The Physics of Quantum Computers

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ABSTRACT

This project takes a dive into the world of one of the most promising future technologies, Quantum Computers. It includes an explanation of the key physics concepts behind the working of this technology such as superposition, entanglement and decoherence and emphasizes on qubits the drive force behind this. The relevance of Quantum Computers is also brought out using its application in modern day computing and physics such as Biomedical Simulations and Data optimization. The data is mainly qualitative and includes expert opinions from MIT scientists, scientific journals, IBM research papers and various open source repositories. Through all this data we also analyze the practicality of modern-day quantum computers and the restraints of these in terms of physics: Absolute Zero Conditions, Size Magnitude. The main goal of this project is to explain the underlying concepts and workings of a Quantum Computer and talk about the future of computing if we can overcome the physical barriers.

What is Quantum Computing and how do quantum computers work?

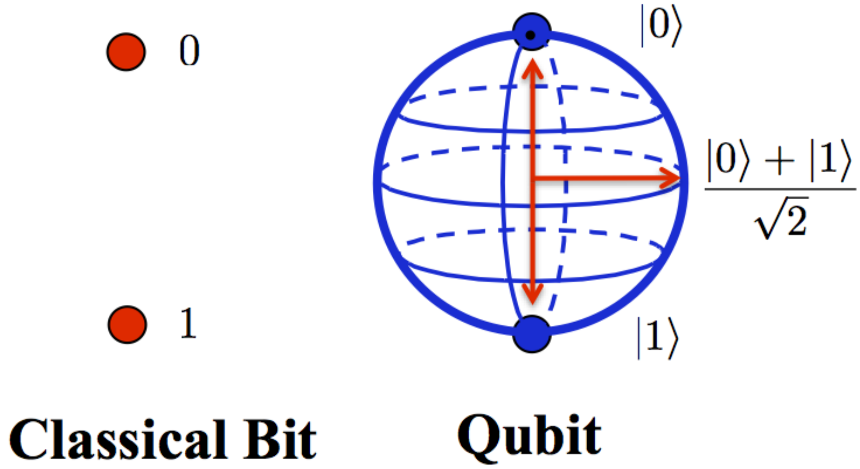
In simple words, quantum computing refers to the usage of the fundamentals of quantum physics, like superposition and entanglement, to carry out computation. This is performed by Quantum Computers.

To understand how quantum computers really work we first need to look at how traditional computers operate. A circuit chip in a traditional computer consists of basic modules which consist of logic gates which are made out of various transistors. A transistor is the simplest form of a data processor in a computer. It can either allow the passage of information or deny it. This information is in the form of a bit. Which are 0 or 1. Combinations of values of transistors make logic gates which together combine to form modules to carry out functions like addition and multiplication. With the help of thousands of modules, you can carry out pretty much any task.

We know that the computer components keep getting smaller year by year. A transistor is essentially a switch for electricity which is composed of electrons. Currently, transistors are less than 15 nano meters or the size of a few atoms. Electrons can now just move around using quantum tunneling. This is where quantum computing comes into the picture, to avoid the physical barrier that modern day computation is reaching with the transistors becoming even smaller.

Now let's look at quantum computers

What are Qubits and Qubits vs Bits



Just like we have bits in conventional computers, quantum computers rely on qubits. Qubits are two-state quantum mechanical systems or particles. This means that qubits actually obey the laws of quantum physics.

Concepts of physics that are behind qubits-

Superposition:

One of the core concepts of quantum physics, superposition is the tendency of a quantum system or particle to exist in two or more states at one time. A well-known experiment that shows this principle is Young's Double Slit Experiment. In this experiment a beam of light passes through two slits and the pattern is recorded on a photographic plate. When one slit is closed, a pattern is observed. But, if both the slits are open, the ray splits into various lines of alternating light and dark waves. Each particle of light, photon, goes through each slit and reaches the plate. The superposition of the particle determines the intensity of light on the screen/plate. This superposition leads to constructive or destructive interference.

Superposition in qubits essentially means that qubits exist in both 1s and 0s at the same time. Well what does this mean? If a quantum computer has multiple qubits, it can assess the various possible outcomes to a problem at once.

These superpositions can be entangled with other objects leading to mathematically related outputs. The mathematical relationships in models can be plugged-in computers to derive relationships that normal computer can't.

