Implementation Aspects of Quantum Computing
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Lecture - 43
Use of Atomic Qubits in Quantum Computing

We have been talking about the different aspects of building of quantum computers and in this regard let us go back and look at some of the cases that we have looked at.

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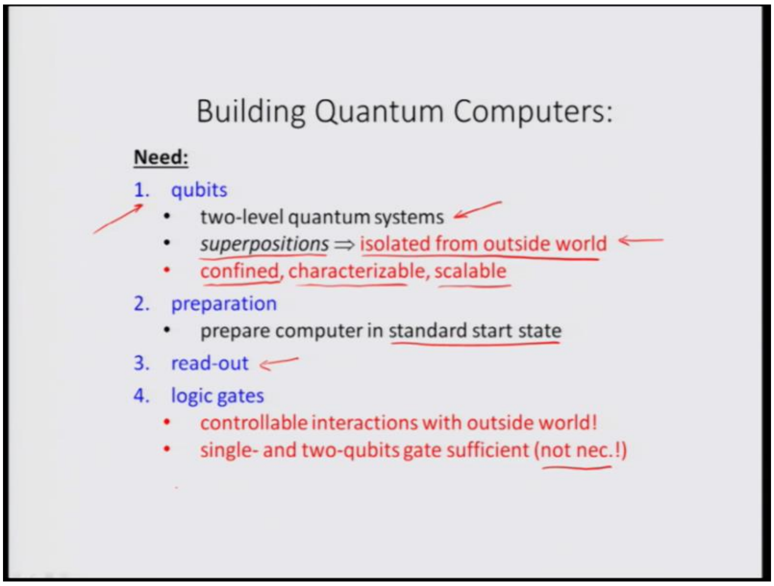

So, let us see what we need are qubits as we have discussed before and which are typically two level quantum systems which can undergo super positions, which means they have to be isolated from outside world; otherwise their super position will not stay, so that is the fragility of this problem. They had to be confined characterizable and scalable.

So the main constrain on the qubit lies on the fact that it has to be at two level quantum system which can undergo super position, but since it can undergo super positions, it becomes fragile which means there it is to be isolated from the outside world. So, such qubits which are confinable, that can be characterized and can be scalable are good qubits for building quantum computers. In terms of preparation, we would like to have the computer being ready in the standard start state. We should be able to have readout of the process and finally, we should have logic gates that are controllable with the interactions with outside world. And we would like to have qubit gates that can be of either single or multi qubit type.

Now that is in not a necessary requirement because there can be qubits which could only work on say the single or a few qubit operations and yet in terms of gates and yet get to useful computation. Generally for a general purpose computer however, may be this requirement is also useful in terms of logic gates.

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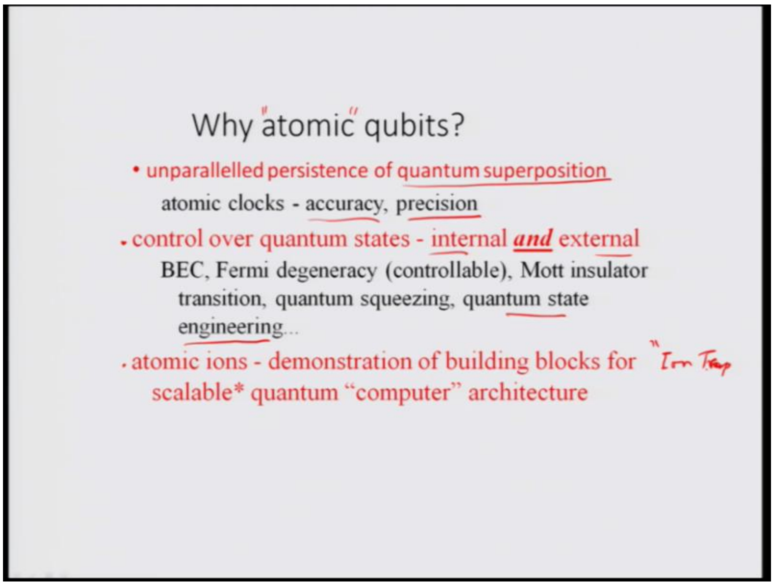

Most of the time in implementations, we have started discussing from atomic states in terms of qubits and so a natural question often may arise is to why atomic qubits mostly because of the fact that they have the unparalleled persistence of quantum super position, that is one of the best situation for atomic qubits; mainly in terms of iron traps and isolated atoms, they can act like atomic clocks which have absolute accuracy and precision.

