i = 1,2,3,\ldots n\}$ When Alice wants to deliver an n-bit secret message M to Bob, Alice performs exclusive OR operations for each bit in M and K, respectively. Then, she sends the resulting bit sequence C to Bob and discards the K. $M = \{mi = 0,1 \mid i = 1,2,3,\ldots , n\}$ $C = \{ci = mi \oplus ki \mid i = 1,2,3,\ldots , n\}$ Bob decrypts the ciphertext C by performing exclusive OR operations with the shared key K and discards the K. This is an entirely secure protocol. The random bit sequence added to the message produces an utterly random bit sequence. Since the key is used only once, there is no possible attack except making a guess of n-bit random bit sequence for an n-bit message. The problem with this method is that there is no perfectly secure way to deliver the key (i.e., K) to Bob prior to the communication. If classical cryptography such as RSA or AES was used, the strength of the one-time pad protocol relies on the strength of the classical cryptography, which is not a perfect encryption scheme. QKD plays a major role in delivering the keys for the one-time pad. The figures below demonstrate the working of Alice and Bob’s filters. The difference is that the polarization angles of Filters are variable.



Alice’s filter can be set to four different angles: 0°, 45°, 90°, and 135° while Bob can change the orientation of the base angle (PBS) to 0° or 45° degrees.

Challenges : In an ideal world, a quantum computer with as few as 100 qubits would suffice to outperform all classical computers on certain classes of computation tasks. Google's Sycamore quantum processor, which has 53 qubits, is nowhere near accomplishing this. The reason is that existing qubits, the computational building blocks of a quantum computer, are extremely sensitive to outside interference. Any magnetic or thermal disturbance will cause the qubit to change its internal state randomly; the classical analogy would be that all the bit values in the working memory of a microprocessor keep flipping from 0 to 1 and back, unpredictably. As a result, quantum computing is still limited to computations taking no more than a few microseconds. Theoretically, if universal quantum gates are developed as hardware, any arbitrary quantum circuit can be designed. However, there are many technical challenges in building the hardware for gate-based quantum computation with a large number of qubits (DiVincenzo, 2000; Nielsen & Chuang, 2010). For example, whatever material chosen as a qubit must be robustly represented as a stable two-level system and must have a longer decoherence time than the gate operations. (Decoherence is the coupling between the qubit and its environment.) If the decoherence time is not enough for a gate operation, the output state from the gate is likely to have errors. Thus, each qubit (e.g., ion, electron) needs to be well isolated from its environment, including neighbor qubits.Also, the operations with the qubits need to be performed at cryogenic temperatures. This requires refrigeration technologies, which are scalable to quantum circuits with a few hundred qubits.

Quantum Key Distribution(QKD) : One of the significant issues with a QKD for the practitioners is that there is no commercially available quantum repeater to extend the distance and to fan out across a network. A photon is, by its nature, prone to interfere with its environment. It is not a critical problem for a short distance QKD scheme because the data transmitted over a quantum channel are random bits that can be discarded when they have errors. For long-distance, the amplification of the signal (i.e., a photon) is necessary due to the high SNR (signal to noise ratio). However, it is very challenging (if possible) to develop a quantum repeater (Meter & Touch, 2013) since replication of a transmitted unknown photon is not possible due to the nocloning theorem. Although quantum repeaters have been proposed (Briegel, Dür, Cirac, & Zoller, 1998; Jiang et al., 2009; Meter & Touch, 2013; Zwerger, Dür, & Briegel, 2012; Zwerger, Pirker, Dunjko, Briegel, & Dür, 2017), current commercially available QKD systems are generally designed to be used with point -to-point dedicated connections between networks (Aleksic et al., 2015). It is not a critical problem for a short distance

QKD scheme because the data transmitted over a quantum channel are random bits that can be discarded when they have errors. For long-distance, the amplification of the signal (i.e., a photon) is necessary due to the high SNR (signal to noise ratio). However, it is very challenging (if possible) to develop a quantum repeater (Meter & Touch, 2013) since replication of a transmitted unknown photon is not possible due to the nocloning theorem.

Attempts to Overcome Challenges:

In December 2020, a Chinese research team said they successfully achieved "quantum advantage" by using quantum computing methods to perform computations that classical supercomputers can't.

Making use of photons, the team carried out a calculation called a boson-sampling problem. The calculation has so many variables that existing supercomputers "would take half the age of Earth" to calculate the problem, according to *Nature*. The team used quantum computing to achieve this exact same calculation in a few minutes.

Several leading companies are working to avoid that problem by developing practical quantum machines and deploying them for real commercial applications.

