Implementation Aspects of Quantum Computing
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Lecture – 27
Qubits used in Commercial Quantum Computing

We have been dealing with implementation of quantum computers. In the last week we went through the idea of ion trap implementation of quantum computing, we will finish it off this week by looking at how these quantum computing options have now been attempted into the commercial angles and we will then go forward to the other more advanced approaches of quantum computing that have been done.

So, last week we dealt with ion traps as one of the important aspects of quantum computing implementation. This week we will summarize our findings and discussions that we did on quantum computing using iron traps and then we will look into the other techniques, some of which are now being attempted commercially.

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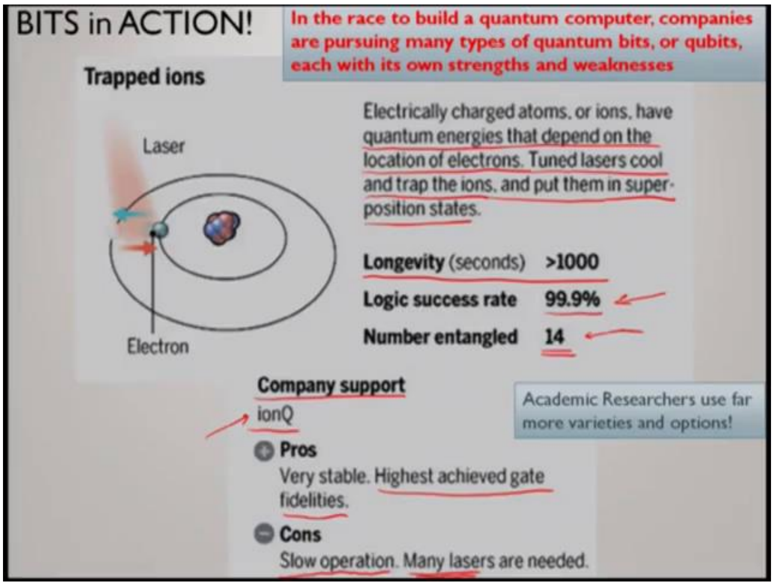

So, let us look at what we had done last week. In terms of the bits in action, we looked at the trapped ions and trapped ions are electrically charged atoms or ions that have quantum energies that depend on the location of electrons. Tuned lasers are used in this particular case to trap the ions and some other lasers can also be used so that they can be put in to super position states.

Often it is not the single laser which is going to do the trapping and cooling of the laser as well as doing the superposition. So, in the sense one of the problems which happens in this particular approach is at several lasers are used for this thing to work effectively. However, this has many advantages; the ions are long lived and they can be greater than 1000 seconds. Their success rate of the logic is also quite high, it is 99.9 percent success in terms of logic applications; the total number of entangled states that have been shown to be successfully achieved with this technique is as high as 14, so that is in fact the highest number of qubits in real sense, that have been used directly in terms of implementation.

So, there has been a lot of affect as a result of this huge success, in terms of using this technique commercially and in the rays to build quantum computer, companies are perusing many types of quantum bits or qubits each of which have been their own strengths and weakness and as we mentioned here ions trap definitely has seen its benefits and as result of this, the brand new company called ionQ has been setup to look into this commercialization of ion traps scheme of quantum computing.

We already know that academic researches use far more varieties and options, but as far as companies are concerned for commercialization, they would be taking approaches where the principles can be scaled and so that way ion trap has a huge benefit in terms of the number of entangles, qubit is quite high in this case.

The advantages are clear, they are very stable and it also has the highest achieved gate fidelities 99.9 percent. However, on the other hand it actually has a fairly slow operational procedure and as I mentioned in the beginning here that there are many lasers that are essentially needed for this particular concept of ion trap base quantum computing to be successful. Anyway because it has become commercially viable, let us look into this new ions company which has brought in the concept of trapped ions as commercial approach to a quantum computing.

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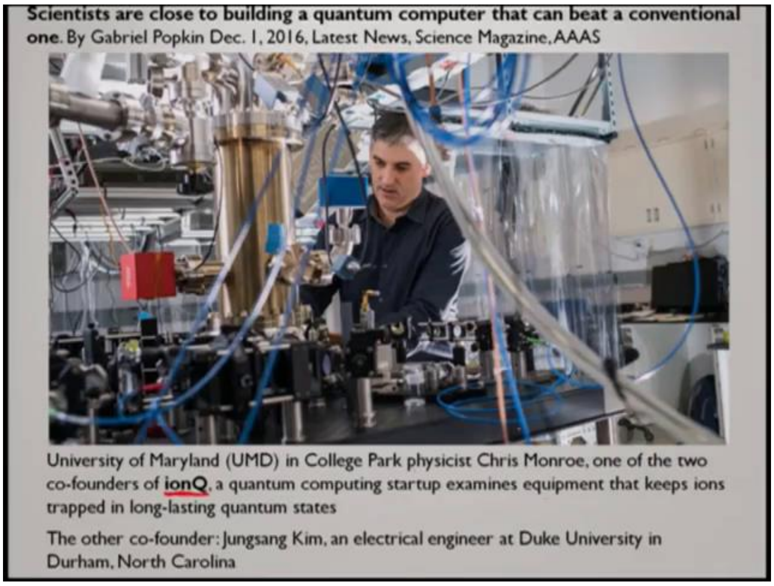

Here is a latest news taken from last year's; December issue of science where they ran a news article saying that scientist are closed to building quantum computer that can beat the conventional 1 and this is based on the ion trap 1. So, this is a picture taken from the lab of the University of Maryland college park physicist Chris Monroe who is one of the co-founders of ionQ, the company it is a quantum company startup that examines equipments, that keeps ions in long lasting quantum states. The other co-founder Jungsang Kim; is an electrical engineer at Duke University Durham, North Carolina.

So, that is one of the points which I wanted to point out here is that quantum computing is now coming to a point where commercialization is becoming a practicality and in this respect let us now look at one of the companies which claim into being in terms quantum computing, quite early in its development and has been successful in one way or the other over the years and this particular company is a Canadian company. I think, I have mentioned about it earlier in the introductory sections; is known as D-wave.

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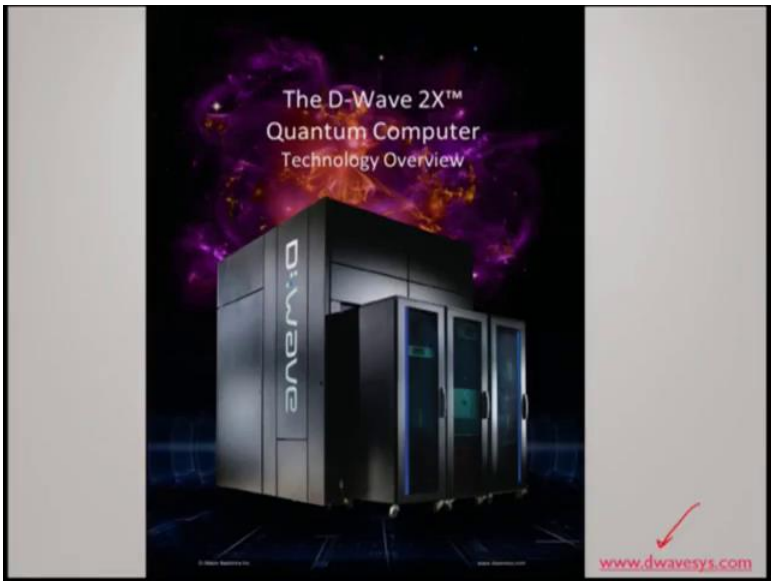

Now, in the next several slides that I will go through discussing about the D-wave computer would be very much in tuned with what it is present in their website. So, let us look at the D-wave quantum computer, so this is the one of the newer versions which they call as the 2 x version. So, that D-wave 2 x quantum computer has the detail of their technology overview and it is available in their website.

