A

Course Seminar Report

Title

“QUANTUM COMPUTING”

Submitted by

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- # ABSTRACT

Quantum computing is a new and exciting field that intersects mathematics, computer science and physics. Computer systems built on the principles of quantum mechanics are capable of performing calculations deemed unachievable for classical computers. It provides high computational power less energy and exponential speed over classical computers by controlling behaviour of small physical objects that is particles like electrons, photons etc. This paper provides an overview of the principles used for quantum computing like superposition, entanglement and quantum tunnelling, also explains what are qubits, in what conditions a quantum computer works and the recent developments in the field of quantum computing.

- # INTRODUCTION

Quantum computing is a modern way of computing that is based on science of quantum mechanics and its unbelievable phenomena. It is a beautiful combination of physics, mathematics, computer science and information theory. In the present global world scenario quantum computers find many applications due to their exponentially high speed they are being used in cyber security, in the field of machine learning and artificial intelligence etc. They are also being used for simulation, cryptography and many other fields.

The field of quantum computing is gaining hype and most the tech giants like Google, IBM etc invest almost 200 million usd every year in the field of quantum computing. We will be seeing about the most recent developments and about future scope in detail in this paper. In this paper we have discussed about the theoretical aspects of quantum computing in such that a layman can also understand these aspects of quantum computing.

- # DETAILS ON TOPIC
- ## QUANTUM SUPERPOSITION

Superposition is the feature in a quantum system such that an element can exist in multiple states at the same time. The element's final state is only set once that element is measured. For example, electrons in the quantum realm have a quantum feature called spin, which is a type of angular momentum. When the electron is in the presence of a magnetic field, the electron exists in two possible spin states, which is usually referred to as spin up and spin down.

Until each electron is measured, it will have a finite chance of being in either state. Only when it is measured is it observed to be in a specific spin state. One way to think about this is to apply superposition to a coin. In classical physics, a coin facing up has a definite value, it has to be heads up or tails up. Even when no one is observing the coin classical physics makes it known that it must be a head or tail. However, in the quantum realm it is not that simple. The material property such as the face of the coin does not exist until the coin is measured. Such that, the unobserved coin has the head face up and the tail face up simultaneously.