D-Wave Systems is one such company at the forefront of recent quantum computing developments. British Columbia, D-Wave makes quantum machines particularly for businesses. Last year, the company announced the general availability of Advantage, its 5,000-qubit quantum system, accompanied by its quantum cloud service, Leap. The company's machines take a unique approach to quantum computing called "quantum annealing," which uses the physics of quantum phase transitions to perform computations. Murray Thom, D-Wave's vice president of software and cloud services, said, "We strongly and passionately believe that annealing is the fastest path to our prior objective: fueling customer value through practical quantum applications." The company says over 250 quantum-powered applications built with its system are now in production from Fortune 500 companies like Volkswagen,BMW,IBM and Accenture. IonQ of College Park, MD, is one more major quantum producer with a big commercial impact. The company uses individual atoms at the heart of their quantum processing units, resulting in machines with atomically perfect qubits. Last year, the company unveiled its most powerful system, with 32 perfect atomic clock qubits. IonQ's systems use a unique architecture of random-access processing of qubits in a fully connected and modular architecture, which the company claims presents a clear path for unlimited scale.Established tech giants also are developing quantum hardware and cloud services.Google last year used its Sycamore quantum processor to perform the largest quantum computation of chemistry calculations to date. The company also partnered with Italian pharmaceutical company Boehringer Ingelheim to research and implement quantum computing for drug design. This work shows progress towards real commercial and scientific use cases for quantum computing, according to a Google representative.Microsoft announced its *Azure Quantum* cloud quantum computing platform for developers in 2019. Companies like Ford already are experimenting with Azure Quantum to solve real-world problems, like traffic congestion, significantly faster than possible using classical computers. Azure Quantum leverages, among others, hardware from IonQ to provide quantum computing power.Amazon's popular cloud computing platform is getting restructured, with Amazon Braket now offering managed quantum cloud services for researchers and developers through Amazon Web Services. The system gives users access to both IonQ's quantum systems and D-Wave's quantum annealing capabilities. Last, but certainly not least, IBM has 28 quantum computers deployed in commercial applications, working with companies like Mitsubishi Chemical, and Daimler to do all from scratch from battery R&D to running chemistry simulations to improving auto manufacturing. The company plans to scale its quantum computing capabilities to a quantum machine with 1,121 qubits (to be called IBM Quantum Condor) by the end of 2023. To get a measure of the extent of progress, IBM released its 65-qubit quantum processor IBM Quantum Hummingbird in the year 2020 and has a 127-qubit processor planned for this upcoming year. Understanding the problems of quantum computing is only the beginning of the much complex conundrum, as quantum is a world apart from what businesses are used to. “Unlike conventionally used computers, quantum computers can only offer a more probabilistic response,” said Vaclav Vincalek, an entrepreneur who assists businesses in implementing cutting-edge technology. They aren’t designed to deliver definite results; instead, the response they present is the most likely, which may require verification by a traditional computer. For instance, a quantum computer may calculate the most likely solution for cracking an encryption scheme, but it will require a classical computer to test the solution to see whether it starts breaking. As a result, coding for quantum technology is a new problem, posing difficulty for everyone. There was no straightforward method to move or reuse code between systems before there existed a real quantum operating system.