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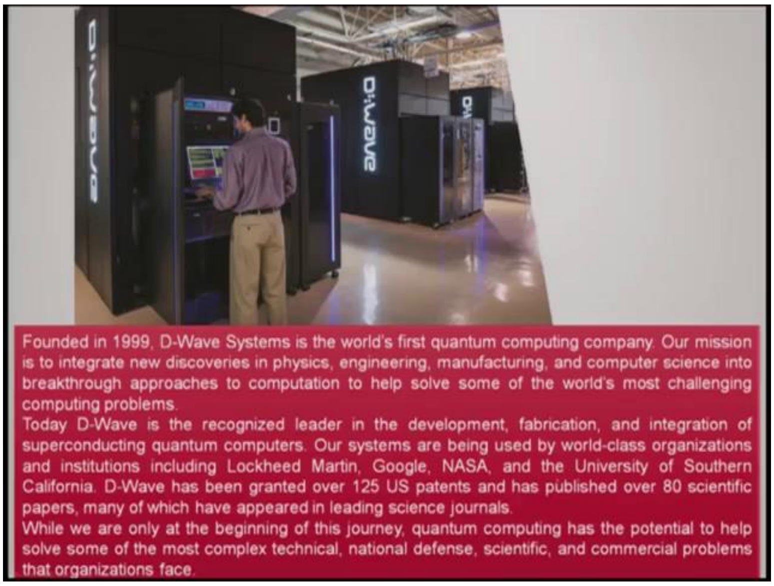

So, as you can see it was one of the first ones founded in 1999 as a point out quite correctly is of world’s first quantum computing company, their mission has been to integrate discoveries in physics engineering, manufacturing and computer science into breakthrough approaches to computation, to help solve some of the world's most challenging computing problems. It is true that today D-wave is recognized in the development fabrication an integration of superconducting quantum computers, their systems are being used by many organizations and institutions including Lockheed Martin, Google, NASA and the University of Southern California. D-wave has been granted over 125 US patents and has published over 80 scientific papers many of which appeared in leading science journal.

In fact earlier in February this year, there was a paper which in used the D-wave quantum computing to report very large number of qubits, 64 qubits to be precise of which in reality the practical number of qubits that they were able to use for computing was much lower, but it does have a lot of advantage; they do admit that it is actually the beginning of quantum computing as we know; however, having these commercial developments really make a huge advantage, so let us look in to them a little bit.

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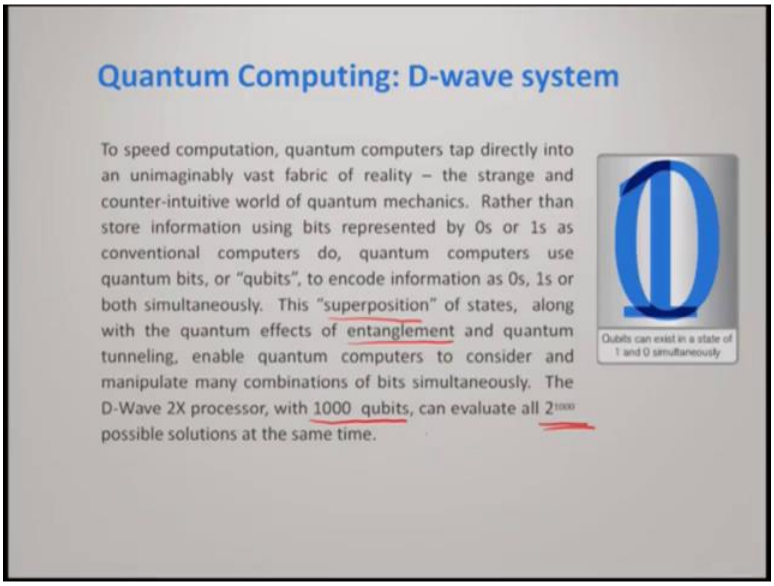

So in order to speed computing, these quantum computers which they have built are based on the idea of super conduction qubits as they mentioned. So, here is little bit of the detail of how the quantum computing as we have been talking about considers the qubits to be encoded in terms of 0s and 1s simultaneously and the superposition of the states along with the quantum effect of entanglement are the ones which go ahead in terms of using their developments for quantum tunneling, enable quantum computers to consider and manipulate many combinations of bits simultaneously. The D-wave 2 x processor has 1000 qubits and therefore can evaluate 2 to the power 1000 possible solutions at the same time.

There are questions in reality about how exactly all of these could be put to use, as I just mentioned earlier that although a lot of these qubits can perhaps be put to use or can be shown to exist their usage in actual computing is often not really use. So, in some sense we can say that there are lots of ancilla qubits which can be available in this kind of operations, so let us see how this has been successful.

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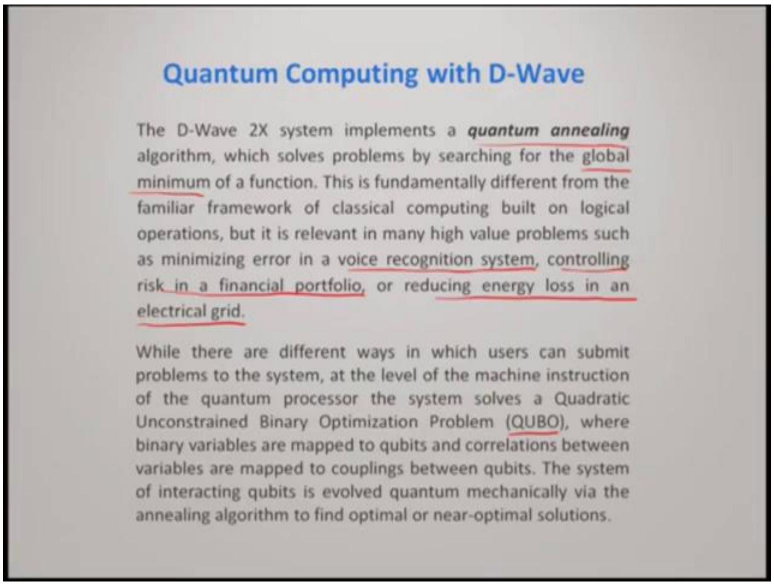

So, in terms of the computing with this kind of D-wave computer, this system implements a quantum annealing algorithm which solves problems by searching for the global minimum of a function. So, this works in a different principle from many of the processors that we have been discussing earlier and this a fundamentally different from the familiar frame work of classical computing built on logical operations, but it is relevant in many high value problems such as minimizing error or in a voice recognition system, controlling risk in a financial portfolio or reducing energy loss of an electrical grid.

