Implementation Aspects of Quantum Computing

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Lecture - 42
Commercial Development in Quantum Computing and Implementation

In the last lecture, we looked at the NMR principles of quantum computing as that was the first one to have the practical implementation problem. Now let us get into the optics part and let us start with the single photon qubits.

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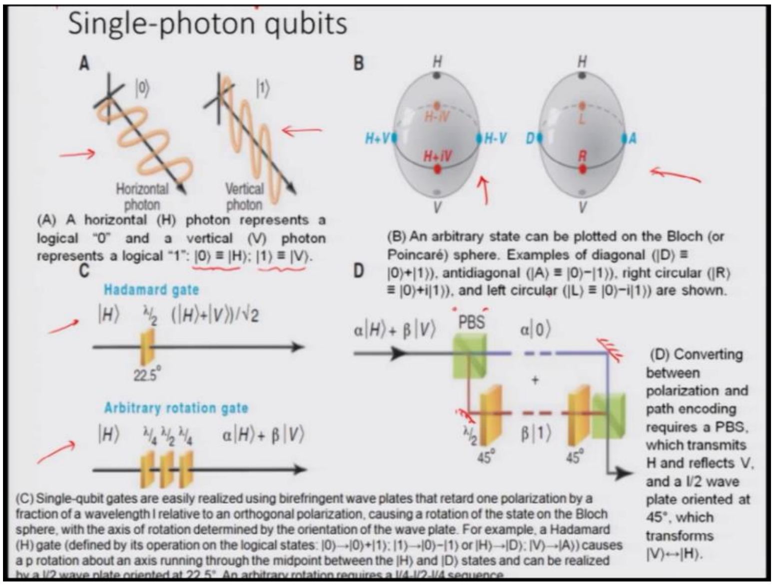

The single photon qubits have the advantage that it can deal with the single aspect of measurement instead of ensembles, which has been one of the difficulties in terms of doing the quantum computing with NMR. One of the popular ways of looking at single photon qubits have been the idea of the polarization, where the photon polarization could be either horizontal or vertical and they are often denoted into the two different states by using this particular polarization principle.

So, a horizontal H photon represents a logical 0 and a vertical V photon represents a logical 1. So, the ket 0 would represent H ket and ket 1 would represent V ket. Any arbitrary state can be then plotted on the block or pointier sphere; examples of diagonal would be like ket D which is equivalent to a superposition of 0 and 1 ket vectors. Similarly anti diagonal would be say the ket A which is a difference of 0 and 1, the other possibilities of right circular and left circular can also be taken and these are all pictorially represented in these pictures that we show here. Application of any gate would then involve using optical elements which can perform the transformations that we are interested in.

So, for example single qubit gates can be easily realized by using Birefringent wave plates that retard one polarization by a fraction of the wavelength relative to an orthogonal polarization causing a rotation of the state on the block sphere with the axis of rotation determined by the orientation of the wave plate. So, for example Hadamard gate could therefore, be achieved by using a half wave plate which would have the horizontal and the vertical polarizations, be equally mixed up once the wave plate is set at half of 45 degrees which is 22.5 degrees.

So, any arbitrary rotation would therefore be possible if we placed series of wave plates as it is shown here by either using a quarter wave and half wave and quarter wave combinations. Converting between polarization and path encoding requires a polarizing beam splitter PBS as it has been shorten here; which transmits the horizontal and reflects the vertical and a half wave plate oriented at 45 degrees which transforms the vertical into horizontal these are essentially mirrors which are turning the laser beams as we are looking at.

So, single photon qubits can be quite attractive in terms of providing the principle of cubit for doing computation. One of the most important part in this process is the concept of generating single photons which involve lasers which we have also discussed it at length in our course and the single photon source would essentially involve reducing the number density of the photons coming out of the light source to a point where the detector starts giving results which could be associated with the single photon essentially clicking the detector in terms of the number of photons, which are received by the detector. So, these are principles which we have discussed at length in class and here is essentially the brief summary of single photons have become useful as quantum computing devices.

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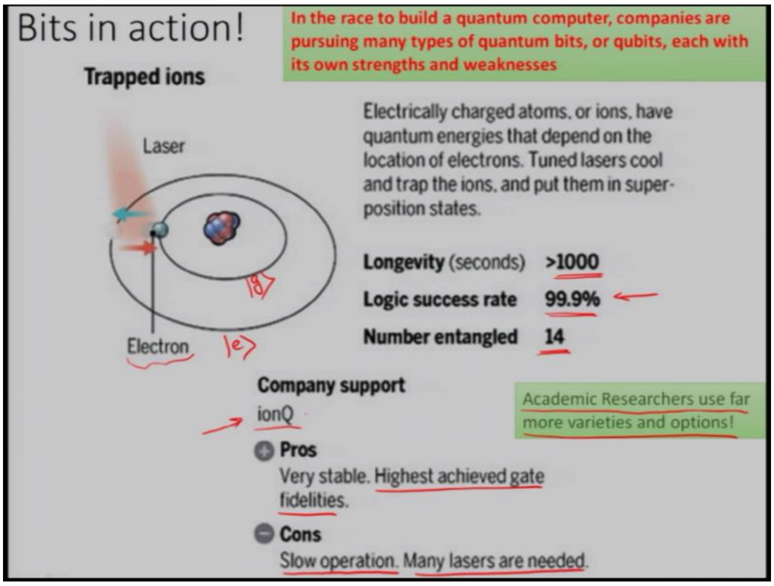

