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Quantum Computers – Hardware

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ABSTRACT

In this paper, we describe the hardware details of various Quantum Computers available and under research.

General Terms

Algorithms, Documentation, Performance, Design, Reliability, Experimentation, Theory.

Keywords

Quantum computing, Hardware, Performance, Comparison, D-wave quantum computer, IBM Quantum computers, Qubits.

1. INTRODUCTION

The first thought of computer generated with the idea of counting. Man always wanted the work to be done accurately with less time and the first step towards this was the ABACUS.

Initially all the calculations were done in decimal system but somewhere man was aware of binary system (on and off state) which was more simpler and it was implemented in electrical circuit with basic assumption that voltage supplied implies state 1 and no voltage implies state 0.Eventually the invention of transistors had led to many research as it was capable of delivering the input states serially. Now it was time to find a material that can make transistor work more efficiently, that can sustain variability, a semiconductor (that is neither an insulator nor conductor) and that was found to be SILICON. There were many more near to ideal semiconductor than silicon but due to its ease availability and nature friendly property it was chosen as most suitable material.

2. Building blocks of Classical Computers

As the research continued in electronic sector, the efficient utilization of transistors led to invention of electronic calculators. It was built with silicon integrated chips and had the ability to compute the decimal numbers given as input, converting it to binary process the calculation and give back the output in decimal but it had no memory in it.

But man as always wanted to have a better equipped device that can store the calculations he made and retrieve it back whenever he needed, this led to the development of classical computers which can not only carry out the calculation but also stores it. Initially this was restricted to play with only numbers and as the technology advanced it started dealing with processing the text ie, it could convert the natural language into machine level language manipulate the things as per the instruction and give the result in the same original language.

Now man wanted his computer not only to compute things but also to visualize and process the image according to his imagination which led to a new field of graphics and animations. These things were magical and could create imaginary things to be realistic.

In parallel with these development humans had put their foot step in the world of internet. We can even say internet brought the universe together, now all of us are connected to different part of the universe because of internet. Millions and millions of data are being stored, exchanged and manipulated in this era. The classical computers which we are using now are running with basic unit called bits ie 0 and 1.If there is n-bit of data then we can have 2^n states but classical computers can access single state at a time so to access 2^n states it has to repeatedly run for same time.

According to the survey more than 295 Exabytes of data is stored in the world per day but its being difficult for normal computers to access these amount of data. All of our needs, works, personal details and confidential things are preserved in these digital word. Along with the advancement of technology security issue is also a major problem.

3. Need of new materials

So there is a serge for better device that has more storage capacity, that works at faster rate, secure our data in a better way and perhaps that works more efficiently than a classical computers. Scientist found a solution that it was possible with quantum computers that works on the basis of qubits (a superposition state of 0 and 1) and not bits. But this was not possible with normal silicon chips.

Here comes the urge for new material that can stay in multiple state at a time and exhibit quantum level features ie it should have qubit as its fundamental. Since qubit has special property of both matter and light, it can stay in multiple state simultaneously.

For this we need a system comprising a single electron trapped in a semiconductor nanostructure. Here, the electron's spin serves as the information carrier. The researchers were able to precisely demonstrate the existence of different data loss mechanisms and also showed that stored information can nonetheless be retained using an external magnetic fiield.

An experiment was done on evaporated indium gallium arsenide onto a gallium arsenide substrate to form the nanostructure. As a result of the different lattice spacing of the two semiconductor materials strain is produced at the interface between the crystal grids. The system thus forms nanometer-scale "hills" - so-called quantum dots.

When the quantum dots are cooled down to liquid helium temperatures and optically excited, a singe electron can be trapped in each of the quantum dots. The spin states of the electrons can then be used as information stores. Laser pulses can read and alter the states optically from outside. This makes the system ideal as a building block for future quantum computers.

If there is n-qubit of data then it can have 2^n states, as we now with classical computers it has to access each state at a time serially but with quantum computers we can access all the 2^n states at a time in parallel. It is estimated that if we can build a ideal 1000qubit quantum computer we can access the complete data in the universe at a time.