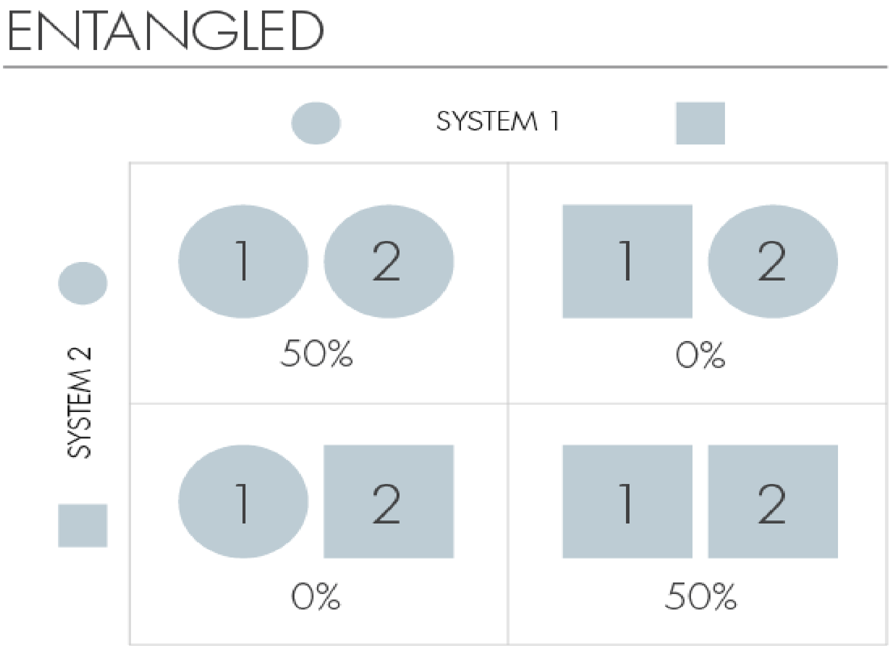
- ## QUANTUM ENTANGLEMENT

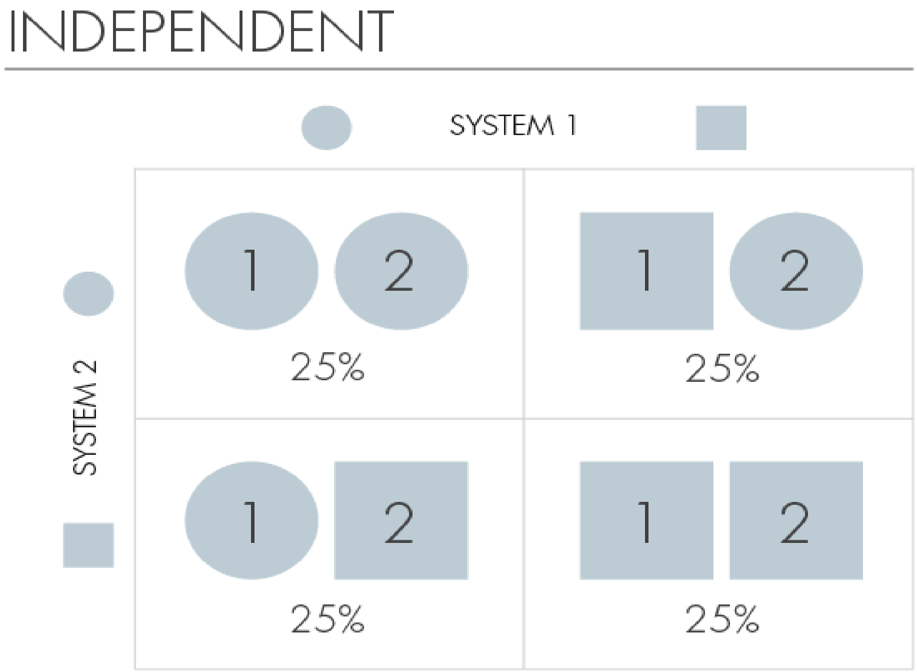
Entanglement arises in situations where we have partial knowledge of the state of two systems. For example, our systems can be two objects that we'll call c-ons. The "c" is meant to suggest "classical," but if you'd prefer to have something specific and pleasant in mind, you can think of our c-ons as cakes.

Our c-ons come in two shapes, square or circular, which we identify as their possible states. Then the four possible joint states, for two c-ons, are (square, square), (square, circle), (circle, square), (circle, circle). The following tables show two examples of what the probabilities could be for finding the system in each of those four states.

We say that the c-ons are "independent" if knowledge of the state of one of them does not give useful information about the state of the other. Our first table has this property. If the first c-on (or cake) is square, we're still in the dark about the shape of the second. Similarly, the shape of the second does not reveal anything useful about the shape of the first.

On the other hand, we say our two c-ons are entangled when information about one improves our knowledge of the other. Our second table demonstrates extreme entanglement. In that case, whenever the first c-on is circular, we know the second is circular too. And when the first c-on is square, so is the second. Knowing the shape of one, we can infer the shape of the other with certainty.





The quantum version of entanglement is essentially the same phenomenon—that is, lack of independence. In quantum theory, states are described by mathematical objects called wave functions. The rules connecting wave functions to physical probabilities introduce very interesting complications, as we will discuss, but the central concept of entangled knowledge, which we have seen already for classical probabilities, carries over.

Inside an atom, when a photon (particle of light) interacts with the strong electric field around the nucleus, it is transformed into two particles *(This is not the only way to create entangled particles). Since* the photon has a zero charge and a zero spin, it is obvious that the two particles created in this process must have charges and spins in such a manner that the total charge and spin for the system is zero. (Since they must be conserved.)

The process mentioned above results into production of an electron (- charge) and a positron (+ charge) both having opposite charges ($E = mc^2$). So, the net charge of the system is zero. But what about their spins? Both electrons and positrons can have two types of spins: spin-up or spin-down. Since the resultant spin of the system must be zero, if one of the particles is spin-up, the other particle must be spin-down.

Thus, the two possible states are:

- Electron (up) and positron (down)
- Electron (down) and position (up)

When the system of electron-positron is not being observed, the system can exist in both possible states at the same time (as seen previously for the electron). Thus, the two particles act as if they're one and exist in multiple superposition states at the same time. Such particles are said to be entangled. But as soon as one of the particles is observed, the wave function collapses and if the measured spin of electron is up, then the spin of the positron automatically takes a down value.