The concept of using quantum annealing for finding global minimum of a function has also been often used earlier, for quantum simulations and classical computers and that is a quite a popular technique for m d super positions for many of the chemists. While there are different ways in which users can submit problems to the system and at the level of the machine instructions of the quantum processor, the system solves a quadratic unconstrained binary optimization problem as they call it QUBO, where binary variables are mapped into qubits and correlations between variables are mapped to couplings between the qubits. The system of interacting qubits is then evolved quantum mechanically via the annealing algorithm to find the optimal or near optimal solutions.

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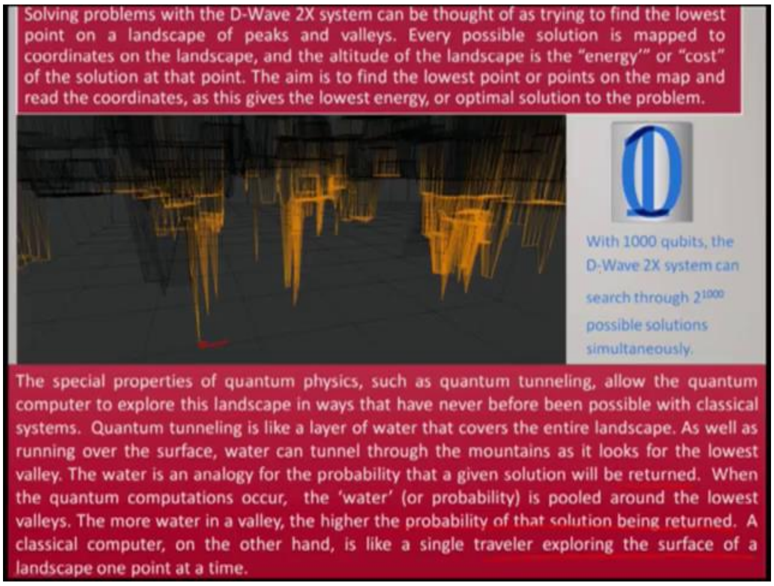

So, that is typically the way how their particular concept of quantum computing works and visually this is a more interesting to note that it is like a landscape on which there are many many possible minima, although the global minima as you can see is a only one; however, there are many other local minima where the system can get stuck and that is one of the most important things of how to find out the right solution. So, the solving problems with the D-wave system can be thought of as trying to find the lowest point in the landscape of peaks and valleys, every possible solution is mapped to the coordinates of the landscape and the altitude of the landscape is the energy or cost of the solution at that point. The aim is to find the lowest point or points on the map and read the coordinates as this give the lowest energy or optimal solution to the problem.

So, in order to do that what is a important is to figure out that the gap that can be achieved for example, to reach the lowest minima as it looks like in this particular case, this particular point is to find out that the energy or the cost function as they define it, is the one where the maxima is at least in this particular visual graphics, at this point where which should also correspond to let say the maximum difference from the mean position of the starting face. So, that is how this is done and one of the most important issues about this particular approach is to ensure that the system does not get stuck in local minima.

So, the special property of quantum physics, so in this case this special property of quantum physics such as quantum tunneling allows the quantum system to explore this landscape in ways that has never been possible with classical systems. So, in classical systems what would happen is, it would be each and every point of the minima would be explored one at a time; minima or maxima and then based on the number of attempts this has been done the solution can be good or bad.

Quantum tunneling on the other hand is like a layer of what are that covers the entire landscape you can visualize it in that way as well as running over the surface water can tunnel through the mountains as it looks for the lowest valley. The water is an analogy for the probability that a given solution will be returned. When the quantum computations occur; the water or the probability is pooled around the lowest valleys, the more water in the valley, the higher; the probability of that solution being returned. A classical computer on the other hand is like a single traveler exploring the surface of a landscape one point at a time.

So, that is the simultaneous nature of this problem which essentially makes the quantum process much more effective, the analogy of several solutions being looked at simultaneously as had been also talked about in terms of Grover solution is one of the ideas which quantum physics addresses very effectively and that is being utilized in terms of this quantum annealing process to get the right answer.

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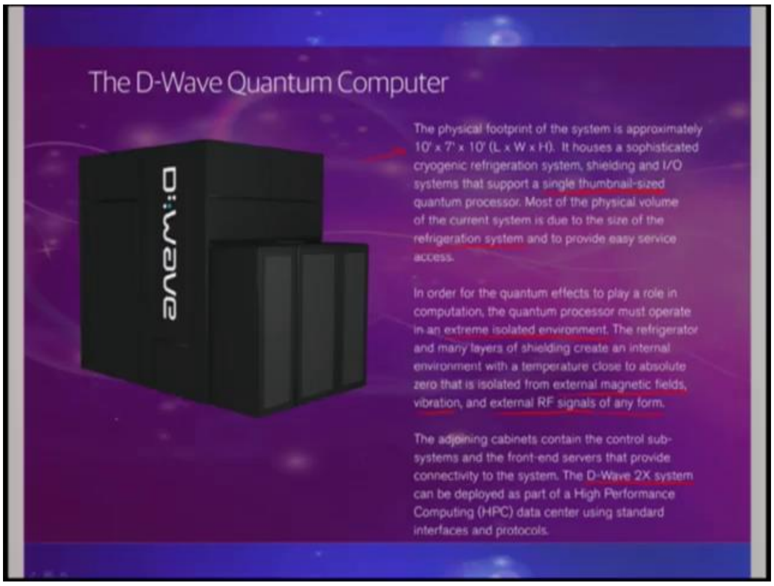

So, that is the basic idea behind this in terms of the actual computer it sort of looks like this where the physical foot print of the system is about 10 feet by 7 feet by 10 feet in terms of it is length width and height, it houses a sophisticated cryogenic refrigeration system because we are talking about very low temperatures, shielding an input output systems that support a single thumbnail sized quantum processor.

So, the essential final quantum processor is only a thumbnail sized one; however, it needs this big of a footage to achieve of the principles of the low temperature and then the shielding as well as the ion system. Most of the physical volume of the current system is due to the size of the refrigeration system and to provide easy service access.

So in order to for the quantum effects to play a role in computation, the quantum processor must operate at an extreme isolated environment that is one of the issues that is always an point in terms of quantum computing. The refrigerator and many layers of shielding creates an internal environment with a temperature close to absolute 0, that is isolated from external magnetic fields vibrations and external r f signals of any form. The adjoining cabinets contain control subsystems and the front end service that provide connectivity to the system. The D-wave 2 x system can be deployed as a part of high performance computing data center using standard interfaces and protocols.