4. History of Materials

We come across many efforts and research in finding very efficient superconducting material to build a quantum computer and here are some of them:

- A metal called NIOBIUM (in contrast to conventional transistors which are mostly made from silicon). When this metal is cooled down, it becomes a superconductor, and it starts to exhibit quantum mechanical effects. - February 13, 2007 (annealing quantum computers)

- BISMUTH TELLURIDE that allows electrons on the surface of the material to act like photons, travel with no loss of energy, and maintain specific spins for an indefinite period of time. Those properties make the new form of bismuth telluride an ideal semiconductor for quantum computer chips. "This material has three unique properties," said Yulin Chen, a Stanford physicist and co-author of the paper, "and those properties allow us to make low-energy spintronic devices that could be a successor to silicon."(jun17 2009)

- LAYERED HEXAGONAL BORON NITRIDE, which is a bit of a mouthful, but all you really need to know about it is that it's only one atom thick – just like graphene – and it has the ability to emit a single pulse of quantum light on demand at room temperature, making it ideal to help build a quantum optical computer chip. (nov 27 2015)

5. The “D-WAVE” Quantum Computers

D:Wave

The Quantum Computing Company™

D-Wave was founded by Haig Farris (former chair of board), Geordie Rose (CTO and former CEO), Bob Wiens (former CFO), and Alexandre Zagoskin(former VP Research and Chief Scientist). Farris taught a business course at the University of British Columbia(UBC), where Rose obtained his Ph.D., and Zagoskin was a postdoctoral fellow. The company name refers to their first qubit designs, which used d-wave superconductors.

D-Wave operated as an offshoot from UBC, while maintaining ties with the Department of Physics and Astronomy. It funded academic research in quantum computing, thus building a collaborative network of research scientists. The company collaborated with several universities and institutions, including UBC, IPHT Jena, Université de Sherbrooke,University of Toronto, University of Twente, Chalmers University of Technology, University of Erlangen, and Jet Propulsion Laboratory.These partnerships were listed on D-Wave's website until 2005. In June 2014 D-Wave announced a new quantum applications ecosystem with computational finance firm 1QB Information Technologies (1QBit) and cancer research group DNA-SEQ to focus on solving real-world problems with quantum hardware.

D-Wave operated from various locations in Vancouver, British Columbia, and laboratory spaces at UBC before moving to its current location in the neighboring suburb of Burnaby. D-Wave also has offices in Palo Alto and Vienna, United States of America.

As the tagline of the company says, the D-wave company is completely oriented towards quantum computers. This is the first company to commercialize the quantum computer.

5.1. The Quantum Transistor

Its a known fact that transistors are the building blocks of a classical computer. Transistor can exist in only two states(0 and 1). The basic idea of the quantum computer is that we need a material that can exist in both 0 and 1 states at a time. In other words we need a quantum transistor which is different form the classical transistors.

Here comes the idea of Superconducting Quantum Interference Device, SQUID. The term 'Interference' refers to the electrons - which behave as waves inside a quantum waves, interference patterns which give rise to the quantum effects. The reason that quantum effects such as electron waves are supported in such a structure - allowing it to behave as a qubit - is due to the properties of the material from which it is made.

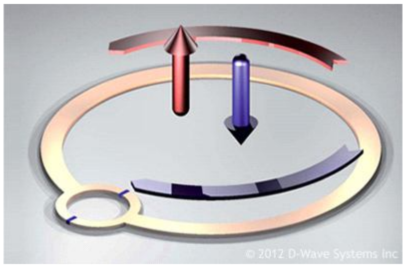

Figure 5.1 - Schematic of a superconducting qubit, the basic building block of the D-Wave Quantum Computer

The large loop in the diagram is made from a metal called niobium (in contrast to conventional transistors which are mostly made from silicon). When this metal is cooled down, it becomes what is known as a superconductor, and it starts to exhibit quantum mechanical effects. A regular transistor allows you to encode 2 different states (using voltages). The superconducting qubit structure instead encodes 2 states as tiny magnetic fields, which either point up or down. We call these states +1 and -1, and they correspond to the two states that the qubit can 'choose' between. Using the quantum mechanics that is accessible with these structures, we can control this object so that we can put the qubit into a superposition of these two states as described earlier. So by adjusting a control knob on the quantum computer, you can put all the qubits into a superposition state where it hasn't yet decided which of those +1, -1 states to be.