Even if you keep one of the particles (say positron) at the edge of the universe, as soon as you measure the spin of the other particle (electron), the spin of the particle at the edge of the universe becomes defined. This gives an impression that the information between the two entangled particles is transmitted instantaneously or faster than light. But this is not true. Quantum entanglement does not violate relativity because no actual information is passed when the entangled particles affect each other.

Quantum entanglement enables us to send information faster than the speed of light, but doesn't necessarily mean that it transfers classical information faster than the speed of light, classical information in the sense, temperature, weight, etc.

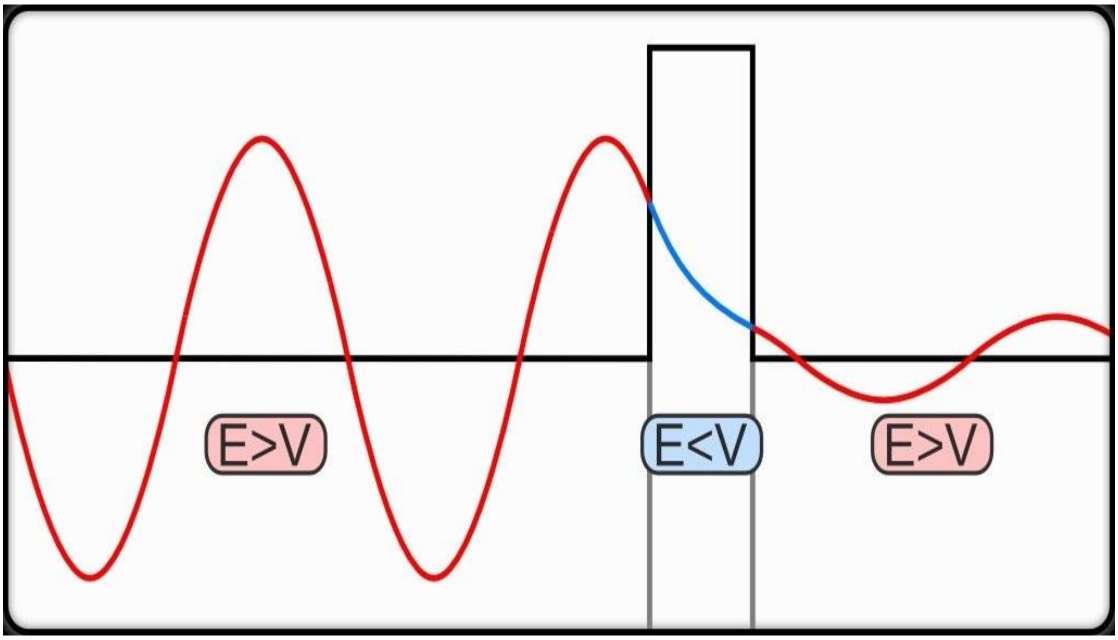
- ## QUANTUM TUNNELING

An outline of the Quantum Tunnelling effect:

When an object encounters a barrier, it is an intuitive understanding that the object will come to a halt or be deflected back. Now, although that's how the world of classical mechanics works, these fairly straightforward situations become slightly wonky when we descend to the quantum realm. In simple terms the quantum tunnelling effect is a quantum phenomenon that occurs when particles move through a barrier that, according to the theories of classical physics, should be impossible to pass through.

Explanation with a figure:

Upon encountering a barrier, a quantum wave will not end abruptly; rather, its amplitude will decrease exponentially. This drop in amplitude corresponds to a drop in the probability of finding a particle further into the barrier. If the barrier is thin enough, then the amplitude may be non-zero on the other side. This would imply that there is a finite probability that some of the particles will tunnel through the barrier as illustrated in the figure below:



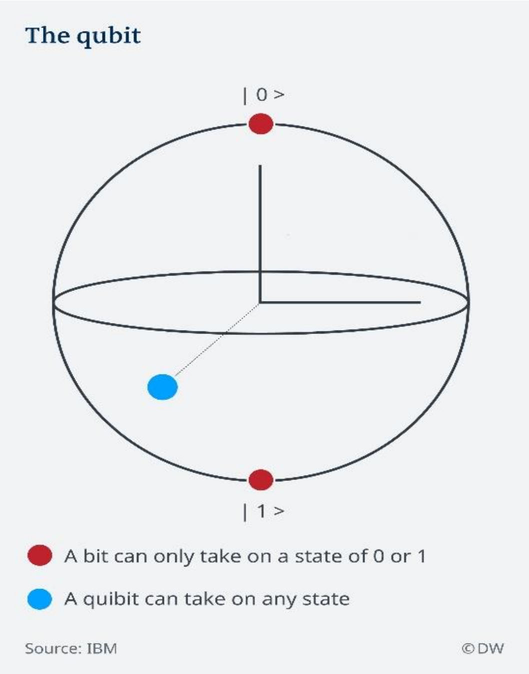
Quantum Tunnelling in stellar fusion reactions.