The state of a qubit is more complex than just a combination of 0 and 1. It also depends on exactly how those two parts mesh, which, in turn, depends on an abstract angle called the phase. The phase can range from 0° to 360° and is key to the wavelike interference effects that give a quantum computer its power. Quantum mechanically, any error in a qubit's state can be thought of as some combination of a bit-flip error that swaps 0 and 1 and a phase flip that changes the phase completely by an angle of 180 degrees.To correct both types, researchers can expand into another dimension—literally. Whereas a string of three entangled qubits, with two ancillas woven between them, is the smallest collection of data that can detect and correct a bit-flip error, a three-by-three grid of qubits, with eight interspersed ancillas, is the simplest one that can detect and correct both bit-flip and phase-flip errors. The logical qubit now resides in an entangled state of the nine qubits—be thankful you don't have to write it out mathematically! Stabilizer measurements along one dimension of the grid check for bit-flip errors, while slightly different stabilizer measurements along the other dimension check for phase-flip errors. Schemes for pushing into two dimensions vary, depending on the geometric arrangement of the qubits and the details of the stabilizer measurements. Nevertheless, researchers' road to error correction is now clear: Encode a single logical qubit in a grid of physical qubits and show that the fidelity of the logical qubit gets better as the size of the grid increases. Experimenters have already made a start. For example, in a *Nature Physics* study published on 8 June, Andreas Wallraff at ETH Zurich and colleagues demonstrated that they could detect—but not correct—errors in a logical qubit encoded in a square of four qubits with three ancillary qubits. Also The state of a qubit is more complex than just a combination of 0 and 1. It also depends on exactly how those two parts mesh, which, in turn, depends on an abstract angle called the phase. The phase can range from 0° to 360° and is key to the wavelike interference effects that give a quantum computer its power. Quantum mechanically, any error in a qubit's state can be thought of as some combination of a bit-flip error that swaps 0 and 1 and a phase flip that changes the phase completely by an angle of 180 degrees.To correct both types, researchers can expand into another dimension—literally. But experimenters face a horrific challenge. Manipulating individual qubits can introduce errors, and unless that error rate falls below a certain level, then entangling more qubits with the original one only adds more noise to the system, says Maika Takita, a physicist at IBM. "To demonstrate anything you have to get below that threshold," she says. The ancillary qubits and other error-correction machinery add even more noise, and once those effects are included, the necessary error threshold plummets further. To make the scheme work, physicists must lower their error rate to less than 1%. "When I heard we achieved a 3% error rate, I thought that was great," Takita says. "Now, it needs to be much lower. "Error correction also requires twiddling with qubits repeatedly. That makes the process more demanding than quantum supremacy, which involves measuring all the qubits just once, says Marissa Giustina, a physicist with Google.Retracing those steps won't be easy. It's not just that any logical gate currently involving two qubits will require thousands of them. Worse, another theorem from quantum mechanics states that, no matter what scheme researchers use, not all of the logical gates can be easily translated from individual physical qubits to diffuse logical ones. Researchers think they can sidestep that problem if they can initialize all the qubits in their computer in particular states that often, do more than half the work of the problematic gates. Error correction "requires you to measure and measure and measure over and over again in a cycle, and that has to be done quickly and reliably," she says. Although a handful of qubits would suffice to demonstrate the principle of quantum error correction, in practice physicists will have to control huge numbers of them. To execute Shor's algorithm well enough to factor, say, a number 1000 bits long—roughly the size used in some internet encryption schemes—they'll need to maintain logical qubits with a part-in-1-billion error rate. That may require entangling a grid of 1000 physical qubits to safeguard a single logical qubit, researchers say, a prospect that will take generations of bigger and better quantum computing chips. Ironically, overcoming that challenge would put developers back where they were 20 years ago, when they were just setting out to make pairs of physical qubits interact to perform the various logical operations, or "gates," needed for computation. Once scientists have begun to master error correction, they'll have to repeat nearly every development so far in quantum computing with the more robust but highly complex logical qubits. "People say that error correction is the next step in quantum computing; it's the next 25 steps," Giustina quips. Retracing those steps won't be easy. It's not just that any logical gate currently involving two qubits will require thousands of them. Worse, another theorem from quantum mechanics states that, no matter what scheme researchers use, not all of the logical gates can be easily translated from individual physical qubits to diffuse logical ones. Researchers think they can sidestep that problem if they can initialize all the qubits in their computer in particular states that often, do more than half the work of the problematic gates. Unfortunately, still more qubits may be needed to produce those magic states. "If you want to perform something like Shor's algorithm, probably 90% of the qubits would have to be dedicated to preparing these magic states," Roffe says. So a full-fledged quantum computer, with 1000 logical qubits, might end up containing many millions of physical qubits. Google has a plan to build just such a machine within 10 years. At first blush, that sounds preposterous. Superconducting qubits need to be cooled to near absolute zero, in a device called a cryostat that fills a small room. A million-qubit machine conjures visions of a thousand cryostats in a huge factory. But Google researchers think they can keep their device compact. "I don't want to tip my hand, but we believe we figured this out," Neven says. Others are taking different tacks. Google's scheme would require 1000 physical qubits to encode a single logical qubit because its chip allows only neighboring qubits to interact. If more distant qubits can be made to interact, too, the number of physical qubits could be much smaller, Gambetta says. "If I can achieve that, then these very scary numbers for the overhead of error correction can come crashing down," he says. So IBM researchers are exploring a scheme with more distant interconnections among the qubits.Retracing those steps won't be easy. It's not just that any logical gate currently involving two qubits will require thousands of them. Worse, another theorem from quantum mechanics states that, no matter what scheme researchers use, not all of the logical gates can be easily translated from individual physical qubits to diffuse logical ones. Researchers think they can sidestep that problem if they can initialize all the qubits in their computer, in particular states that often do more than half the work of the problematic gates. Nobody can really predict how long it might take researchers to master error correction. But it is time to turn to the problem in earnest, Rigetti says. "So far, a major part of all the researchers who would identify themselves as error correction researchers are theorists," he says. "We need to make this an empirical field with real feedback on real data generated with actual machines." Quantum supremacy is so outdated and obsolete. In quantum computing, error correction is the next best thing.upon research , we found that Quantum error correction has been done before on smaller arrays of qubits, and on other types of qubit than the superconducting transmon qubits that Sycamore uses .An error-correcting unit with measure and data qubits constitutes one 'logical qubit', the building block for implementing and executing quantum algorithms. Yet, significant hurdles remain to achieving practically useful logical qubits.Quantum error correction is done by adding 'measure' qubits to the original data qubits. In one error-correction cycle, the measure qubits compare various combinations of data qubits, then the values of these measure qubits can be read out, after which they are reset. This allows the detection of error events in the data qubits without actually detecting their individual values In fact , the key achievement of the Google team was showing that the probability of errors decreased exponentially when using more qubits. That means even large qubit circuits can be made resilient to error by adding a few more qubits.

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