So, the technology exists in terms of using atoms in this form, so also possible to have control over the quantum states both internal and external in the case of atomic qubits for example, Bose Einstein condensate, Fermi degeneracy which is controllable, Mott insulator transition quantum squeezing, quantum state engineering and so on and so forth, so there are several control points in case of atomic qubits. The atomic ions have been demonstrated for building blocks of scalable quantum computer and that is one of the cases where ion traps have remained very useful in terms of quantum computing and we have also shown that very recently even commercial ventures are starting on the ion trap principle.

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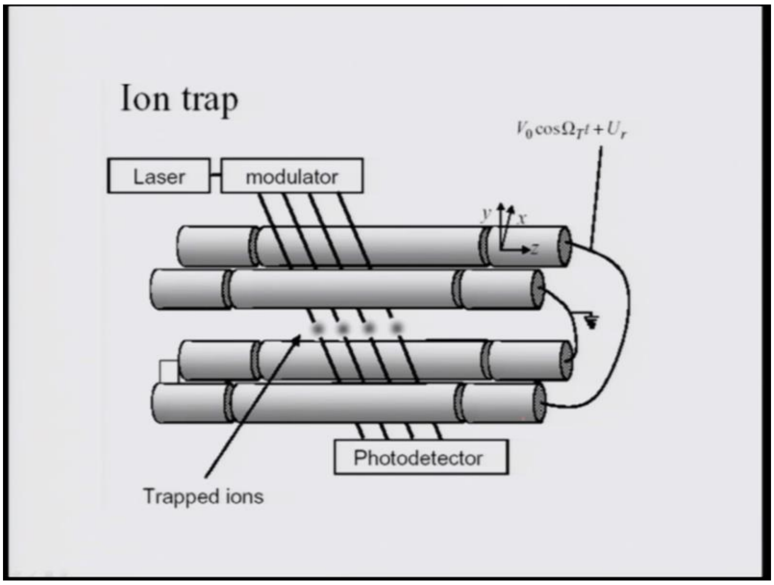

Ion traps are basically trapped ions which are placed in controllable conditions by the trap itself if we generated through electromagnetic interactions which is possible through the magnetic and electric fields that are provided to such trapped ions either through the laser or through the field providing gradients, that are possible through the electrodes and as far as detection is concerned light can be used to have some interaction with the trapped ions which can be then looked at through a photo detector.

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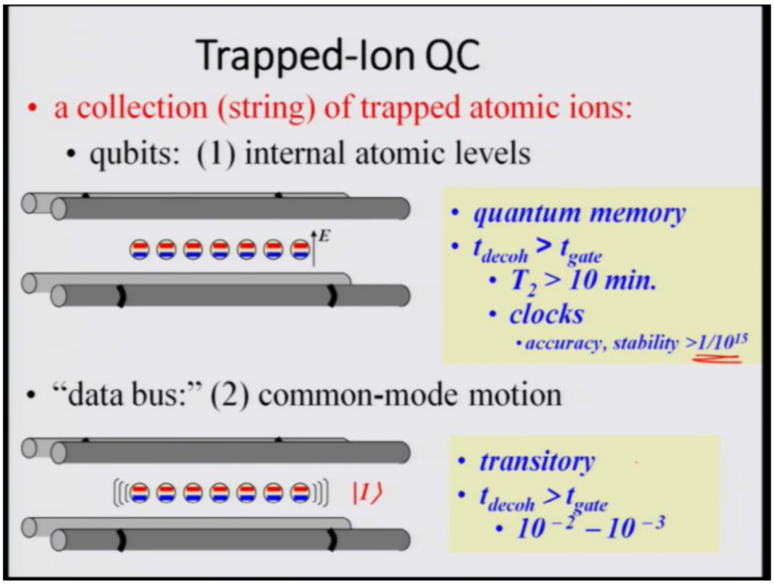

In terms of trapped ion quantum computing, a collection or a string of a collection or a string of trapped atomic ions are used as qubits, which could be the internal atomic levels of the system or it could be the relative condition of these ions. So, for example in this particular case; we have all the trapped ions having the same nature, so ground and excited they have the same condition.