Fusion occurs much more often than what was originally thought. As all nuclei are positively charged, they repel each other very strongly, and their kinetic energy is very rarely sufficient to overcome such repulsion and allow fusion to occur. If tunnelling effects are taken into account, however, the proportion of hydrogen nuclei which are able to undergo fusion increases dramatically. This phenomenon helps to explain how stars are able to remain stable for millions of years. The process, however, is still not fully supported by science, as an average hydrogen nucleus will undergo over 1000 head-on collisions before it fuses with another.

- ## QUBIT

Instead of bits, which conventional computers use, a quantum computer uses quantum bits—known as qubits. To illustrate the difference, imagine a sphere. A bit can be at either of the two poles of the sphere, but a qubit can exist at any point on the sphere. So, this means that a computer using qubits can store an enormous amount of information and uses less energy doing so than a classical computer.

A single qubit can store 2 bits, so N qubits can store 2^N bits.



In classical computing a bit is basically the electronic charge on transistors and chips. However, in quantum computing, things are a bit complicated, here we use something known as 'Q-Bits' or 'Quantum-Bits', these not only can assume the states 1 or 0, but can also assume every possible state between them.

- **THE QUANTUM CHIP:**

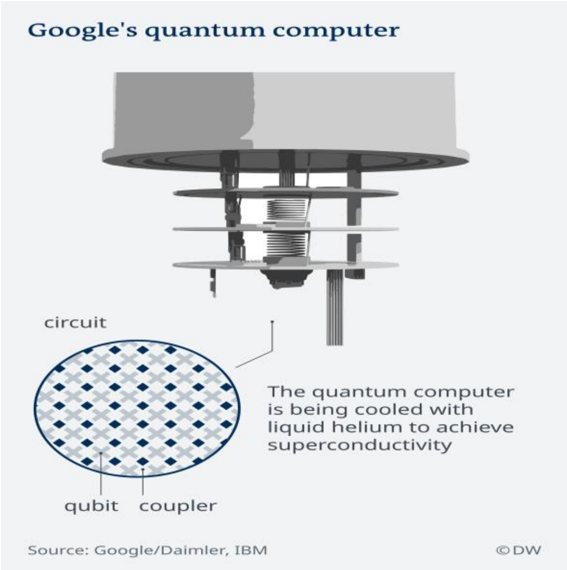
At first glance, a quantum computer resembles a giant chandelier made of copper tubes and wires – that's also what the experts call the structure, a chandelier.

Its core contains a superconducting chip on which the qubits are arranged like on a chessboard pattern.

The qubits on the chip are tiny capacitors made of niobium, which is a chemical element that's as hard as titanium. Their charges, similar to the rotating coins, are made to oscillate. In other words, they have no fixed states. Between them, there are small adjustable couplers. These consists of tiny antennas that respond to microwaves, called resonators. The superconducting chip is located in an electromagnetic microwave field. It operates under extreme cold, at temperatures near absolute zero. For example, the quantum computer developed by google operates at 0.015K.

Such low temperatures can only be achieved by liquefied helium. The engineers use dilution refrigerators with a Helium-3/Helium-4 mix to achieve the extremely low temperatures.

As described above, the operation of a quantum computer demands highly specific and extreme conditions, and the slightest interference from external factors can lead to exponential breakdown of the computing power.



- **ADVANTAGES**
  - In quantum computing qubit is the conventional superposition state and so there is an advantage of exponential speedup which is resulted by handle number of calculations.
  - The other advantage of quantum computing is even classical algorithm calculations are also performed easily which is similar to the classical computer.
  - Quantum computing takes only days or hours to solve problems that would take billions of years using today’s computers.
  - Quantum computers will enable new discoveries in the areas of healthcare, energy, environmental systems, smart materials, and beyond.
  - Finding solutions to challenges like global warming and world hunger may require a quantum system with thousands of millions of qubits.
  - With the aid of quantum computers, chemists can work to identify a new catalyst for fertilizer to help reduce greenhouse emissions and improve global food production. This solution requires the ability to model molecular interactions which are too complex for classical computers, but well-suited for quantum computers.