Qubits start at 0 and using a Hadamard gate they enter a state in which they exist as both 0s and 1s. Qubit states are represented by a0 and a1.

The sum of probabilities of each quantum state of a qubit is defined by the equation:

| a0 | 2 + | a1 | 2 = 1

A qubit can be any two-level quantum system such as a spin and a magnetic field or even a single photon particle.

Well so why's superposition important?

We know 4 bits can be in 2 to the power 4 or 16 different combinations. Out of these it is in only one at a time. Whereas, qubits can exist in all 16 states at once. This means that 20 qubits can store a million values in parallel (2 to the power 20). Something essential to note is that superposition collapses while the state is measured.

Entanglement

Entanglement is a phenomenon by which particles which share proximity in a system, cannot have defined states independently of other separates particles in the system. In his famous entanglement experiment Albert Einstein dismissed it as 'spooky action at a distance.'

How does Entanglement apply to qubits?

Due to this a change in the state of some other qubits makes a different qubit react too. My measuring the properties of a single qubit, you can also deduce properties of other entangled qubits.

How does the process of computation work?

There are quantum gates which manipulate the inputs of superpositions states, invert probabilities and produces another superposition output. A quantum computer has some qubits which are entangled using quantum gates and then their superposition states are measured, which causes the superposition to collapse and then you get a definite sequence of 0s and 1s. This usually the most probable and optimum computational result.

Types of Quantum Computing

There are 3 types of quantum computing

1. Quantum Annealing

   Quantum Annealing is the least powerful but the most used form of quantum computing presently. These are used for optimization purposes and find the most efficient and quickest answer to a problem.

   It solves optimization problems and probabilistic sampling problems.

   Optimization problem – Searching for best possible solution

   How can we solve these using physics and especially quantum physics?

Well, you can define it as an energy minimization problem. Everything is trying to reach the minimum energy level. We have studied that hot objects tend to transfer heat to cooler surroundings. Hence, using quantum annealing to find the minimum energy solution to something.

Probabilistic Sampling -

Although related to Optimization problems, sampling problems include examining various low energy states and coming up with a solution. This works hand in hand with machine learning.

Both of these cannot be easily solved by traditional computers.

An Example of quantum annealing – Volkswagen is using quantum computing to optimize traffic in Beijing. This can be done by giving each vehicle the best and most efficient path to get from point A to B. Now imagine if we can optimize every single road, airway, waterway, etc. with this.

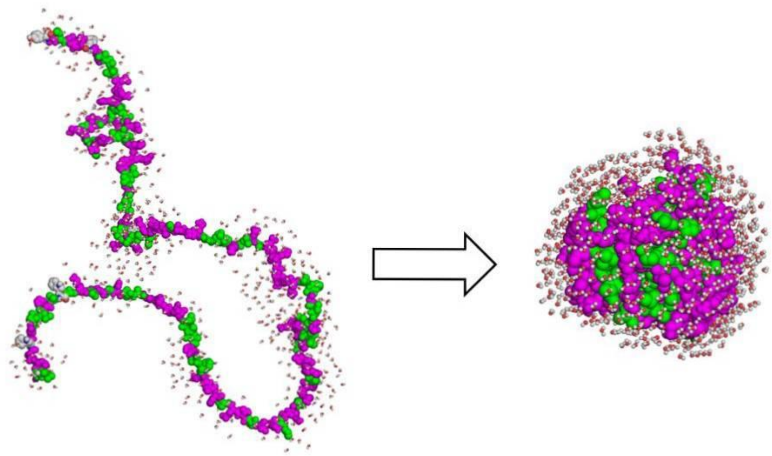
This process is carried out by a Quantum Annealer. The leading brand that produces these annealers is Dwave.

A 2000 qubit quantum annealer by Dwave.

2. Quantum Simulators

Quantum Simulators can be defined as digital quantum computers. They allow us to study quantum systems in labs and model it. This won't be possible with a supercomputer which can handle close to only 30 particles. They provide insight into specific problems. Quantum Simulators can be used to simulate problems with quantum physics concepts such as entanglement and superposition.

An example - It has been used in biochemistry to simulate the folding of proteins. Mapping this folding sequence can help against diseases like Parkinson's and Alzheimer's.