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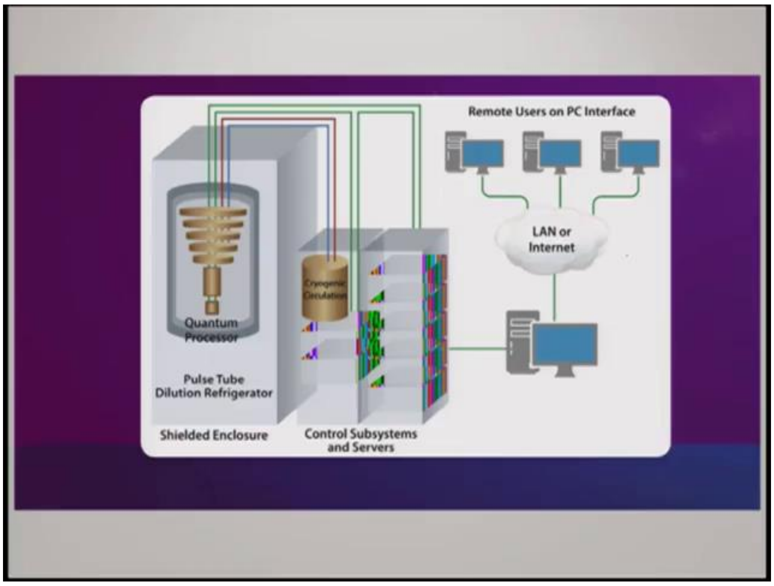

So, this is the current commercial system which exists and the way it is being used by other users as well as multiple users point of time is through this kind of a operational procedure whereas, we already saw the picture in which the shielded and closer has the quantum processor as we talk about it and the next one is slightly smaller or foot print part is you having the control and sub system and service. The quantum processor as I mentioned is only about a thumbnail sized, but which is kept inside the pulse tube dilution refrigerator, which is the part which takes most of the space and it is completely shielded otherwise it would get into a lot of problem.

So, that is the basic idea behind this the schismatic of this picture which shows how this works and this can be then controlled through another computer as well as a server which can then serve many other remote users or regular p c interfaces.

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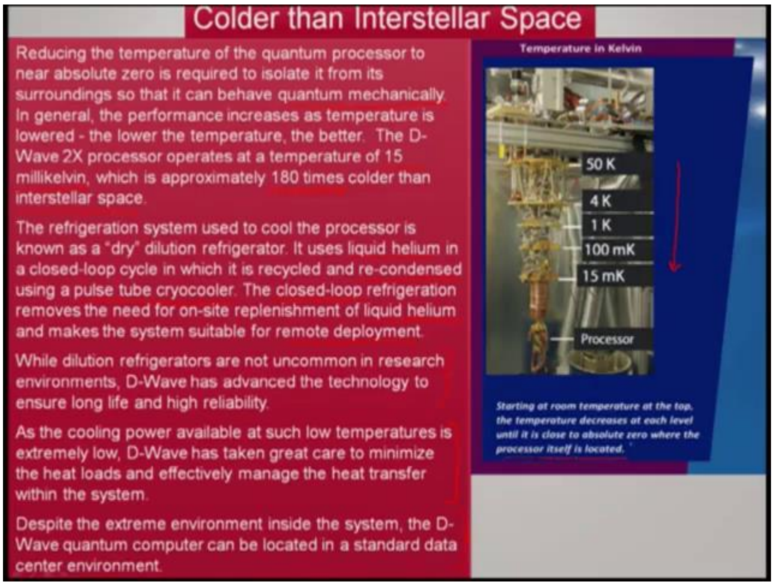

So, the major part of this has been mentioned is the temperature controlled part where the processor is kept at near 0 temperature, so the idea here is that the processor is in fact kept at colder than interstellar space, in order to achieve that this is the sort of the layering system which is done to ensure that the processor is really completely shielded in terms of the conditions as well as the temperature required is achieved as a result of this particular way of the geometry. So, there the temperature in the quantum processor is reduced to near absolute 0 which is required to isolate it from it is surroundings, so that it can behave quantum mechanically. So, that is one of the most important things which technology needed to make sure that it works, in general the performance increase as the temperature is lower, the lower the temperature the better is a performance. The D-wave 2 x processor operates at a temperature of 15 millikelvin which is approximately 180 times colder than interstellar space.

The refrigeration system used to cool the processor is known as dry dilution refrigerator, it uses liquid helium in a closed loop cycle in which it is recycled and re-condensed using a pulse tube cryocooler. The closed-loop refrigeration removes the need for on-site replenishment of liquid helium and makes the system suitable for remote deployment. So, the closed loop cooling is essential to make sure that the liquid helium could be reused and can be used remotely. While the dilution refrigerators are not uncommon in research environments D-wave has advanced the technology to ensure long life and reliability and this is one of their technology developments, such as made this kind of a quantum computer possible.

As the cooling power available at such low temperatures is extremely low, D-wave has taken great care to minimize the heat loads and efficiently manage the heat transfer within the system. So, these are design aspects that they had to actually engineer to ensure that such a system can operate at such very low temperatures and sustain it there. Despite the extreme environment inside the system, the D-wave quantum computer can be located in standard data center environment. So, that is one of the major developments that they have managed to achieve and that as it shown here is partly possible because of the way they have done these stratification of the temperature processor starting at room temperature throughout the temperature decreases at each level until it is close to absolute 0, where the processor itself is located.

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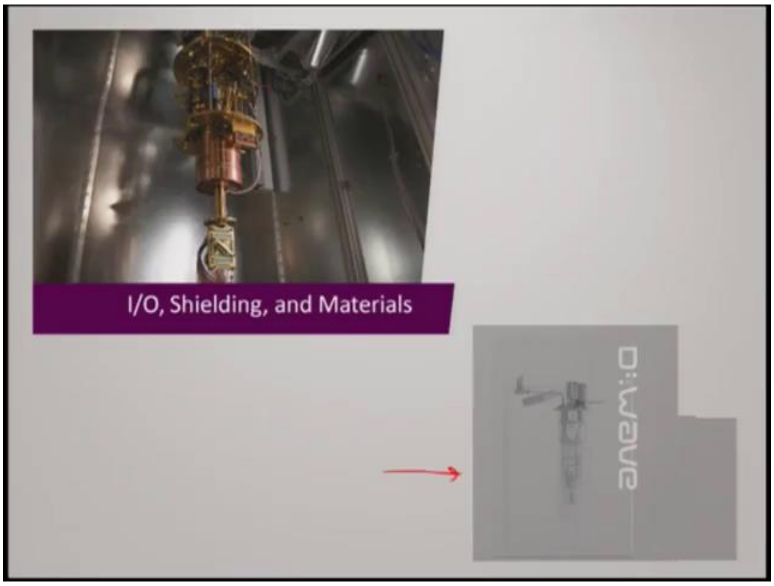

So, the main part of the system definitely then relay on the input, output shielding and the materials this by the way is the logo of the D-wave.