The other important development in terms of quantum computing has been the trapped ions where an atom have been isolated into an environment where it can be kept in an isolated condition so that it can be made to change its property in a quantum mechanical way. So, electrically charged atoms or ions have quantum energies that depend on the location of electrons, tune blazers can cool and trapped ions and put them in superposition states. So, here is an example where a laser can essentially put the electron in a superposition state between the ground and the excited state, so if this is the ground state and this is the excited state of the atom or the ion concerned.

The use of a laser can essentially create a superposition state between the grounds in the excited state. The advantage of such isolated ions is that they have very long longevity greater than 1000s of seconds and the logic success rate because it uses laser switch attuned precisely, it could be as high as 99.9 percent and by using this technique until now 14 entangled ions have been shown to be trapped; it is a very high number in terms of qubits and as we discussed in the class, presently a new company have been floated it is called ionQ; which is going to look at building the commercial version of this development. The advantage in this technique as I mentioned before, it is a very stable, it has the highest achieved gate fidelities 99.9 percent. However, it has difficulties in terms of it is slow operation and for making any of these processes to go on many lasers are needed.

In terms of commercial aspects; in the race to build quantum computers companies are pursuing many types of quantum bits or qubits; each with it is own strengths and weaknesses; however, that is still limited as compared to the academic researchers, who used far more varieties and options. So, we will first look at the commercial ones as we have seen ionQ is gearing up to get into the commercial mode for this.

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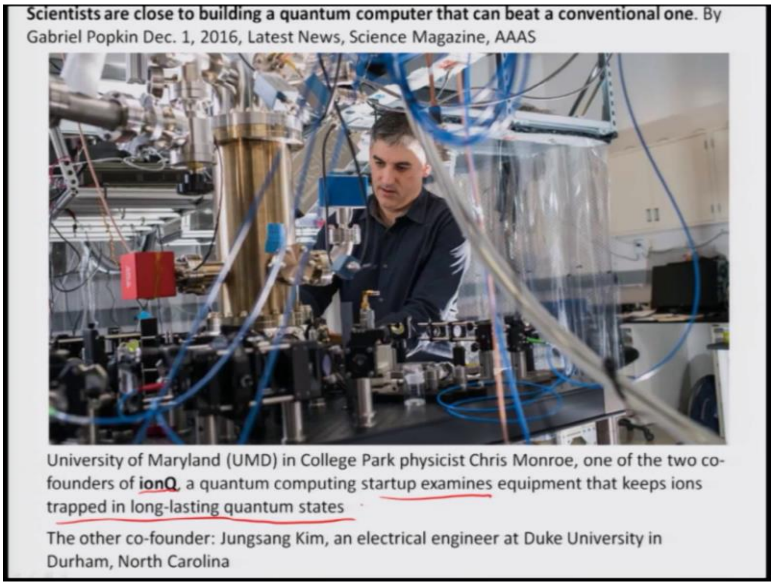

One of the new information which is come out as late as December 1st 2016 as I mentioned in class, it was the fact that the University of Maryland college park physicist Chris Monroe along with Jungsang Kim from Duke University have floated this company ionQ to setup and ion trapped based quantum computing. So, this the quantum computing startup that examines equipment that keeps ions trapped in long lasting quantum states so that is one of the areas this particular development is going.

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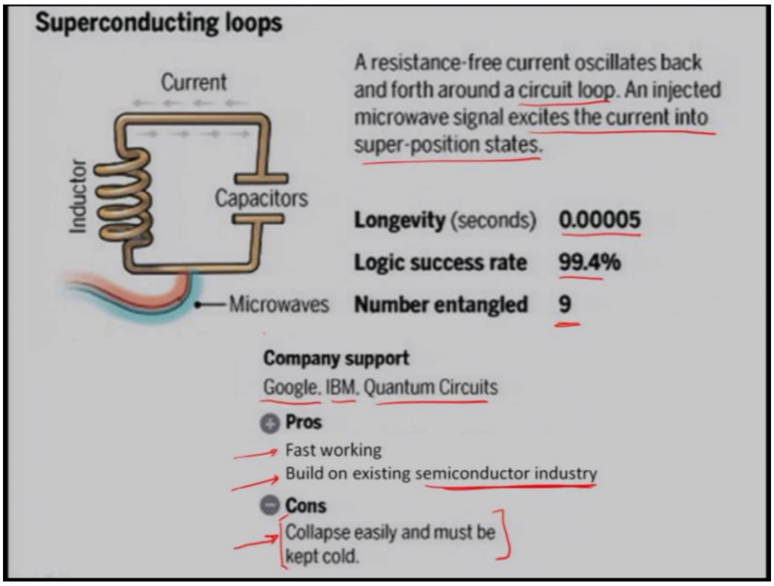

The other commercially viable approach that has been looked at is the superconducting loops for quantum computing, where a resistance free current oscillates back and forth around a circuitry. An injected microwave signal excites the current into superposition states; here the difficult is the longevity is in terms of a very short time 5 into 10 to the power minus 5 seconds. The logic success rate is still quite a 99.4 percent and the numbers of entangled qubits have been about 9. There have been quite a few companies who are interested in this and they have been supporting this area of research which includes Google, IBM quantum circuit's etcetera.