3. Universal Quantum Computing

This is the most powerful and most advanced form of quantum computing. Scientists believe that we would require 10,000 to 100,000 qubits for this. As of now, we have barely hit triple digits in terms of total number of qubits in a machine. The main objective is to use a quantum machine to solve any problem using quantum computing be it annealing problems, simulation problems, etc. It should also achieve quantum supremacy in the solution of every problem. A quantum computer achieves quantum supremacy when it solves a problem that cannot be solved by a traditional supercomputer.

A possible representation of a universal quantum computer

These very powerful machines will be able to carry out algorithms that scientists developed theoretically but could not implement in computation. The most famous of these are Shor's Algorithm and Grover's Algorithm.

Quantum Computer vs Normal Computers and Supercomputers

Quantum Computers	Supercomputers
Usage of quantum physics processes to carry out computation	Usage of large computation large computation resources like multi core processors, large databases and General Processing GPUs.
Uses Qubits for Computation and Quantum gates	Uses Bits for Computation and classical gates
Will be used to solve probabilistic and optimization problems and can be used to make systems more efficient	It is used in various industries currently like weather forecasting, etc. To solve problems with large datasets that require raw computation
Still in development Annealers are available but they do not have a lot of applications. Universal Quantum Computers are not yet developed due to various physical constraints.	Fully developed and used in various industries like meteorology.

Applications of Quantum Computing

Quantum Computing in Biology

In 2018, a study conducted in the Viterbi School of Engineering at the University of Southern California showed an application of Quantum Computation in Biology and especially, genetics. For this they used an annealer by a famous brand D Wave. We know that the genes are instructions for the production of proteins. Due to the environment, the cells might have to produce a specific type of gene. This process of controlling certain proteins is called gene regulation. The proteins that regulate genes have to attach themselves to a particular genome by locating it. More understanding of this is required so that scientists can find out how mutations in proteins lead to certain conditions. To learn more about DNA transcription, the researchers at USC sought out to conduct research on the binding of proteins. Why is this important? The successful binding of proteins is less than a percent successful. Using Machine learning models, they were able to find out whether a particular sequence of DNA will make a successful binding site. A quantum machine mapped these patterns and could estimate the strength of protein binding. This was an important experiment as it brought out the future of quantum computing in genetics and how this can be used to identify whether a site will be weak or strong.

Quantum Computing in Physics

Quantum Computers are being used by CERN to analyze the large data from the LHC (Large Hadron Collider). LHC can carry out a billion particle collisions per second. These collisions produce about a petabyte of data per second. Even though most of this data is not utilized but staggering amounts of data are still produced. This computing relies one million computer cores. By 2027, this computation of data is set to increase a hundred times. Companies like IBM have built quantum computers that can carry out commercial calculations. CERN started collaborating with IBM.

The team at CERN used IBMs quantum computers and simulators. They used quantum computing along with machine learning to classify and segregate data. They analyzed the data from Higgs experiments. They did not publish the results of their Higgs experiments. Using the quantum computer, they were able to train five variables and in their words the results came very close to or even better than using their classical classifiers. Hence, this application of Quantum Machines in LHC shows that there is a lot of scope for quantum computing in the field of particle physics.

Other applications in physics include

Quantum Computers can be used to simulate the most basic particle interactions of our universe, Fermions and Bosons. Fermions are the blocks of matter and Bosons are particles that pull other matter. Scientist at Fermilab have figured out a way to model these interactions. Earlier scientists were able to model fermions, but they could not figure out a way to model bosons. Fermilab found a method to model both. Fermions could be given the values of either 1 or 0 signifying either occupied or unoccupied. But bosons have varying states. So, a single qubit cannot be used for boson representation.

Hence, they decided to represent bosons a harmonic oscillator. You can represent harmonic oscillators by only a few qubits on a quantum computer. This trial worked and they could calculate the bosons systems properties with 20 qubits.

Other non-scientific applications of quantum computing

Database Searching:

The entry to be found must be compared with every other record in the database to return the values when a database is being traversed by a traditional computer. Whereas, Quantum Computers will be able to that in the square root of time and operations. So, this will be extremely beneficial for companies like Facebook and Government databases for example Aadhar, which have databases of more tens of millions of users.