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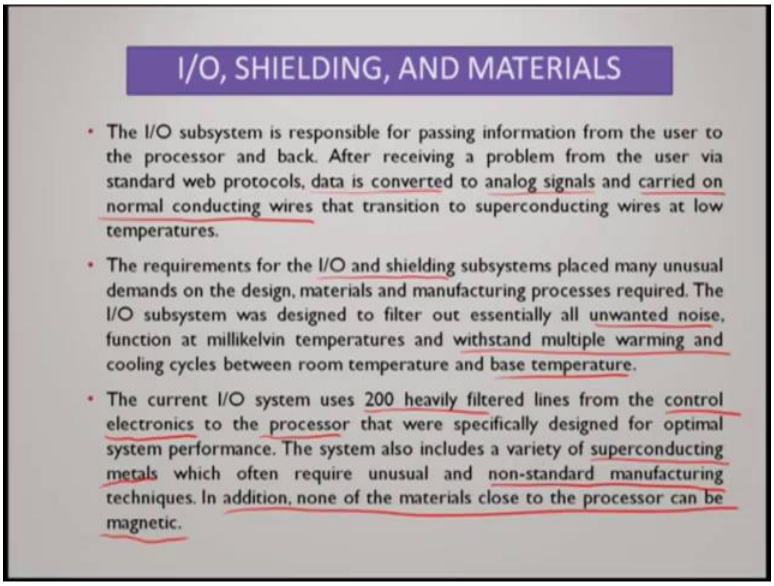

So the; I O system is responsible for passing information from the user to the processor and back. After receiving a problem from the user via standard web protocols, the data is converted to analog signals and carried on normal conducting wires that transition to superconducting wires at low temperatures. The requirements for the input output and shielding subsystems placed many unusual demands on the design materials and manufacturing processor required that is typically expected. The I O system was design to filter out essentially all unwanted noise functions at millikelvin temperatures and withstand multiple warming and cooling cycles between room temperature and base temperature.

The current input output system in their case; uses 200 heavily filtered lines from the control electronics to the processor. So, from the control electronics to the processor they are about 200 heavily filtered lines that were specifically designed for optimal system performance. The system also includes a variety of superconducting metals which often require unusual and non standard manufacturing techniques. In addition none of the materials close to the processor can be magnetic, so this is actually another very important aspect that they have to worry about, that near the processor nothing can be magnetic in that sense.

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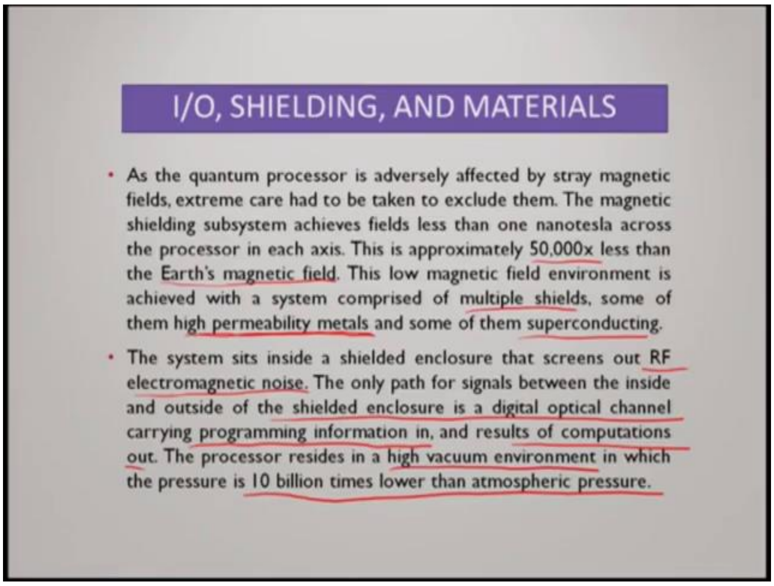

As the quantum processor is adversely affected by stray magnetic fields extreme care had to be taken to exclude them. The magnetic shielding subsystem achieves fields less than 1 tesla across the processor in each axis, this is the approximately 50000 times less than the earth magnetic field, this low magnetic field environment is achieved with a system comprised of multiple shields, some of them high permeability metals and some of them superconducting.

The system sits inside a shield enclosure that screens out r f electromagnetic noise, so all kinds of radio frequency electromagnetic noise is sort of shielded off because of the shielding enclosure. The only path was signals between the inside and the outside of the shielded enclosure is a digital optical channel, carrying programming information in and results of computations out. The processor resides in a high vacuum environment in which the pressure is 10 billion times lower than atmospheric pressure.

So, essentially this is a environment, which is often what we have used for many conditions under the n m r, well the n m r does not need that level of vacuum, but ion traps for instance have similar environments that are often necessary. So, this is basically the principle which they have done is that they have essentially made the inside of the computing environment, so shielded and so correctly available so that the principle of quantum computing or the quantumness can be preserved.

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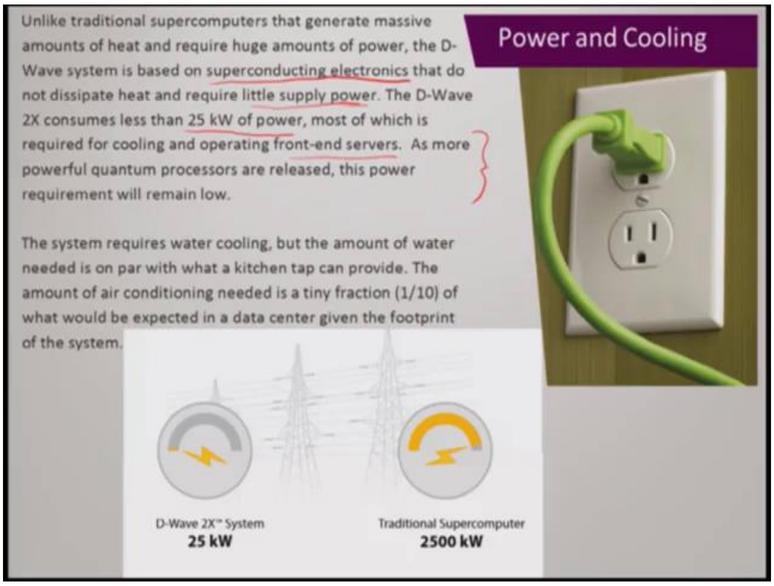

So, in spite of all this they have manage to do a few important aspects which are necessary, which is the power requirements have been kept to a normal level. Unlike the traditional super computers that generate massive amounts of heat and require huge amounts of power, the D-wave system is based on superconducting electronics, so the superconducting electronics is an important part of this process, that do not requires heat dissipation and require little power supply.

The D-wave 2 x consumes less than 25 kilo watts of power, most of which is required for cooling and operating front end servers, as more powerful quantum processors are released this power requirement will remain low. So, this is one of their claims and they have been managing to do that which is very important because otherwise the power requirement can create other issues which they are trying to avoid. The system requires water cooling, but the amount of water needed is on power what a kitchen tap can provide, the amount of air conditioning needed is also a tiny fraction of what is expected in a data center given the footprint of the system.