The advantage here is that it is fast working and it builds on the existing semiconductor industry that is one of the biggest advantage and that is why the companies are interested; however, the difficulties are also quite pronounced that it can collapse easily and must be kept quite cold. The advantage of the semiconductor industry in terms of fabricating and working on this essentially has made this an area where a lot of effort has going on in terms of commercial aspects.

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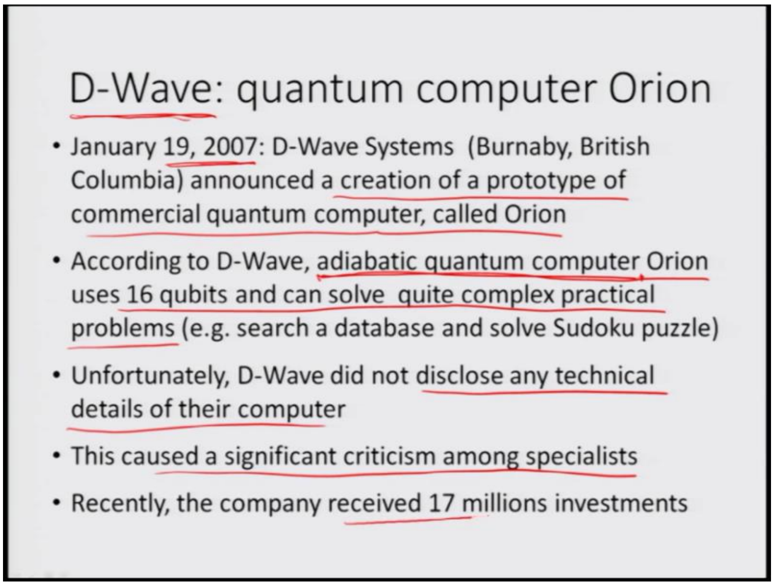

The main commercial quantum computers are from D-wave systems which is a company based in Canada. So, they started their venture as early as January 19; 2007 when they announce the creation of a prototype of commercial quantum computer called Orion. According to D-wave adiabatic quantum computer Orion uses 16 qubits and can solve quite complex practical problems. Now this was way back in January; 2007; 10 years ago and they use the principle of adiabatic quantum computer to do this heroic feet and initially they had this difficulty that they were not disclosing any technical details of their computer which caused a significant criticism among specialist; however, their stand has changed over the years and it has been put to use in many places including IBM and recently the company received 17 million investments.

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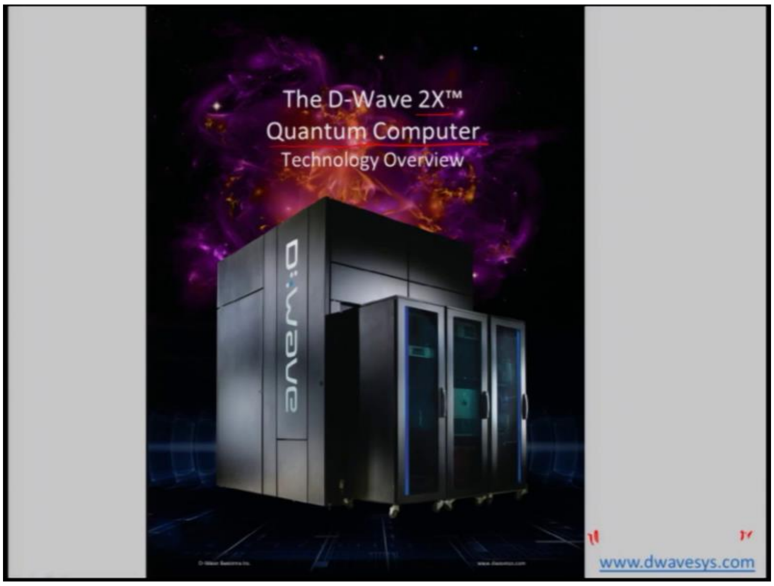

So, one of the later versions of the D-wave quantum computer is known as the D-wave 2 x quantum computer which came out about a couple of years ago and had a lot of nice review on it and we discussed at length about this; this is from the website of the company which is given here again.