- Quantum computers will help advance materials science, creating superior new alternatives and greener technologies. One potential quantum computing application is the development of high-temperature superconductors which could enable lossless transmission of energy.

- Quantum computers will help identify materials with properties suitable for high-temperature superconductivity, a level of complexity that is out of reach for the computers we use today.

- Quantum computing can bring speed and efficiency to complex optimization problems in machine learning.

- **DISADVANTAGES**
    - First thing first, it is cost. Quantum computers are cooled by helium dilution refrigeration system (liquid helium) to meet the required operating temperature of chips of about 0.015 Kelvin. This is the main reason for quantum systems being expensive.

    - The disadvantage of computing is the technology required to implement a quantum computer is not available at present. The reason for this is the consistent electron is damaged as soon as it is affected by its environment and that electron is very much essential for the functioning of quantum computers.

- The research for this problem is still continuing the effort applied to identify a solution for this problem has no positive progress.
- Hard to control quantum particles.
- Lots of Heat
- Difficult to build.
- Not enough is known about quantum mechanics.
- When a measurement of any type is made to a quantum system, decoherence is totally broken down and the wave function collapses into a single state.

- **APPLICATIONS**

Many quantum algorithms have been evolved for quantum computers that deliver speedup which is a result of some fundamental mathematical methods like Fourier transform, Hamiltonian simulation, etc.

These algorithms are formed in blocks rather than as a whole combined application since it is not practical. Therefore, it is a great challenge to create quantum applications that are really practically useful along with providing speedup with no error.

The potential utility or say useful application of a quantum computer is an area of ongoing research.

Below are some of the primary applications that we will see soon in the upcoming era:

- **Cryptography:**
  Many important elements of IT security and online security such as e-commerce and electronic secrecy depend on encryption and mathematical algorithms which are difficult to break such as factoring very huge numbers into primes.

Quantum computers can do all these kinds of stuff in exponentially less amount of time.

- **Optimization Problems:**
  Optimizing a problem implies finding the best solution to that problem out of all the possible solutions.

  Quantum computers are best in solving optimization problems. There are a lot of quantum algorithms out of which quantum optimization algorithms might improve the already existing optimization problems which are solved using conventional computers currently. For Example, it can solve travel-related problems in real traffic just like traveling salesman problems to find the shortest path between many cities, going to each city once and returning back. Traveling optimization is the major work under Volkswagen recently.

- **Artificial Intelligence:**
  Artificial Intelligence counts on processing large and complex datasets. It is responsible for learning, inferring, and understanding. It learns until it stops mistaking and making errors in its task. It takes a significant amount of time in learning too. But quantum computing can make it easy and more accurate.

  Quantum computers can train these models over a huge dataset without sticking into the exponential time.

- **Quantum Simulation:**

  It is an important utility in the field of quantum chemistry and material science. This problem needs solving ground state energies of electrons and their wave functions, with or without the presence of some external electric or magnetic field. From the structure of atoms and electrons in chemistry to the rate at which chemical reactions are taking place, everything can be simulated very well. The classical computer when applied to this problem often fails to reach the level of precision needed to predict the rate of the chemical reaction.

- ## FUTURE SCOPE

A significant amount of struggle is remaining before a practical quantum computer can be launched. There are some future advancements that are needed. Some of the future needs are enabling a Quantum Error Correction algorithm that requires low overhead and decreases the error rates in qubits, developing more algorithms with lesser qubits for solving problems.

‘Quantum games’ are predicted in the future that will give unexpected situations and results that a player can experience because quantum computers will take all the possible operations and throws them into the game randomly due to its quantum properties like super positioning and entanglement of qubits. It will be a never-ending experience.

‘Quantum computing in Cloud’ has the potential to overtake business initiatives like in other emerging technologies such as cryptography and artificial Intelligence.