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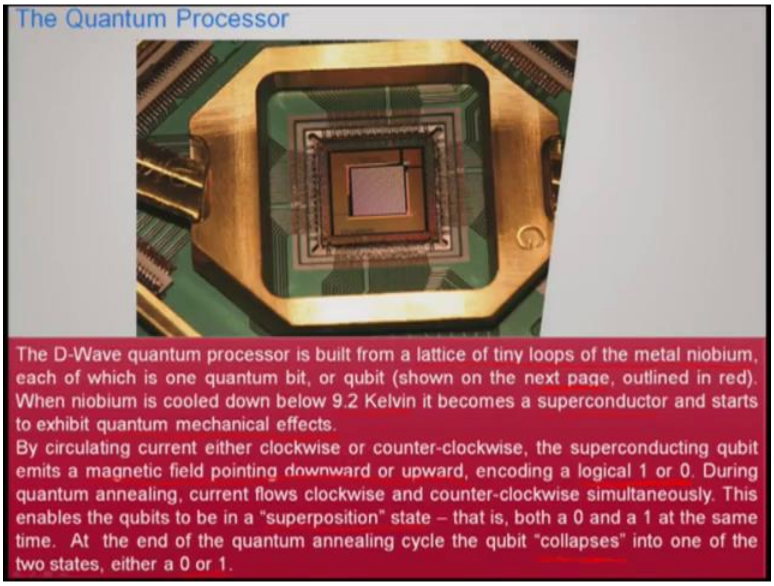

So, this is one of the important parts which they have also had to build up, to make sure that it is a possible to be put in to a regular computing environment where the classical computers reside. So, now the main part which is the quantum processor, which requires all these shielding's and all these advantage of putting it away from everything. So, the D-wave quantum processor is built from a lattice of tiny loops of metal niobium, each of which is 1 qubit computer, it is a lattice of tiny loops of metal niobium, each of which is 1 quantum bit or qubit.

So, I will show it to you in a slightly more detail in the next slide here it is perhaps the whole processor is shown, but the highlighted parts that would be shown in the next slide with the outline red. When then niobium is cooled down below 9.2 Kelvin, it becomes a superconductor and starts to exhibit quantum mechanical effects, so that is the principle which is used behind this quantum computing device of the D-wave.

By circulating currents, either clockwise or counter clockwise, the superconducting qubit emits a magnetic field pointing downward or upward, encoding a logical 1 or 0 and that is one of the reasons why, they have to be so careful about shielding it in terms of magnetic fields. So, because this is operated mostly in terms of the magnetic field creating the logical qubit 1 or 0, it has to be very highly shielded.

During quantum annealing, current flows clockwise and counter clockwise simultaneously. This enables the qubits to be in a superposition state that is both in a 0 and 1 at the same time. At the end of the quantum annealing cycle, the qubit collapses into one of the two states either 0 or 1. So, the preparation phase in this case essentially involves applying the circulating current clockwise or counter clockwise to create the superconducting qubit.

In terms of a magnetic field pointing upward or downward, creating the logical 0s and inward and that is the part which is your preparation and then the quantum annealing process which where the processing occurs, current is flowing either clockwise or counter clockwise simultaneously and this enables the qubits to be in the superposition state and when the computation is done then it finally, collapses to one of the two states either 0 or 1 and thus the magnetic field with essentially be either pointing upward or downward or in other sense there would be a clockwise or a counter clockwise signal in terms of circulating current.

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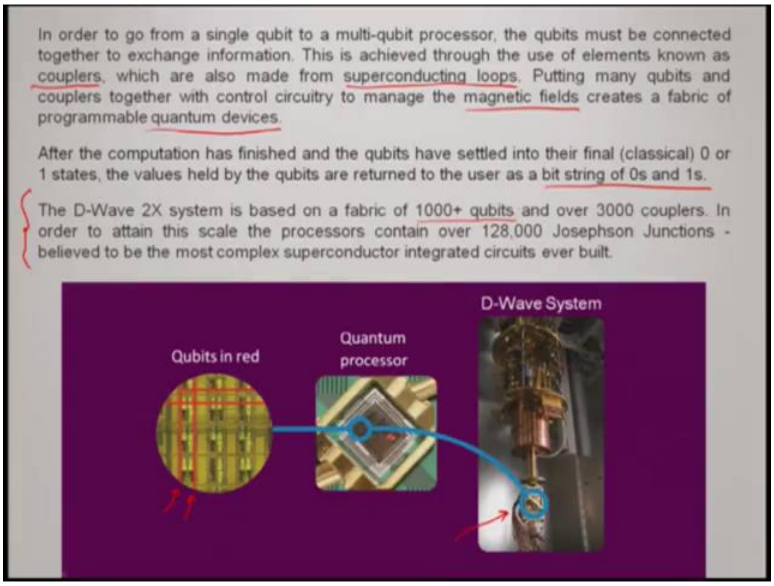

So, these are the various taps in it and as I mentioned here is the detail of these red lines where in the niobium metal is been shown in the actual processor. So, as mentioned here one quantum qubit or is shown outlined in red, so these are the tiny loops of the metal niobium so here are the tiny loops of the metal niobium which are essentially showing the qubit. So, the processor is sitting as mentioned at the colder zone that is being amplified to show the qubits in the red.

So in order to go from a single qubit to a multi qubit processor, the qubits must be connected together to exchange information, this is achieved through the use of elements known as couplers, which are also made from superconducting loops; putting many qubits and couplers together with control circuitry to manage the magnetic fields, create a fabric of programmable quantum devices. After the computation has finished and the qubits have settled into their final 0 or 1 states which is generally the classical condition the values held by the quibts are returned to the user as a bit strings of 0s and 1s because by that time everything information is classical.

The D-wave 2 x system is based on a fabric of 1000 plus quibts and over 3000 couplers, in order to attain this scale the processor contain over 128000 Josephson Junctions believed to be the most complex superconductor integrated circuits ever built. So, that is the claim which the D-wave system makes in terms of what they have managed to achieve in terms of 1000 plus qubits.

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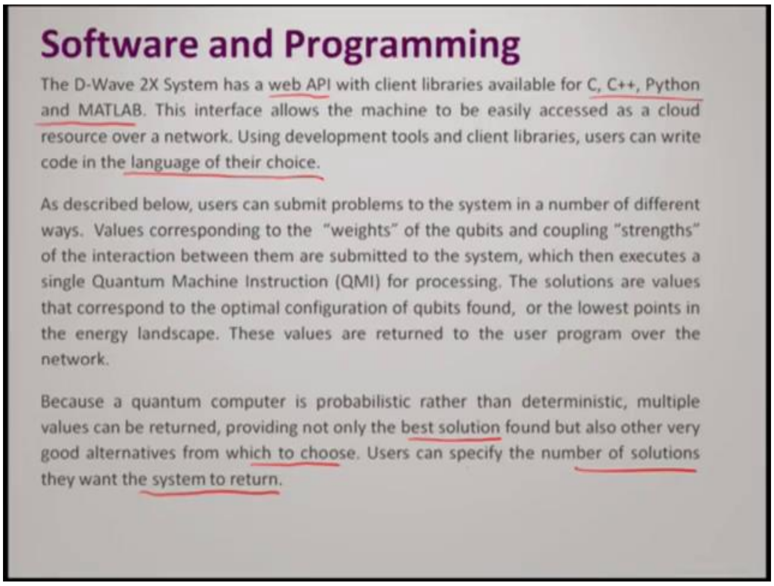

To complete the story about the D-wave computer in terms of it is commercialization, I would like to point out the software and the programming aspects in their case and comes with the help of a web API with client libraries available for C, C++, Python and MATLAB, the most common programming environments this interface allows the machine to be easily accessed as a cloud resource over a network using development tools and client libraries users can write codes in the language of their choice and then interface it with the available ones.

As described below the users can submit problems to the sub system, as described the users can submit problems to the system in a number of different ways, values corresponding to the weights of the qubits and coupling strengths of the interaction between them are submitted to the system which then executes single quantum machine instructions for processing. The solutions are values that correspond to the optimal configuration of the qubits found or the lowest points in the energy landscape, these values are returned to the user program over the network.