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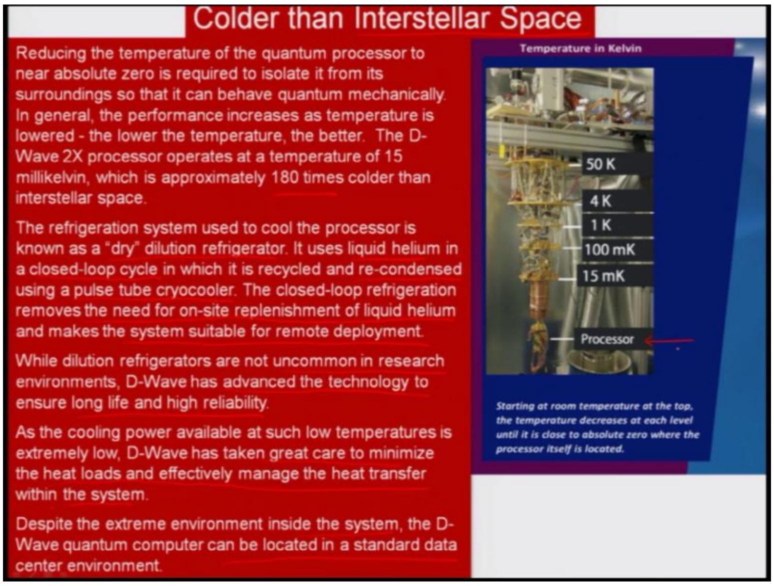

And their main advantage has been the fact that they have managed to isolate the system where the quantum processor works to a temperature which is colder than interstellar space and this feet which they were able to achieve has managed to isolate their system quite effectively and given them the power of the quantum processor. So, they give quite a bit of a detailed nowadays about how they go ahead about doing their computation and this is quite impressive. Reducing the temperature of the quantum processor to near absolute 0 is required to isolated it from it is surroundings so that it can behave quantum mechanically.

In general the performance increases as temperature is lowered, the lower the temperature the better the D-wave 2 x processor operates at a temperature of 15 milli Kelvin which is approximately 180 times colder than interstellar space. The refrigeration system used to cool the processor is known as a dry dilute refrigerator, it uses liquid helium in a closed loop cycle in which it is recycled and re-condensed using a pulse tubes cryocooler. The closed-loop refrigeration removes the need of the onsite replacement of liquid helium and makes a system suitable for remote deployment and that has been their biggest achievement in terms of commercial viability.

While dilution refrigerators are not uncommon in research environment D-wave has advanced technology to ensure long life and high reliability. As the cooling power available at such low temperatures is extremely low, D-wave has taken great care to minimize heat loads and effectively manage the heat transfer within the system and given their development, they have managed to ensure that despite the extreme environment inside the system, the D-wave quantum computer can be located at a standard data centre environment.

So, these have been some of the major technological developments which the company was able to achieve which made sure that their processor was able to be placed at near 0 kelvin temperatures so that it could behave in a manner close to quantum conditions.

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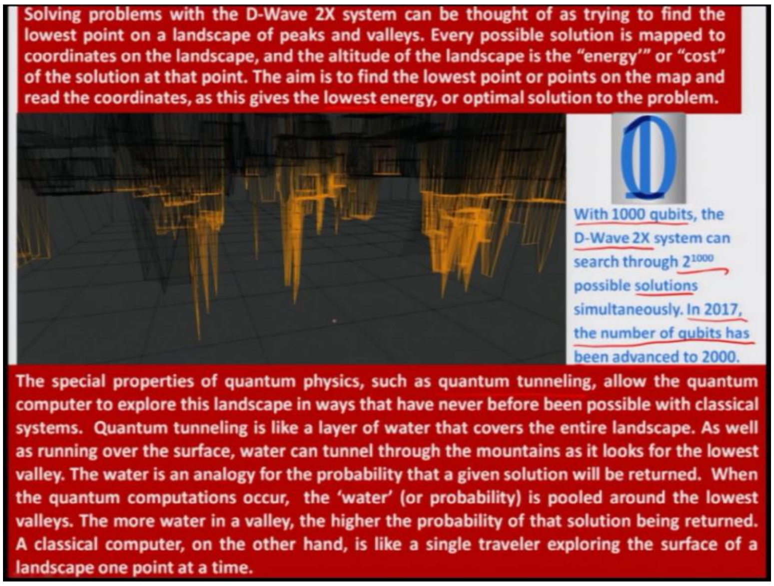

So, this is the slide that I used in the lectures with the only exception that I have upgraded the fact that in this year, the number of qubits now they have advanced to 2000. So, they had 1000 qubits until last year, where this particular D-wave 2X system could search through 2 to the power 1000 possible solutions simultaneously and the search principle that they use is based on simulated annealing concept. So, their specific idea is quoted here. Solving problems with the D-wave 2X system can be thought of as trying to find lowest in a landscape of peaks and valleys. Every possible solution is mapped to coordinates on 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 gives the lowest energy or optimal solution of the problem. So, essentially this is looking for the lowest energy point or energy minimization principle. What it takes advantage of is the principle of quantum tunneling, which allows the quantum computer to explore the landscape in a way that is otherwise not possible with the classical systems, the quantum tunneling is explained in terms of say a layer of water that covers the entire landscape 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 probability is pooled around the lowest valleys, the more water in a valley in terms of the analogy, the higher the probability of the solution being returned. A classical computer on the other hand is like a single traveler exploring the surface of a landscape or one point at a time. So, this is the analogy to finding out how they get to their best possible solution in a search environment.