5.2. The SQUID Fabric

Practically, there is no use of a single SQUID. If an array of these SQUID is made then it is of some use. In order to go from a single qubit to a multi-qubit processor, the qubits must be connected together such that they can exchange information. This is achieved through the use of elements known as couplers. The couplers are also made from superconducting loops. By putting many such elements (qubits and couplers) together, we can start to build up a fabric of quantum devices that are programmable.

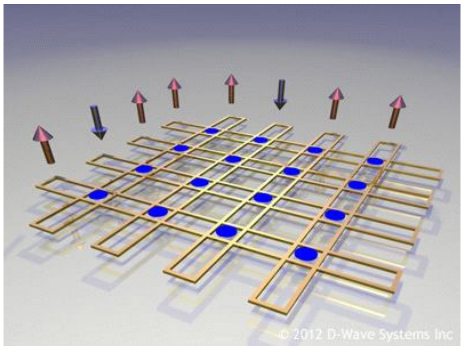

Figure 5.2 - A schematic illustration of 8 qubit loops (gold). The blue dots are the locations of the 16 coupling elements that allow the qubits to exchange information

5.3. The Circuitry

There are several additional components necessary for processor operation. A large part of the circuitry that surrounds the qubits and couplers is a framework of switches (also formed from Josephson junctions) forming circuitry which both addresses each qubit (routes pulses of magnetic information to the correct places on chip) and stores that information in a magnetic memory element local to each device. The majority of the Josephson junctions in a D-Wave processor are used to make up this circuitry. Additionally, there are readout devices attached to each qubit. During the computation these devices are inactive and do not affect the qubits' behavior. After the computation has finished, and the qubits have settled into their final (classical) 0 or 1 states, the readouts are used to query the value held by each qubit and return the answer as a bit string of 0's and 1's to the end user.

The main difference that can be observed in Quantum circuitry when compared to the classical one is that, there is no large space dedicated for the cache memory. Each SQUID has its own memory and there is no need of cache.

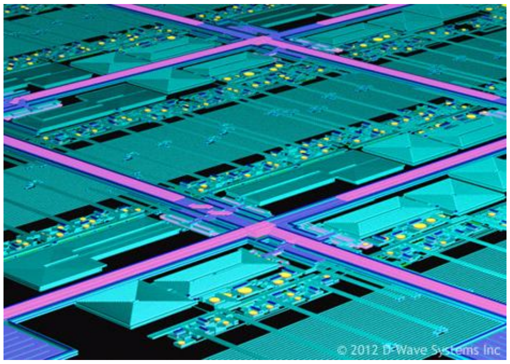

Figure 5.3 - The qubits are now shown as long pink strips, The green and yellow elements that sit in the spaces between qubits are components which make up the programmable circuitry. The yellow dots are Josephson junctions embedded within this circuitry.

5.4. The Quantum Processor

The fabrication of the quantum processor is almost similar to the classical silicon processor. The chips are 'stamped' onto a silicon wafer using techniques modified from the processes used to make semiconductor integrated circuits. There are several processors visible on this wafer image. The largest, near the bottom center, has 128 qubits connected together with 352 connection elements between them. The qubit/coupler circuits on each individual processor are the cross-hatched looking patches. This is known as a Rainier processor and it was the type of processor found inside the D-Wave One.

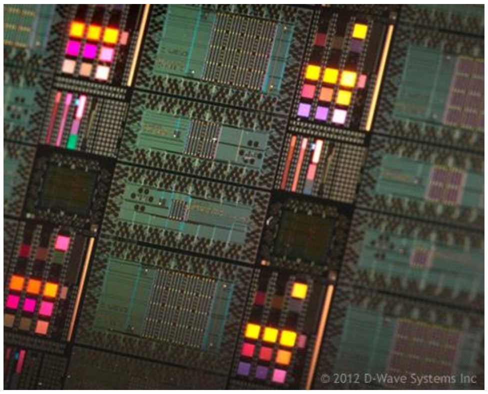

Figure 5.4 - Photograph of a wafer of Rainier processors, including the 128-qubit processor used in the D-Wave One™ QC system.