Because a quantum computer is probabilistic rather than deterministic, multiple values can be returned providing not only the best solution found, but also other very good alternatives from which to choose, users can specify the number of solutions they want the system to return. So, these are some of the advantages or additional options that the quantum processor can provide which are provided by them.

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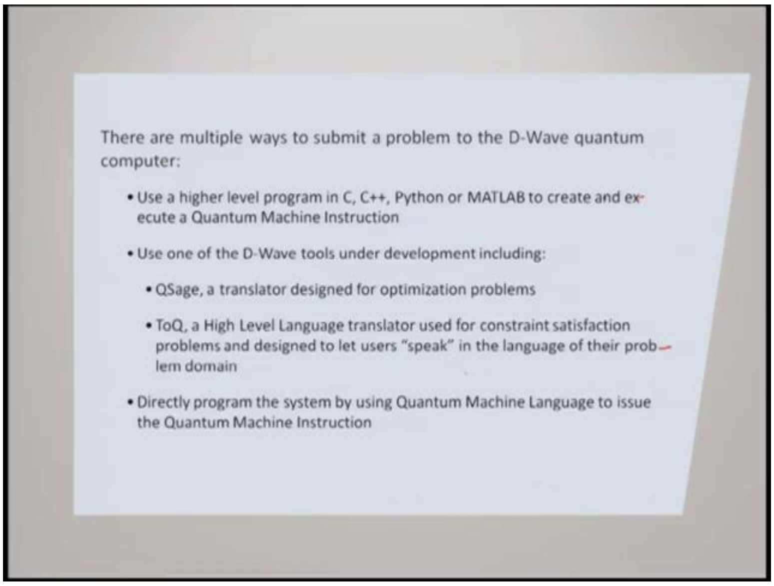

There are multiple ways to submit a problem to the D-wave quantum computer as mentioned in the last slide, these are the many different ways one can use a higher level programs in C, C plus plus Python or MATLAB to create and execute a quantum machine instruction, use one of the D-wave tools under development including QSage, a translator designed for optimization problems, ToQ; a high level language translator used to constraint satisfaction problems and designed to let users speak in the language of their problem domain or directly program the system by using quantum machine language to issue the quantum machine instructions.

So, these are the various different ways how these particular systems can be connected to and programmed to submit their problems.

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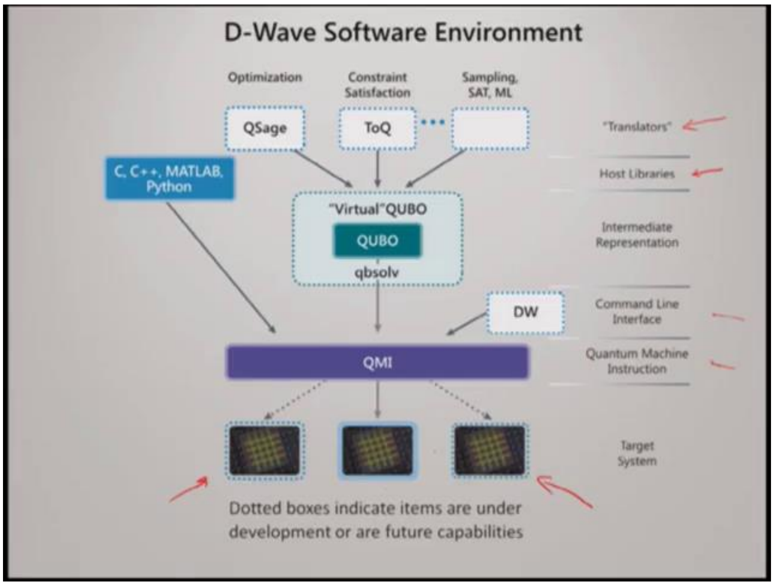

So, in a sense the overall system looks in the environment of the D-wave software environment looks like this. They have the different processors available at different levels, so the optimization usage a QSage constraint satisfaction uses ToQ and there are many others that can be sampling ml these are the different translators that can be used, there are lots of host libraries which can be of different kinds as we mentioned, as well as there are various different independent representations and the comment line interfaces as well as quantum machine instructions.

So, these are the various different ways of interacting with the machine and many of the developments, so for example, this one and this one mentioned in this particular slide taken from their website essentially mean that they are the under development for feature capabilities, only the direct solid lines are the ones which have been used currently. So, generally speaking this QUBO is currently developed, the C, C++, Python, MATLAB these are developed, direct quantum machine instructions are developed, the rest of the devices which are in dotted forms are being developed and finally, the instructions are provided to the target system which is a quantum system, which does the operations of quantum annealing and gives the best possible result as well as several close enough results which can be utilized.

So, basically this whole principle is based on superconducting loops and this is the idea of a resistance free current that oscillates back and forth around a circuit loop, an injected microwave signal excites the current into super position states and this can be put into a lot of a developments.

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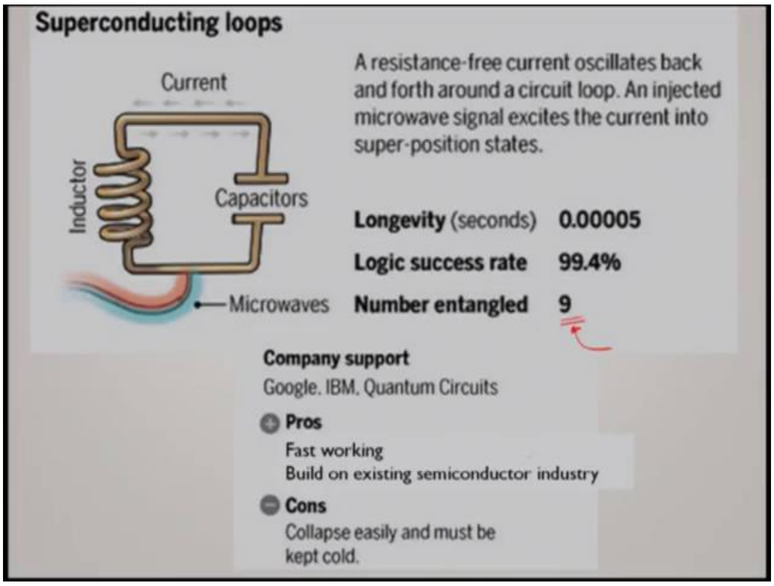

And this is one of the principles and it is associated environments which sort of gave rise to the advantageous that we discussed as of now. The point to remember; however, is that as I mentioned earlier this number has changed very recently, however these numbers are the real possible entanglements which have been achieved although there are many mores states which can be available, the longevity of these states are not very high but it is long enough to take advantage of many of the processors.

Now, this particular superconducting loop approach is slightly different from the principle of D-wave that we discussed which use the quantum annealing approach; however, one of the advantage of these is that, it is open source as of now for many other companies to look at and therefore, Google, IBM and quantum circuits are looking at these kinds of approaches or looking at it, now this has the advantage of fast working and it is build on the existing semiconductor industry.