So, they basically rely on the idea that there is an adiabatically cooled system so that the lowest possible is possible to be seen; however, it would also involve assigning very judiciously the probabilities to all the values that come out as a result of this. So, there are applications of search computers; however, this is not the very straight forward way of the developments of quantum computer that we have been discussing or for that matter how the evolutions of quantum computers have happened over the years. It is one of the places where certain levels of advantage exist and so a lot of effort has gone into developing this kind of quantum computer.

Some levels of skepticism still exist around the D-wave computers; however, they have had certain applications and certain areas advances with respect to classical computers have been noticed, but it is not possible to ascertain a complete benefit of the number of qubits that seem to exist in such systems. We discussed at length in more detail about the D-wave computing in our regular classes, if you wish to you can go back and revise those lectures to ensure that you understand the little bit more on the principle of their operations and the technology that they have used in terms of the superconducting circuitry and connectivity to their quantum computing processor that they have kept at very low temperatures.

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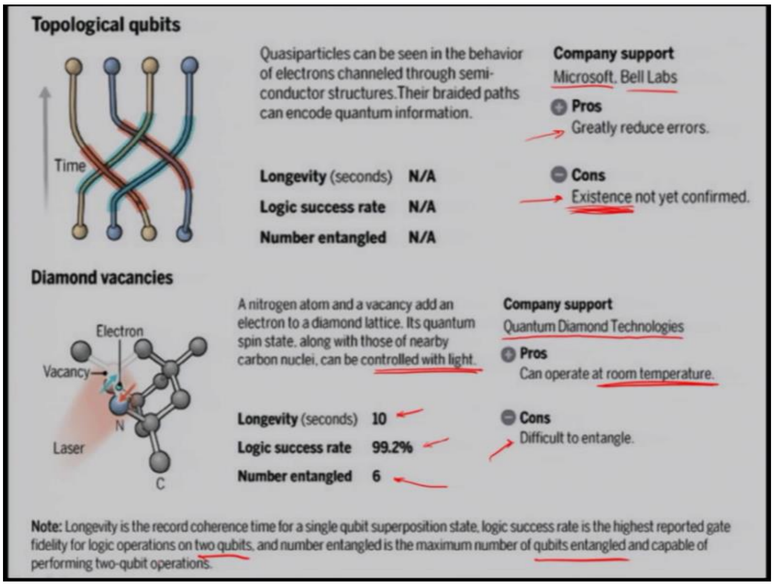

The other areas of commercially viable quantum computing approaches include topological qubits where quasi particles can be seen in the behavior of electrons channel through semiconducting structures, their braided parts can encode quantum information and this kind of work has been supported through Microsoft and bell labs. A lot of information on this particular area is yet to be forthcoming. The advantage of this technique is that it is a greatly reduced error process; however, the biggest difficulty of this process is the fact that the existence of this theoretical concept is yet to be confirmed completely through experiments, there is still a lot of dilemma about this development.

Another area where a lot of effort has been going currently is in the area where vacancies in diamonds have been utilized for quantum computing and nitrogen atom and a vacancy add an electron to a diamond lattice diamond as you know are made from carbon atoms put together, its quantum spin state along with those of nearby carbon nuclei can be controlled with light; it is a fairly long longevity about 10 seconds and it is logic success rate is also not bad 99.2 percent, number of entangled qubits as of now is 6; however, it is difficult to entangle; 6 is a heroic number in this particular case.

The advantage is that it can operate at room temperature that is one of the huge advantages as of now because most of the techniques that we discussed are not quite operable at room temperatures and this is being supported by the quantum diamond technologies. In most of these cases as had mentioned previously, the longevity is the record coherence time for a single qubits superposition state; while the logic success rate is the highest reported logic fidelity for logic operation on 2 qubits and number of entangled state is the maximum number of qubits entangled and capable of performing 2 qubit operations. So, these have been the benchmarks which have been utilized for understanding or making a comparison between these different techniques.

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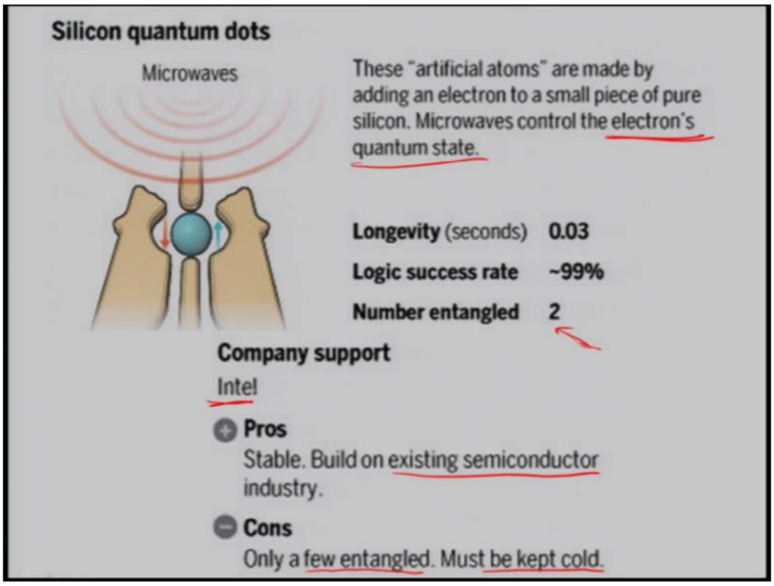