Now the preservance of this condition is the quantum memory of the system, the time it takes for this system to change from its original state would be its decoherence; which is in relation of each of them being in ground state if some of them flip then that is the decoherence time and therefore, it is important that the decoherence time be larger than the application of the gate, as the gate itself is doing trying to do some operation of this kind.

For many cases, it is known that these are long times in terms of decoherence T 2 for instance is 10 minutes in a situation like this where the relative states are all the same. So, this is a very good system in that sense and as we know has been used in clocks with accuracy and stability of a very large number. So, once we apply the field which is the one which would be used for gate processing others, the system can be made to go from the ground to the excise state from the zeroth state to the first excise state and the other option is to use them in terms of data bus or which is the common mode motion condition which can be achieved through transitory activities.

Once again here the decoherence has to be greater than the gate operation mode and so here for instance, this particular set would be your ground state, whereas the other one where the ions are being squeezed to come closer would be your excised state and this have a time scale of 10 to the power minus 2 to 10 to the minus 3 seconds, which is not as great as the other case of changing the nature of the ground or the excise state is the relative closeness of different ions which are being played with in this case. So, this is a transitory operation in that sense; both of them are useful for doing quantum computing with ion traps.

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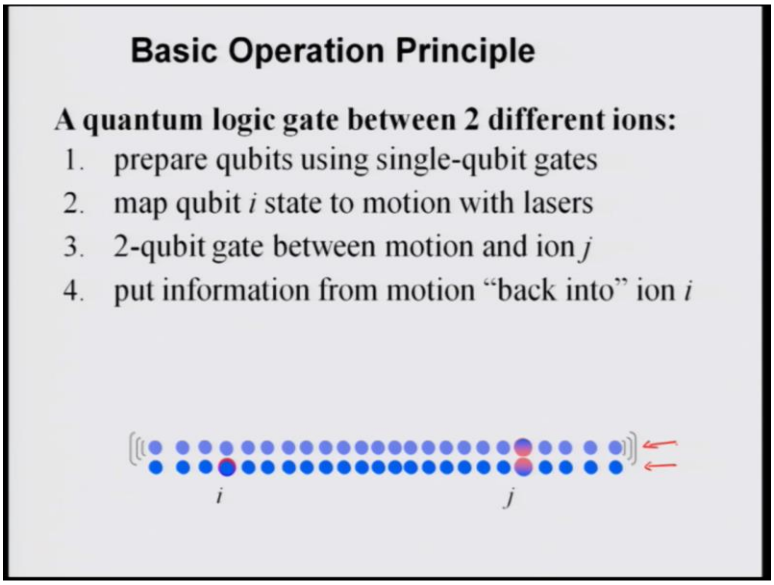

So, here is basic an operation principles which have been earlier shown to you in one of the earlier lectures. A quantum logic gate between two different ions for instance has been shown and I take this opportunity to revisit that part because that is a very interesting point.

In this particular case the qubits are being prepared using single qubit gates by the use of a laser where the laser would be used to map the qubit i state to motion with laser. So, for example, this is the case where this state was put to motion and so their relative conditions change between the first case to the case where the laser selective to the ith state was applied. So, once more first a laser is provided to prepare the qubit in the single qubit gate condition, next the qubit ith state is set to motion with the laser; the j state remains the same and now that has happened, we now have this condition and then the two qubit gate between the motion and i and j is being possible to be generated. So, we can put the information from motion back into i and I by using the laser.

So, that was the set of operation where the basic principle case is often used in terms of ion traps, where the utility of having several ions being together can be said to use both in terms of their energy states as well as their relative position and their addressability with the lasers with relative to each other; that is the advantage which is used.

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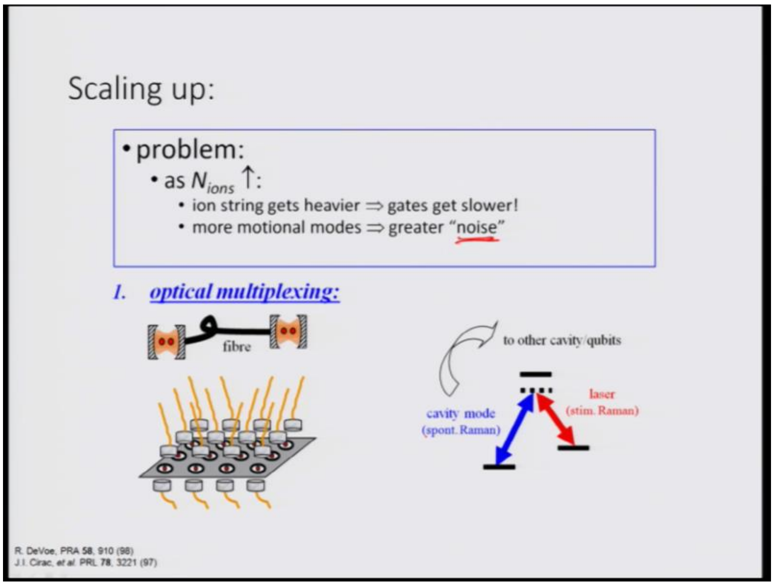