Constraints of Quantum Modern Day Computing

Sensitivity with environment:

The interactions with the environment are very sensitive and a slight variation can cause the system to collapse. This is known as decoherence. This is a phenomenon with which qubits interact with the environment, change states uncontrollably and lose their information. Decoherence jeopardizes the property of qubits to stay under entanglement and superposition. Decoherence mainly occurs when multiple qubits entangle with their environment. The various causes of this are radiation, light, sound, vibrations, heat, etc. All of these factors are very tough to control in the natural environment and hence specialized vacuum chamber need to be created for quantum computers. There is also time limit after which qubits entangle with the outside and disrupt their quantum information processing. Coherence length is the time for which a qubit can survive in a quantum system with its properties. The record for the coherence length is 39 minutes.

This may seem like a small duration but in this time frame a qubit can carry out millions of operations. This still makes quantum computers impractical as the surroundings need to be perfectly avoided and there should be negligible interferences with the surroundings. But even with that current qubits cannot last for long and hence cannot be used for normal use cases. Hence, to make the qubits last longer in the quantum state QEC is required. Quantum Error Correction (QEC) process of protecting information from loss due to decoherence. Further research is required in this field to make Quantum Computers commercially available. We can use various cloning algorithms to clone qubits to minimize information loss.

Absolute Zero Conditions: Qubits have to be placed in absolute zero conditions. 0 Kelvin or –273.15 degree Celsius. To explain this phenomenon, we can take the following scenario. We know that qubits exist in two possible values, 0 and 1. Let's consider these to be the two states of our qubit. So, the two states 0 and 1 are achieved due to varied voltages. Till a certain voltage it's in 0 and from that till a certain voltage it's in 1.

Let's say for 0.25-0.5v its in state X and for 0.5-0.75v its in state Y. The ranges in actual quantum computers are way smaller than this. This means that for a slight variation in voltage, the qubit can be pushed to another quantum state and there is observed error. Hence, we need the absolute zero temperature, as in this coldest possible temperature, there is negligible movement in molecules and atoms and hence there are no state and voltage fluctuations. The less energy there is in the system, the lesser the fluctuation in voltage.

Well this seems great theoretically, but we have till date never achieved absolute zero. That does not mean we have not reached close or in the future we won't achieve this. Companies right now are able to operate their quantum computers at –450 Fahrenheit. Just 9.67 Fahrenheit away from absolute zero!

However, absolute zero conditions will greatly improve the Coherence length and efficiency of the quantum computers. As of now, we can only keep them in giant laboratories and offices as not everyone has a large hyper cooled room for their quantum computer.

Number of Qubits required for Quantum Supremacy

In 2001, IBM came out with a 7-qubit quantum computer. IN 2007, D-Wave came out with a 16-qubit quantum computer. In October of 2019, IBM unveiled a quantum computer with 53 qubits! This is currently the quantum computer with the most qubits.

But we need way more qubits than this to actually carry out the high-level applications of quantum computing I.e. Quantum Supremacy. Quantum Supremacy is described as the aim of a quantum computer to solve a certain problem that a traditional computer cannot solve in a rational time frame. So, the main giants that quantum computers need to beat are super computers. The best supercomputer can carry out operations at 10^18 FLOPS (Floating-Point Operations Per Second). A paper states that to achieve this Quantum Computer will need upwards of 10,000 qubits. For current applications 200-400 qubits will be sufficient based on the use case but a way higher number is required for the future applications.

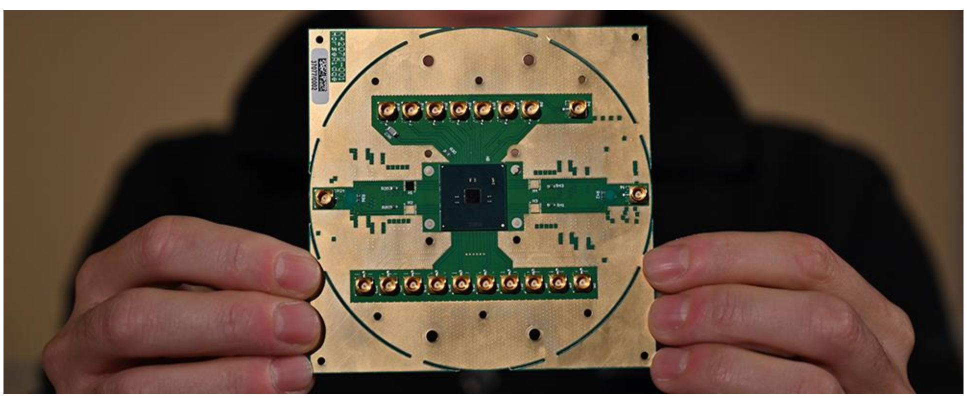
This at moment is infeasible as we need about 5-8 times our current qubit count to compete with supercomputers in modern day computation.