Another area where a lot of effort have actually gone in although the number of entangled qubits are low this is the area of silicon quantum dots, where the artificial atoms silicon quantum dots which can be controlled by using microwave radiation, these artificial atoms are made by adding an electron to a small piece of pure silicon. The microwaves control the electrons quantum state, longevity is not great it is about 0.03 seconds and the logic success rate is about 99 percent and the number of entangled states are still not very large about 2, the advantage is on it is stability and it is built on existing semiconductor industry.

The difficulty and the negative part is the fact that only a few entangled qubits are demonstrated and it has to be kept cold and an Intel is the company which is supporting this effort given the fact that it is a connected to the semiconductor industry.

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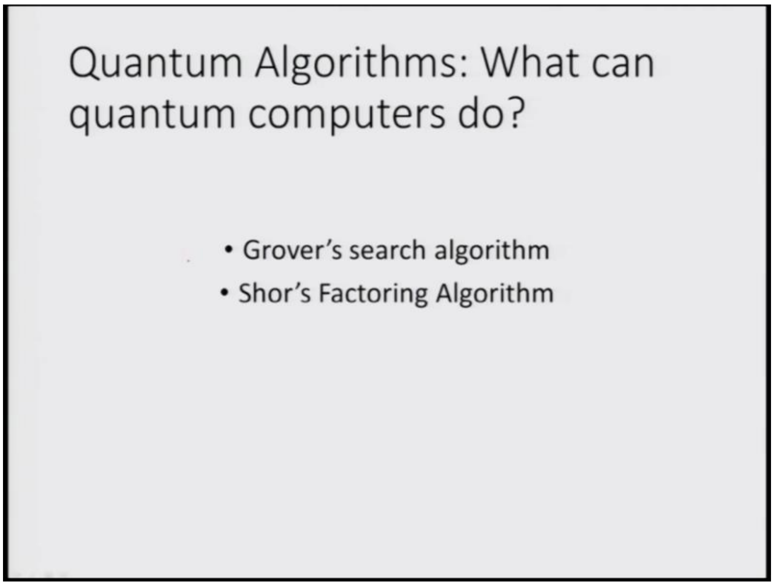

Based on these discussions, we would like to revisit the quantum algorithms that such quantum systems have been looking at, since we already discuss the Grover's search algorithm and the Shor's factorization algorithm earlier even in this week; I am going to start off by discussing these concepts.

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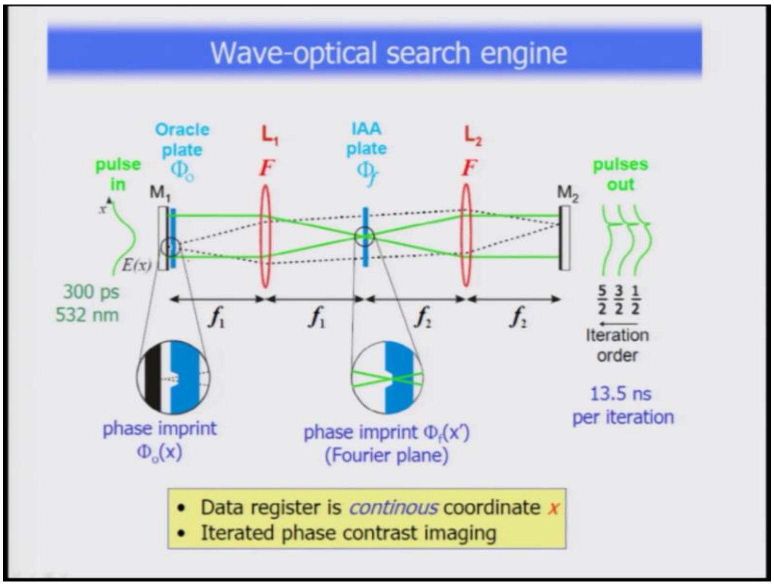

And in going forward with this; let me first give you the principle behind the Grover's algorithm where in one of our lectures before, we had even shown wave optical search engine which did not have anything to do with quantum systems, but it was the wave nature of light that was utilized to show at Grover's algorithm could be demonstrated in principle.

So, it is indeed possible to show that wave optics principles can demonstrate superposition as well as the principle of Grover's algorithm because it relies on the concept of superposition; however, the resources scale higher in this process of classical nature of the wave compared to the quantum process. So in a true quantum computing scheme, the space resources necessary would be much less as compared to that what is necessary for the classical wave operation case.

So, this was one of the cases that we had discussed before and I thought I would bring it back on to make sure that you understand that just because classically it is possible to do superposition, it does not mean that I just thought that I will bring it back to you in order to remind you that although Grover's algorithm could work in a complete classical manner in terms of having superposition alone, the idea of not having the quantum nature in the process of developing it would give some difficulty in terms of scaling the problem. So, that was one of the things which I just wanted to bring back to your memory.