Now, the difficulty in terms of scaling up as the number of ions keep on increasing is that the iron strings get heavier and the gates gets lower and the more motional modes essentially also lead to greater noise and therefore, it becomes harder and harder to do it. One of the advantages is to apply optical multiplexing between different states by using optical fibers and detectors and lasers being operated; simultaneously in this form and this is one of the ideas which have been utilized where the cavity modes of different states have been excited so that they can be also additionally used and laser Raman stimulated emission and all these other characteristics by use of laser have also been applied for making this go further. Details of this have been discussed in the earlier week's lectures where we dealt with ion trap quantum computing.

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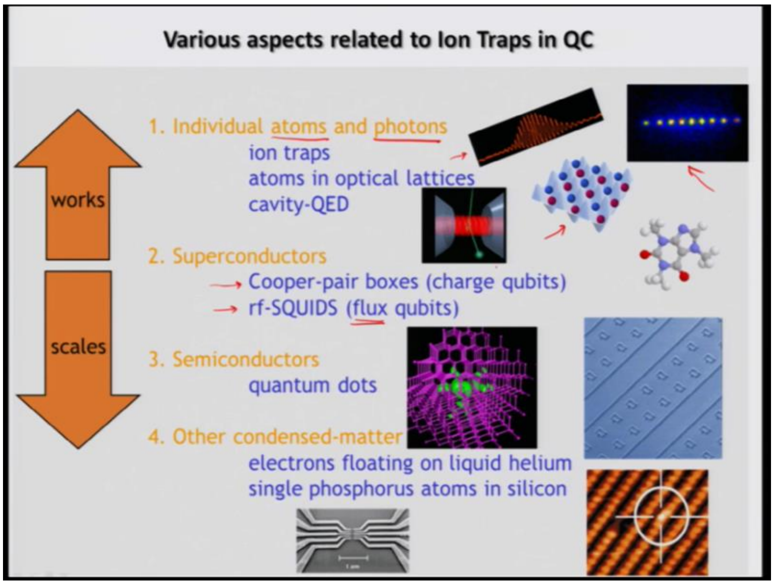

The major part of the effort in that direction in terms of using single atoms per say for doing quantum computing are related in this fashion, we know that there are different parts where the principle works and can be scaled some of them do a better job in terms of scaling versus the others. So, in terms of ion traps and atoms in optical lattices as well as cavity QED, it is essentially the individual atoms and photons which are in action in terms of doing that quantum computing.

So, it is either the cavity modes of the QED which is as represented in this form or the atoms in optical lattices has been shown here or the ion traps as we just showed with their relative positioning or their energies, which have being conditioned in terms of individual atoms and photons in this particular idea of using this individual atoms and photons for quantum computing. So, this works there are difficulties but they can be made to work and the advantage here is the sensitivity as well as the coherences is very less and so it can help in terms of executing the operations.

The other principles that we have used throughout this course have been in terms of using superconducting materials or superconductors per say and there we have discussed about cooper-pair boxes, which are basically charged qubits as well as r f-SQUIDS which change their property based on the applied radio frequency fields and they act as flux qubits. So, they have also shown promise and have been used in fact, certain types of applications of the superconducting qubits have been shown to be of much use in the

D-wave computer also. They use some parts of this technology to build their commercial quantum computer.

Semiconductors or quantum dots are the other kinds of qubit structures that we have also discussed in this course in terms of using for quantum computers and they have their advantages, although the lifetimes and others associated issues we have discussed can be difficulty as well as addressability sometimes can become very difficult. The other condensed matter aspects or applications which have come to quantum computing are the electrons floating on liquid helium or single phosphorous atoms in silicon, this is one of the areas where defect atoms have been utilized for quantum computing and their properties have been manipulated and shown to be useful in terms of quantum computing. So, there are various aspects related to single atoms and photons which have been put to use when we use these kinds of approaches towards quantum computing.