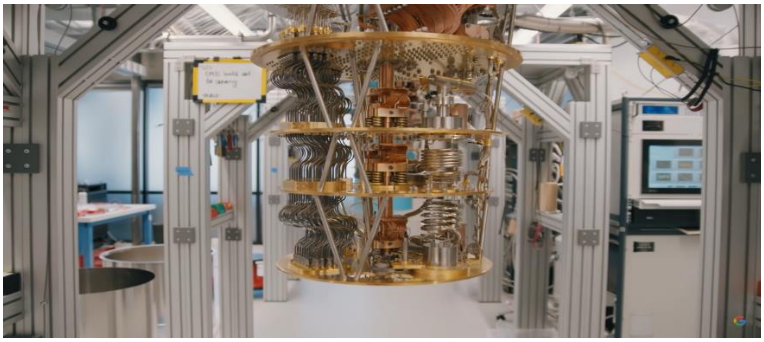
AI and machine learning problems could be solved in a practical amount of time that can be reduced from hundreds of thousands of years to seconds. Several quantum algorithms have been developed such as Grover’s algorithm for searching and Shor’s algorithm for factoring large numbers. More quantum algorithms are coming soon. Google has also declared that it would produce a workable quantum computer in the following 5 years with a 50-qubit quantum computer and will achieve quantum supremacy. IBM is also offering commercial quantum computers soon.

The progress of development in the field of quantum computers depends on many factors. Interest and financial support from the private sector can help developing commercial applications for NISQ computers. It depends on the progress of quantum algorithm development, availability of enough investment in the quantum technology field from government and the exchange of ideas within researchers, scientists and engineers. To illuminate the limitations of quantum technology, a defensive result is also beneficial. It can help in overcoming those negative results which can lead to a new discovery.

- # RECENT DEVELOPMENTS

  - A team of Chinese scientists has developed the most powerful quantum computer in the world, capable of performing at least one task 100 trillion times faster than the world's fastest supercomputers. The Chinese team, based primarily at the University of Science and Technology of China in Hefei, reported their quantum computer, named Jiuzhang, is 10 billion times faster than Google's. To test Jiuzhang, the researchers assigned it a "Gaussian boson sampling" (GBS) task, where the computer calculates the output of a complex circuit that uses light. That output is expressed as a list of numbers. (Light is made of particles known as photons, which belongs to a category of particles known as bosons.) Success is measured in terms of number of photons detected. Jiuzhang, which itself is an optical circuit, detected a maximum of 76 photons in one test and an average of 43 across several tests. Its calculation time to produce the list of numbers for each experimental run was about 200 seconds, while the fastest Chinese supercomputer, TaihuLight, would have taken 2.5 billion years to arrive at the same result. That suggests the quantum computer can do GBS 100 trillion times faster than a classical supercomputer.

  - In the case of Google's Sycamore, 54 qubits were used, which were cooled to fractions of a degree above absolute zero. Only one qubit didn't work but the remaining 53 were enough to demonstrate supremacy over conventional computers on a carefully chosen statistical problem. Google has a 72-qubit device (Bristlecone).



1.GOOGLE'S QUANTUM COMPUTER

- IBM promises 1000-qubit quantum computer a milestone by 2023. IBM has a quantum computer of 53 qubits (Paris) and quantum processors of 65 qubits (Hummingbird). That's a long way from the millions of qubits likely to be needed to do practical computations. IBM plans to launch a 127-qubit processor next year, with a 433-qubit machine hot on its heels in 2022. And by 2023 they expect to hit 1,121 qubits with a processor codenamed Condor, which they think will be the inflection point for the commercialization of quantum technology.

2. *IBM'S QUANTUM COMPUTER*

- A Chinese start-up has unveiled plans to sell a desktop quantum computer costing less than $5,000. The new portable device is one of a range called SpinQ, aimed at schools and colleges. It is made by the Shenzhen SpinQ Technology, based in Shenzhen, China. This is not the company's first quantum computer. Last year, it started selling a desktop quantum computer for around $50,000. The desk in question would need to be sturdy given that the device weighs a hefty 55kg (121 lbs)—about the weight of a small adult. But the new machine will be simpler, more portable and cheaper. "This simplified version is expected to be released in the fourth quarter of 2021".

- # CONCLUSION

Quantum computers have the potential to revolutionize computation by making certain types of classically intractable problems solvable. While no quantum computer is yet sophisticated enough to carry out calculations that a classical computer can't, great progress is under way. Additionally, quantum simulators are making strides in fields varying from molecular energetics to many-body physics. The current challenge is not to build a full quantum computer right away; instead to move away from the experiments in which we merely observe quantum phenomena to experiments in which we can control these phenomena.

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