The techniques learned from the semiconductor industry have resulted in the construction of a Large-Scale Integration (LSI) fabrication capability owned by D-Wave. This fabrication capability is unique. The fabrication process that has been developed is able to yield LSI (128,000+ Josephson junctions for the 1000 qubit processor in the D-Wave 2X) superconducting circuits. It is the only superconducting fabrication facility capable of yielding superconducting processors of this complexity. Fabrication yield is critical to improving processor performance and requires on-going significant investment, and in order to maintain historical qubit doubling rates, investments are being made to improve the capability into VLSI (1,000,000+ Josephson junction per processor) territory over the next five years.

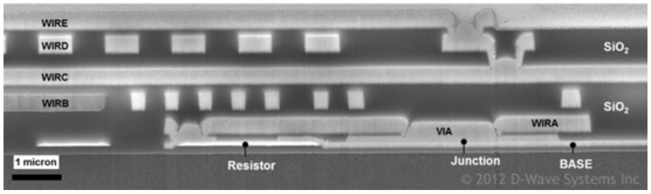

Figure 5.5 - A microscope cross-section of a D-Wave processor, fabricated using a 6-metal wiring layer process. The layer which is used to form the Josephson junctions is shown near the bottom of this sandwich structure

5.5. The Temperature Factor

Reduction of the temperature of the computing environment below approximately 80mK is required for the processor to function, and generally performance increases as temperature is lowered - the lower the temperature, the better. The latest generation D-Wave 2X system has an operating temperture of about 15 millikelvin. The processor and parts of the input/output (I/O) system, comprising roughly 10kg of material, is cooled to this temperature, which is approximately 180 times colder than interstellar space! Most of the physical volume of the current system is due to the large size of the refrigeration system. The refrigeration system used to cool the processors is known as a dilution refrigerator.

The specialized equipment to allow cooling to these temperatures is available commercially and runs reliably. The refrigeration technology is also mature enough that the system has a turnkey operation. The computer can be cooled down to operating temperature within several hours, and once this temperature is reached remain cold for months or years.

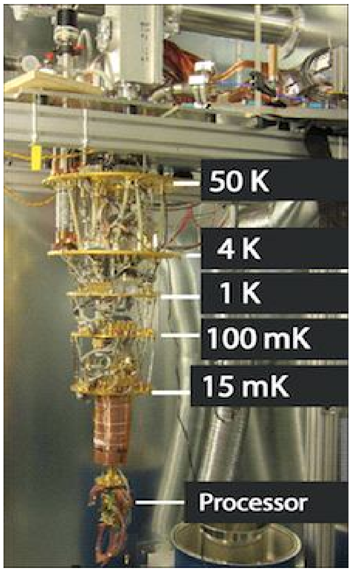

Figure 5.6 – Temperature in different levels.

5.6. The Final Outlook

Figure 5.7 - Using the SQUID as the building block, D-Wave systems has built the Quantum computer which looks as this

5.7. Generations of Quantum Computer

The computer we use today did not come from infinity. Many previous versions have contributed in the development of the modern computer. Similar is the case with D-Wave quantum computers. Many generations of quantum computers have passed to give us the present 1000 qubit quantum computer.

5.7.1. Orion Prototype

On February 13, 2007, D-Wave demonstrated the Orion system, running three different applications at the Computer history museum in Mountain View, California. This marked the first public demonstration of, supposedly, a quantum computer and associated service. The three applications include:

1. Pattern Matching

It performed a search for a similar compound to a known drug within a database of molecules.

2. Seating Arrangement

It computed a seating arrangement for an event subject to compatibilities and incompatibilities between guests.

3. Sudoku

It solved the sudoku puzzle.