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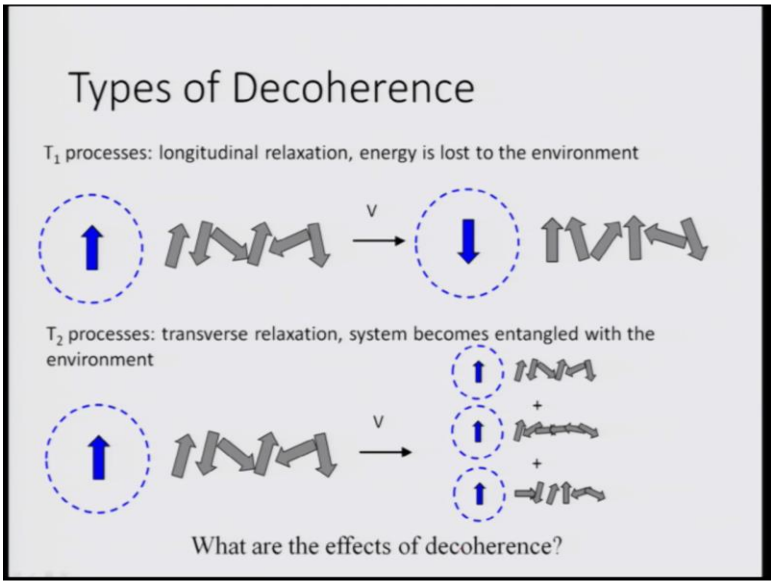

One of the biggest issues in almost all of them has been the idea of noise and the concept of decoherence, where the relative phase of the system is going to interact with environment so that the system can no longer keep its information intact. So in other words, the question which we always ask is what happens to a qubit when it interacts with an environment in terms of a quantum computer as long as its isolated; it has the quantum property and its information; however, if this information is lost due to decoherence as the environment essentially removes its quantum nature and sort of brings it back to an interaction condition where it loses the particular characteristic.

So, this is a very important issue and this had always been addressed in various different cases in different ways. Now there are two types of decoherence which is typically talked about; one is the T 1 process which is longitudinal relaxation; energy is lost to environment through the potential interaction, the other one is the T 2 process or the transverse relaxation, where the system becomes entangled with the environment and instead of having the entire information in the particular quantum state of interest, it is distributed over the entire system and so in essence the information is no longer easily perceivable. So, in order to look at this it is important to see how decoherence effects, it is one thing to just say that it is a loss of information but it is also important to know; what are the exact consequences.

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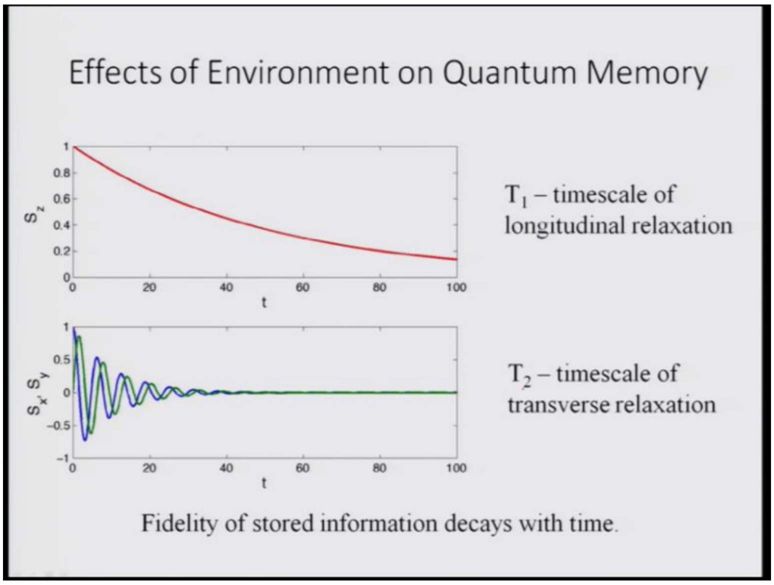

So, here are the effects of environment on quantum memory, the one which is more known as the longitudinal or the T 1 effect has a straightforward exponential decay in its behavior; whereas, the T 2 or the transverse relaxation procedure has an oscillatory kind of a behavior and overall the fidelity of the stored information essentially decays with time; however, in the transverse relaxation case; the decay is oscillatory in nature and there is a coupling and that is why it is considered to be an entangled with the system and the decay is in oscillatory fashion.