Future of Quantum Computing and Recent Advancements

Cryogenic Chips:

This invention brings us the closest to actual production of quantum computers. Qutech has created an Integrated Circuit (IC) that can control qubits at sub 270-degree temperatures. Like modern day ICs, thanks to this development you can have your qubits and their controllers on the same chip. We know that the information inside qubits gets lost due to decoherence at normal temperatures and we need temperatures close to absolute zero. The best benefit of this is the scalability. So due to this chip the electronic applications that will be connected to a qubit will be connected to this IC directly. Hence instead of attaching a wire to every qubit and connecting it to the application, you can directly attach it. Can you imagine a wire coming out of each of the million pixels on your television screen?

This IC, Horse Ridge, has a CMOS integrated circuit. CMOS or Complementary Metal Oxide Superconductor is used to dissipate less power and are now the conventionally used transistors. These CMOS integrated ICs can operate at 3K or –270-degree Celsius. Each of the ICs have 4 by 32 matrix and can control 128 qubits.

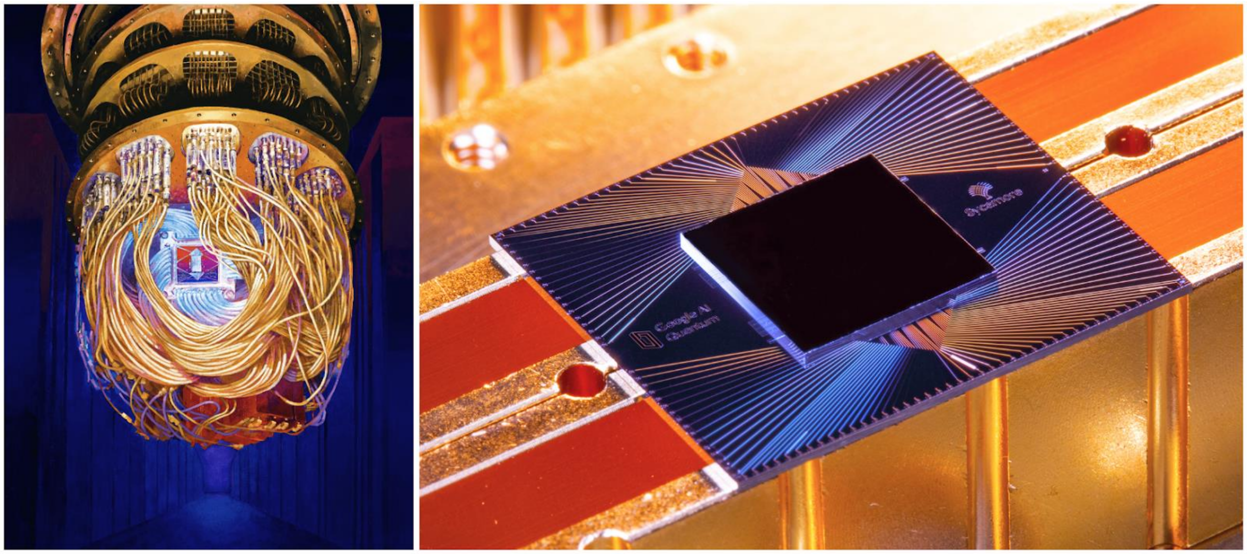


The Qutech Cryogenic Chip

Google's Sycamore:

In October od 2019 Google announced Sycamore, a processor. Consisting of 54 qubits (53 working), this can carry out a calculation in 200 seconds that would take the world's fastest computer close to 10,000 years. Hence, somewhat achieving Quantum Supremacy.