5.7.2. D-wave one

On May 11, 2011, D-Wave Systems announced the D-Wave One, an integrated quantum computer system running on a 128-qubit processor. The processor used in the D-Wave One code-named "Rainier", performs a single mathematical operation, discrete optimization. Rainier uses quantum annealing to solve optimization problems. The D-Wave One is claimed to be the world's first commercially available quantum computer system.

5.7.3. D-wave two

In early 2012, D-Wave Systems revealed a 512-qubit quantum computer, code-named *Vesuvius*, which was launched as a production processor in 2013.

5.7.4. D-wave 2x

On August 20, 2015, D-Wave released general availability of their D-Wave 2X computer, with 1,152 qubits. The D-Wave 2X processor is based on a 2,048-qubit chip with half of the qubits disabled, but these may be re-activated later on.

5.8. The Commercial Aspect

D-Wave Systems Inc., announced that it has entered into a new agreement covering the installation of a succession of D-Wave systems located at NASA's Ames Research Center in Moffett Field, California. This agreement supports collaboration among Google, NASA and USRA (Universities Space Research Association) that is dedicated to studying how quantum computing can advance artificial intelligence and machine learning, and the solution of difficult optimization problems. The new agreement enables Google and its partners to keep their D-Wave system at the state-of-the-art for up to seven years, with new generations of D-Wave systems to be installed at NASA Ames as they become available.

Since 2013, when the previous generation 500-qubit D-Wave Two™ system was installed at NASA Ames, scientists at Google, NASA and USRA have been using it to explore the potential for quantum computing and its applicability to a broad range of complex problems such as web search, speech recognition, planning and scheduling, air-traffic management, robotic missions to other planets, and support operations in mission control centers.

Installation of the new D-Wave 2X™ system was recently completed and the system is now operational at NASA Ames, one of the world's leading high performance computing (HPC) centers.

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5.9. The Challenges

Its said that D-wave systems is only using a part of the capabilities of a quantum computer. Its only using the concept of quantum annealing. There are still many more concepts in quantum computer ready to be invaded. D-wave systems is producing a pseudo quantum computer, as its quoted. But the reality is this the quantum computer manufactured by D-wave is 36,000 times faster than the super computer. And also the company is constantly working on improving this. Hope to see the next version of D-wave quantum computer over coming all these.

5.10. Quantum Computer ahead

For the past 8 years, the number of qubits on D-Wave's processors has been steadily doubling each year. This trend is expected to continue. To create processors with numbers of qubits up to around 10,000, the current fabrication process can simply be scaled to add more qubits in the same way that they are arranged currently. To go beyond ten thousand into hundreds of thousands or millions of qubits will require processor redesign, but there are certainly ways in which this can be achieved and it is not seen as a fundamental obstacle to improving the hardware.

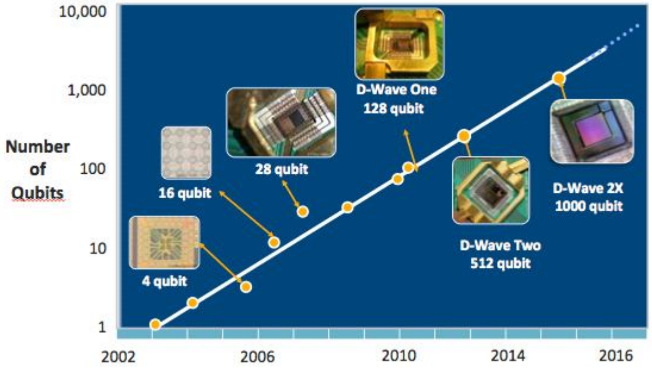


Figure 5.8 – Development curve

6. The “IBM” Quantum Experience

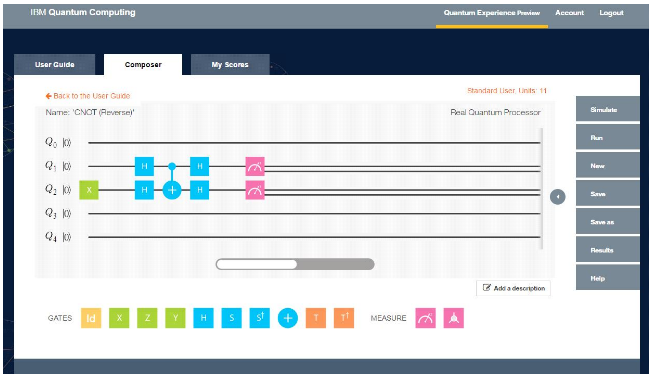
The world’s first quantum computing platform delivered via the IBM Cloud.