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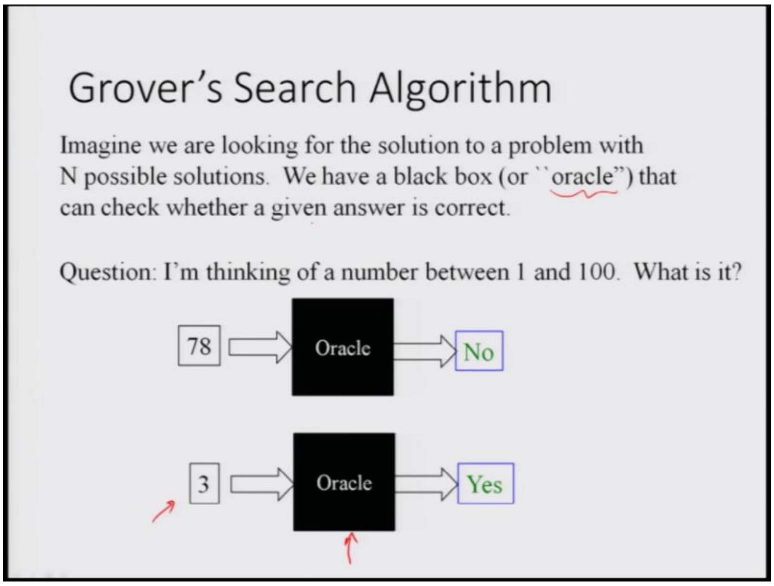

In typical Grover search algorithm, we are looking for a solution to a problem by utilizing the oracle or a black box that can check whether a given answer is correct. So, for example, if we are thinking of a number for instance here I think of 3 and we put in any other number than 3 the oracle is supposed to say no until and unless I put in the number 3 and the oracle is supposed to say it is correct. So, the idea of an oracle in this context is basically to ensure that it can check the correct answer.

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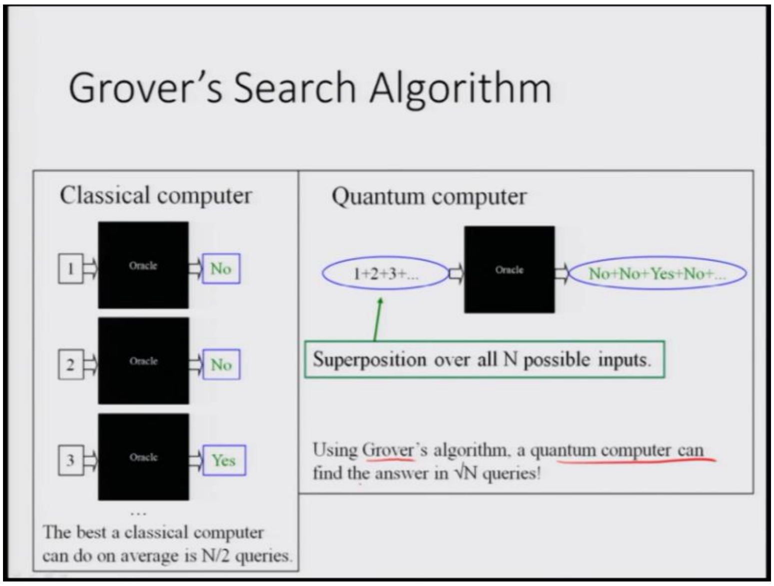

So, in terms of a classical computer you need to have at least N by 2 queries to be made on a data set for the oracle to check the correct answer. So, the best classical computer can do on an average is N by 2 queries, so this query concept is the principal where the oracle becomes critically important. Whereas, in case of a quantum computer since the superposition of all n possible inputs are possible this can be achieved much faster and that was the basic idea behind the Grover's algorithm which says that a quantum computer can find the answer is root N queries.

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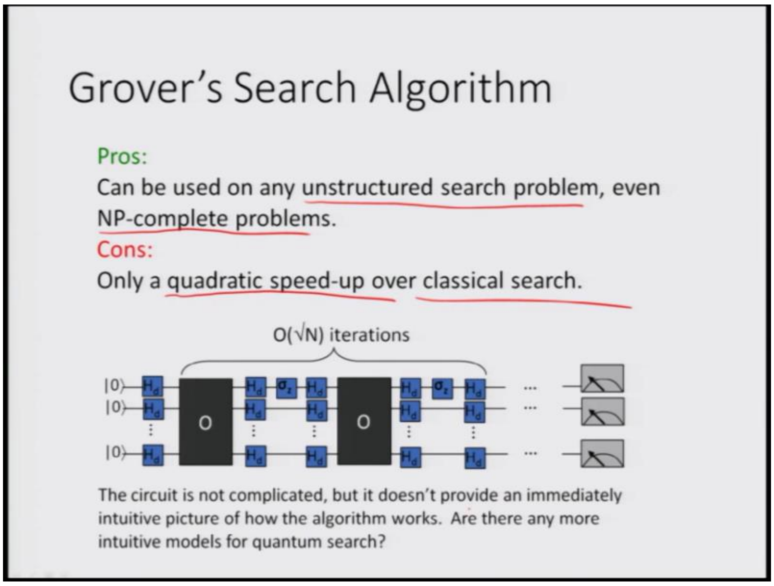

The advantage of this is the fact that it can be used on any unstructured search problem even in terms of non determined polynomial complete problems; however, the disadvantage is that it is only a quadratic speed up over the classical search. The circuit is not complicated because it essentially involves a bunch of Hadamard operations followed by policy operations, but it does not provide any immediacy intuitive picture of how the algorithm works. So we could ask the questions are there any intuitive models for quantum search.