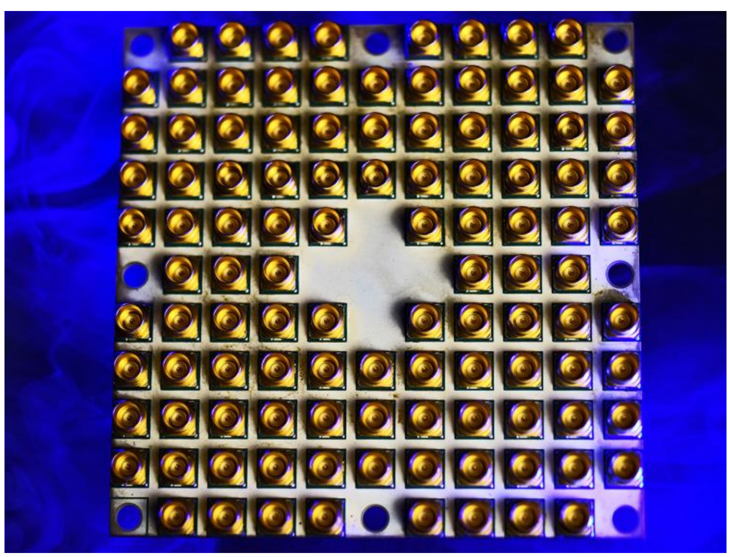
The task that this Quantum Computer completed was of pseudo random number generation. Essentially, qubits were entangled through gates and Each run produced a binary bit string (s string of bits like 0010101). After a million runs, it started producing random bit strings.



The Sycamore chip (right) and its quantum computer (left)

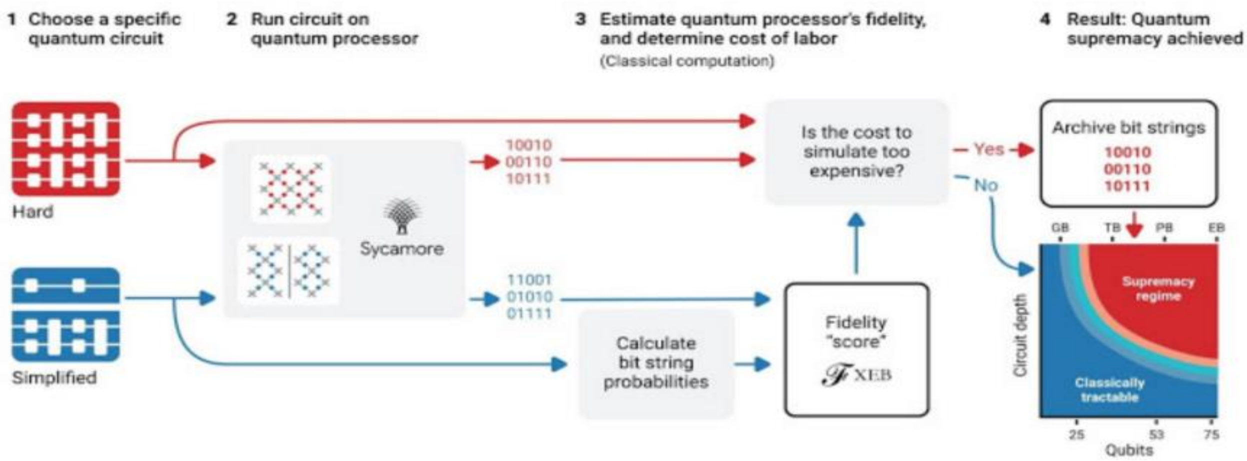
Intel Tangle Lake:

In 2018, Intel unveiled its Tangle Lake Chip, a 49-qubit chip. It’s a small 3 inch by 3-inch chip. It is based on the research conducted by Intel on Spin Qubits. These rely on a single electron spin in silicon and resemble. These spin qubits are better than the previously used superconducting qubits as spin qubits work with the semiconductor components of silicon.



Why this algorithm?

A- The randomness obtained in this quantum simulation is very difficult for normal supercomputers to handle. Google deliberately chose an algorithm they would be able to perform better at compared to a supercomputer.



Process for demonstrating quantum supremacy.

CONCLUSION

Quantum Computers are one of the most promising technologies of the future and judging by the way research is being conducted, it can become a reality in the distant future. While your qubit iPhone will not be hitting stores yet, we have made some considerable strides in this field. We already have annealers and simulators for commercial use, but universal quantum computers require a very large number of qubits, which will take several years to make. We also need to overcome various challenges such as decoherence and the harsh temperature conditions to make these a commercial reality. However, the applications and advantages are endless. It can potentially help us find the cure and prevention to any disease. We can optimize fuel and resource use in the entire world saving billions of dollars. This amount of power can also be enough to break encryption, cracking your passwords and credit card details and revealing your data. There is no doubt that this field will strongly impact the future of computation and physics.

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