The disadvantage here is that the collapse is easy and should have been kept cold. So, many of these quantum computing approaches as I have been talking about up late including the most commercially successful D-wave ones have their difficulties and there are commercial attempts which are being attempted at many different cases. So, the D-wave system which uses the quantum annealing method of going from the Josephson junction approach of producing quantum states and going ahead with this has been more successful till date in terms of commercial.

The other ones are coming into the picture and before I close today's lecture, let me actually tell you about the few other approaches in which I have already mentioned the superconducting loop one, which is similar to in principle to the one that D-waves are using, although the D-wave essentially makes the advantage of the principle of quantum annealing on top of it to achieve the number of entangle states and others.

However as you understand the approach of quantum tunneling to get quantum computing is different from what people would and discuss in terms of the way we have developed and discussed in terms of quantum computing. So, there are lots of questions on the D-wave system although it is been used in many places. The more traditional approach of using the same scheme, it does not use quantum annealing essentially you would be what this other part which I just discussed in terms of semiconductor loops talk about where there are other companies which have now started looking into this process hence seeing how this can be taken into next level as it also involves the advantage that it is based on the existing semiconductor industry.

However, all of these as in the D-waves have shown would require the maintenance of very good quality refrigeration and the isolation. So, that it can be kept cold and which is not going to interact much with other states.

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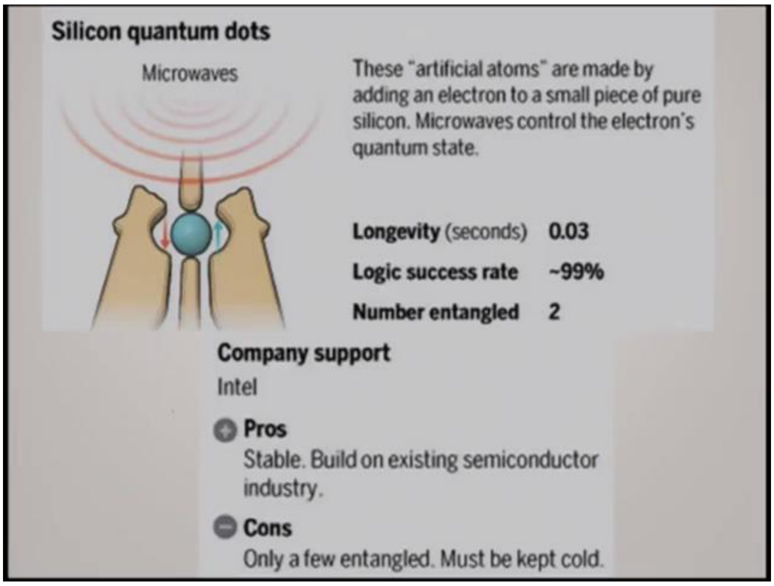

The other area where a lot of effort has been put in terms of commercial basis is the silicon quantum dots, these are artificial atoms made by adding an electron to a small piece of pure silicon. The microwaves control the electrons quantum state in this particular case, this has a fairly long longevity 0.03 seconds and the logical success rate is also reasonable 99.9 percent, however the scalability has not yet been achieved much only 2 qubits which have been shown to be entangled as of now and again this needs to be kept cold and is the difficult of this; however, this is also a stable system and it is built on existing semiconductor industry.

So, this is another one of these approaches which is been supported through Intel, IBM for example, which is going ahead with the semiconducting loops has declared that sometime later in this year they are going to come up with their version of quantum computers and the silicon quantum dots is another area where as I just mentioned lot of effort is going on and Intel is gearing up more on this direction.

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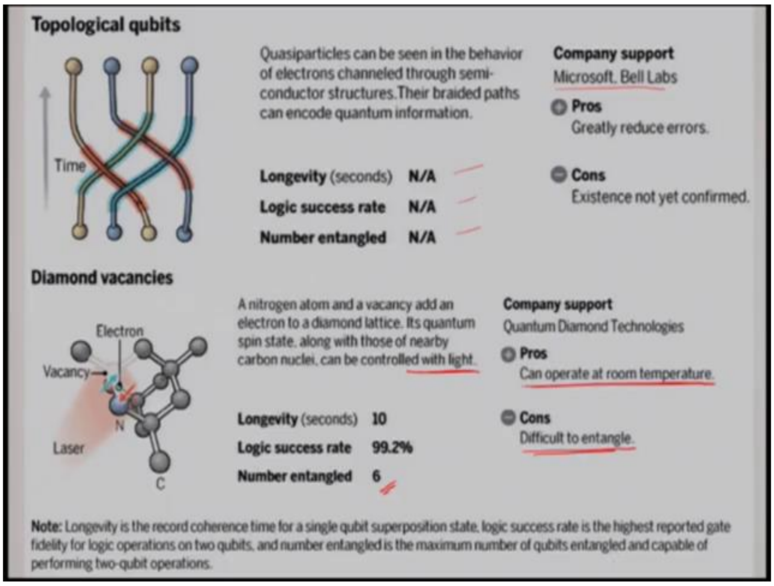

The other approaches which are also been explored and there are two more which I have been mentioned here before I close today's lecture and those are one of them is known as the topological qubits, which are supposedly one of the most sort after concept although it is very new and therefore, not much development has been achieved.

However this has a very interesting principle because it is based on the idea of quasiparticles which can be seen when the electrons are channeled through semiconducting structures, their braided paths can encode quantum information and the advantage of this is that, it has a the huge reduction in error processing; however, it is exist in this is all in theory as of now and it is existence and other details in terms of longevity, logic success and number of entangled are not yet available and Microsoft and bell labs are basically pursuing this kind of effort.

The other one which have been shown to exist and quite a few entangle states have been achieved is the vacancy states inside diamond. A nitrogen atom and a vacancy add an electron to a diamond lattice and it is quantum spin state along with those of the nearby carbon nuclei can be controlled with light. Now this is also another area where in this quantum diamond quantum technologies, it is a company which has come on to try to operate that and this advantage the biggest advantage of this that it can operate at room temperature. Most of the other techniques that we have been talking about all this time requires very low temperatures and stability and isolation is one of the biggest issues, but this one can operate at room temperature and can be addressed with light, it has a long longevity 10 seconds, I mean not has high as entraps, but fairly long and it has a fairly decent success rate logic in it is success rate in terms of 99.2 percent and as of now about 6 qubits have been shown to be entangled.

So, the difficulty however, in this case is to entangle the state and keep it at that level. In all these cases one of the things which whenever we have mentioned longevity, it is basically means that the record coherence times for a single qubit superposition state and where as the logic success rate is the highest reported gate fidelity for the logic operations on 2 qubits and the number of entanglement is the maximum number of qubits entangled and capable of performing 2 qubit operations. So, these are the basic principles and the basic schemes and qubits which have been brought into the commercialization angle.

As mentioned there are earlier, there are many other approaches to quantum processing which have been attempted in the laboratory procedures in an the academic circles, but these are the few which I thought would be presented, would be a good idea to present it altogether which are in terms of commercialization so that you can all look at the commercialization angle of quantum computing in one short.

So this is what I tried to present in today’s lecture. In the next lecture, we will go into more of Spintronics, which I talked about in the last week and we will take it from there. See you in the next lecture.