The IBM Quantum Experience represents the birth of quantum cloud computing, offering students, researchers, and general science enthusiasts hands-on access to IBM’s experimental cloud-enabled quantum computing platform, and allowing users to run algorithms and experiments, work with quantum bits (qubits), and explore tutorials and simulations around what might be possible with quantum computing.

The results of more than 35 years of IBM Quantum Computing research are now available for exploration at the click of a button.

> “ Controlling a quantum system with enough precision to make it compute, it’s not just about achieving more computation power, it will allow us to understand nature itself better. ”
>
> Dr. Jay Gambetta, Manager,
> Theory of Quantum Computing and Information IBM Research

6.1. The IBM Quantum Experience cloud platform for quantum computations (5 qubit system)



Standard User, Units: 11

Name: 'CNOT (Reverse)'

Figure 6.1 – IBM's 5 qubit system on cloud

The user can use the composer to compose his own algorithm (IBM calls these algorithms scores analogous to musical scores) that can be run on a real quantum processor present at the IBM quantum computing laboratory in Yorktown Heights, New York. This is facilitated by using the IBM cloud – The IBM Bluemix.

The cloud provides a user interface between the user and the real processor. The scores which request the use of the real processor are queued for executions and the results are made available to the user once his score has been executed.

6.2. Overview of the IBM Quantum Processor

The IBM system uses superconducting quantum interference devices as qubits (quantum bits) . At present the processor houses 5 qubits which are maintained at temperature near to the absolute zero using appropriate refrigeration.

One of the major obstacles to building a quantum computer is creating and packaging high-quality qubits in a way that enables them to perform complex calculations in a controllable and scalable manner. Qubits are very fragile. Expose them to electromagnetic radiation, sound or variations in temperature, for example, and you introduce what’s known as quantum errors or DE coherence. Simply put, the qubits lose their quantum information and their ability to compute. That’s why quantum systems are stored in quiet places and chilled by refrigerators - like the cylindrical device pictured above in the IBM Quantum Computing Lab - to near absolute zero. How cold is that? It’s a temperature consistent with outer space.

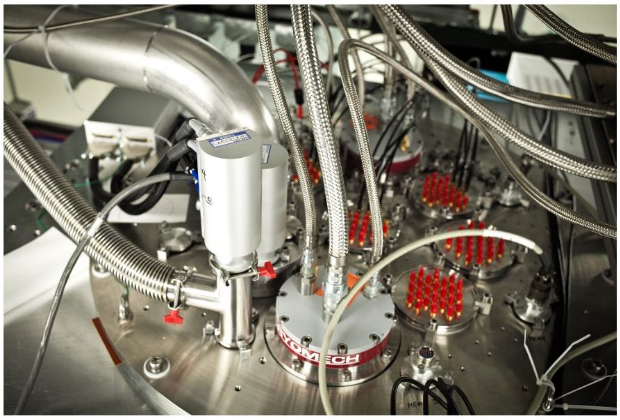
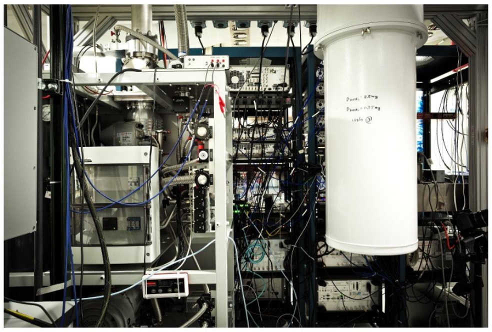


Figure 6.2 – The Quantum Processor



In 2015, IBM scientists unveiled two critical advances toward the realization of a practical quantum computer. One breakthrough involved developing a new ability to detect and measure both kinds of quantum errors simultaneously. The other was the development of a new, square quantum bit circuit design. It’s the only known physical architecture that could successfully scale to larger dimensions.