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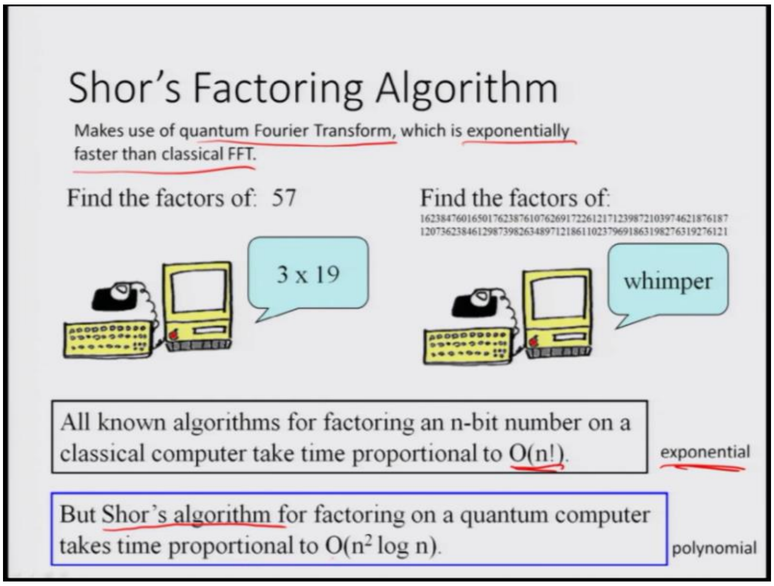

When we utilize Shor's factory in algorithm, it utilizes quantum Fourier transforms which is exponentially faster than classical Fourier transforms. So, for example if you would like to find the factors of 57 which is 3 and 19 you take at least exponential time to get to the answer; all known algorithms for factoring an n bit number on a classical computer takes time proportional to order of n factorial which is an exponentially growing problem; however, the Shor's algorithm for factoring on a quantum computer takes time proportional to order of n squared log n which is the polynomial scaling.

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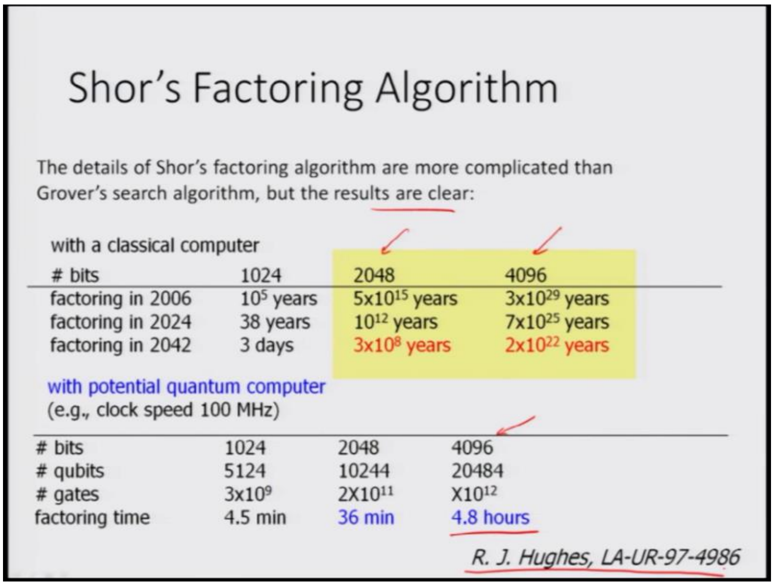

The details of Shor's factoring algorithm are more complicated than the Grover's search algorithm, but the results are very clear with classical computers, the number of bits are 1024 as our computers become more and more powerful, we could achieve this in let us say 3 days in the year 2042 whereas, if we increase the number of bits to 2048 or 4096, it just becomes more and more complex to the point that it is not possible to really make a much of say about it can be say factored or not.

But on the other hand with potential quantum computers where the order is polynomial, it would still only take 4.8 hours if you get to a 4096 bit system. So, this was essentially shown by his work by Hughes and it is straight out of this write up that they had on this work. So, this particular part of the lecture was dedicated towards showing how the commercial principles of quantum computing and the developments have been utilized in recent times to get to developments where the most important aspects of quantum computing developments in terms of Shor's and Grover's are possible to be shown by these techniques and they seem to do a pretty good job in terms of showing the scaling is in our favor in terms of getting the use of quantum computing.

So, with that I would like to end today's lecture, we will see you next time with more details on some of the other parts of the course that I have not discussed until now; see you next time.