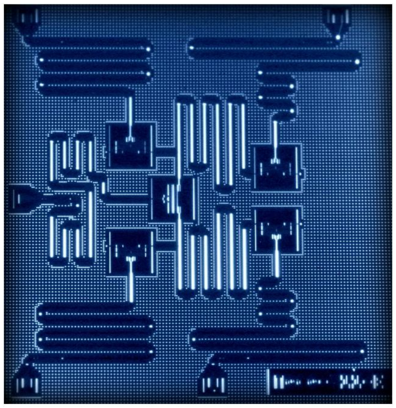


Figure 6.3 - The new 5 bit processor schematic

6.3. The Major Leap: The ability to address and measure the state of each qubit individually.

IBM can address and measure the state of each qubit individually. The company can measure (and has) all the critical features of its device. If you want to know how long a qubit retains its state, IBM can tell you. IBM even shows that addressing multiple qubits in a random way doesn't affect the state of the others too badly.

The problem in measurement: Error Correction

Quantum computing has a problem with error correction—a far worse one than classical computing faces. Let's put it in perspective. One option for a qubit is a superconducting quantum interference device where the typical energy difference between a one and a zero is on the order of 10-24 joules. For a classical system, we can choose whatever energy difference we want by setting thresholds for voltages and/or currents, so we set it to something convenient, usually something on the order of a volt.

To come close to having the same 10-24J difference between a one and zero, any chip would have to operate with a gate voltage of ten microvolts. So, at minimum, classical and quantum computers operate at energy scales that are different from one another by about a factor of 10,000.

Making matters worse, a qubit state is not a one or a zero but is a probability to produce a one or a zero on measurement, and this probability evolves in time. I can take two qubits that are set identically and then measure them some time later. After repeating this many times, I should find that the probability distributions are the same. That's the theory; in practice, they experience slightly different environments, so at some point later in time, one will have slightly changed relative to the other in an unpredictable way.

So, in addition to a bit-flip error, you can also have a phase-flip error, which is an error in the relationship between two bits rather than an error in the value of one particular bit.

And this makes error correction for a quantum circuit very difficult—and very, very necessary. In classical computers, the first processors could be implemented with minimal (or no) error correction. Quantum computing will require sophisticated error correction from the get go. It is not just a case of flipping a bit; you have to know how the different qubits evolve differently in time and how to correct for that before you measure them.

Let me give you an idea of how difficult this is. A typical qubit might have a lifetime of about 50 microseconds and a coherence time of 20 microseconds. What does this mean? It means that once your qubits are set, you have to apply error correction within the first 20 microseconds and complete a step of your calculation within 50 microseconds. That doesn't seem too bad, right?

But the operations to manipulate a qubit—either to perform a logical operation or to correct an error—involve microwave pulses that have a certain amount of energy. They can either be short, sharp pulses or long, slow pulses, as long as the area of the pulse remains the same. Unfortunately, short, sharp pulses cause problems, so typical pulses are 50 to 60 nanoseconds long. Given that you need to have everything done within 50 microseconds, this means you have a total of 1,000 operations for calculation and error correction. This makes it an extra-tough problem.

7. Comparison between Classical Computer, IBM Quantum Computer and D-Wave's Quantum Computer.

Table 1. Comparison between Classical Computer, IBM Quantum Computer and D-Wave's Quantum Computer.

On the basis of	Classical	IBM	D-Wave
Fundamental Computational unit	Bits	Pure qubits	Anneling Qubits
Material	Silicon	Super conducting quantum interference devices	Niobium
Maximum Fundamental Computational units	64	5	1000
Country of origin	UK	USA	Canada
Current Funtioning Status	Completely Commercialized	Under research	Commercialized to few clients(Googlr

			, NASA, USRA)
Size	Compact	Very Massive	Massive
Temperature	Room temperature	Near to absolute zero	15mk

8. ACKNOWLEDGMENTS

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