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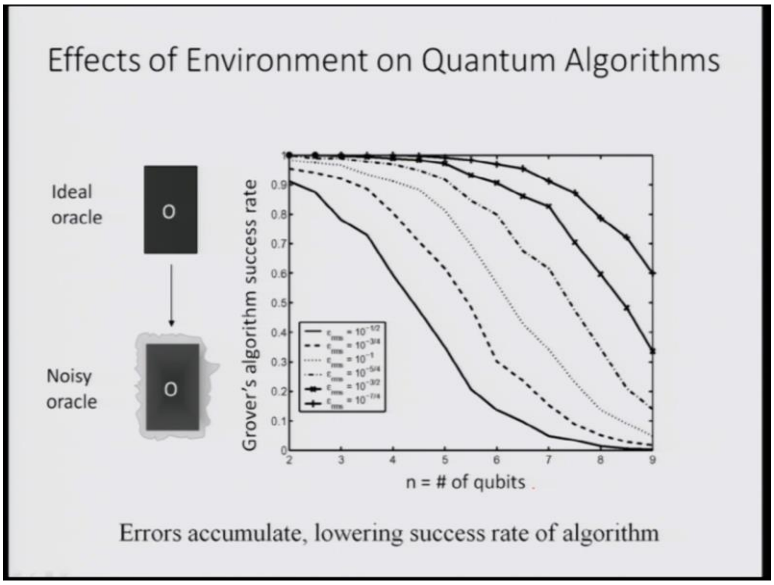

So, the effect of environment on quantum algorithms can be seen in terms of this kind of a modeling where; in case of an ideal oracle to measures the results as the number of qubits increases, the decoherence increases and this is an example case for the Grover's algorithm, where the success rates for the number of qubits keeps up going down in this particular format as we show here. As the oracle gets more and more noisy, it becomes difficult to look at it. In some sense the errors accumulate lowering the success rate of the algorithm and that is one of the reasons why environment has a large effect on quantum computing.

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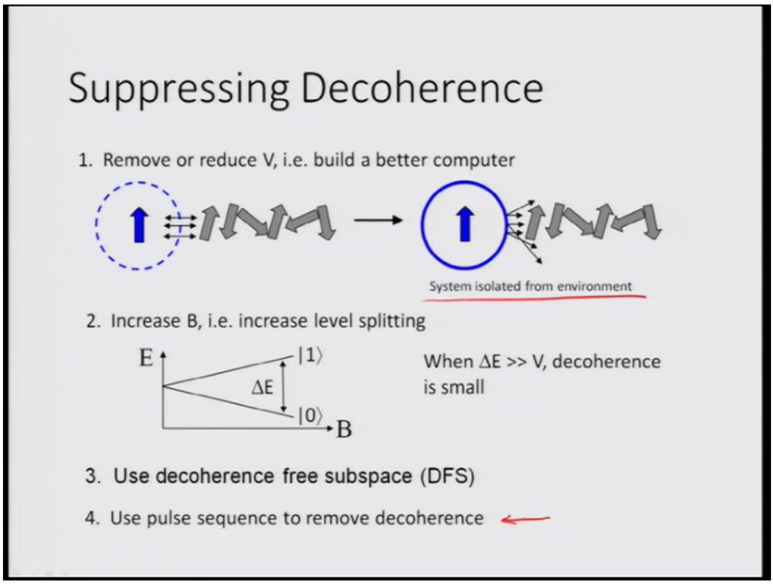

So, a lot of effort goes in suppressing decoherence; one of the approaches is to remove or reduce the effect of the environment or the coupling potential between the quantum and the environment and this can be done by reducing the coupling or potential that is can build a better computer; the system is to be isolated for the environment and that is whereas, one of the greatest strengths which the D-wave quantum computing has shown in isolating their system so well from the environment and making sure that it works much better way as compared to the others.

You can also increase the applied field, so that the splitting our cross the levels increase and so the decoherence is also lesser and in terms of magnetic field applied spins and other cases, this is how it can made to work. Other option is also often use is to use decoherence of free subspace and finally, we can use pulse sequences to remove decoherence and this is one of the cases that we will discuss later on in a case where we have shown how pulse sequences can be used to remove decoherence from such systems.

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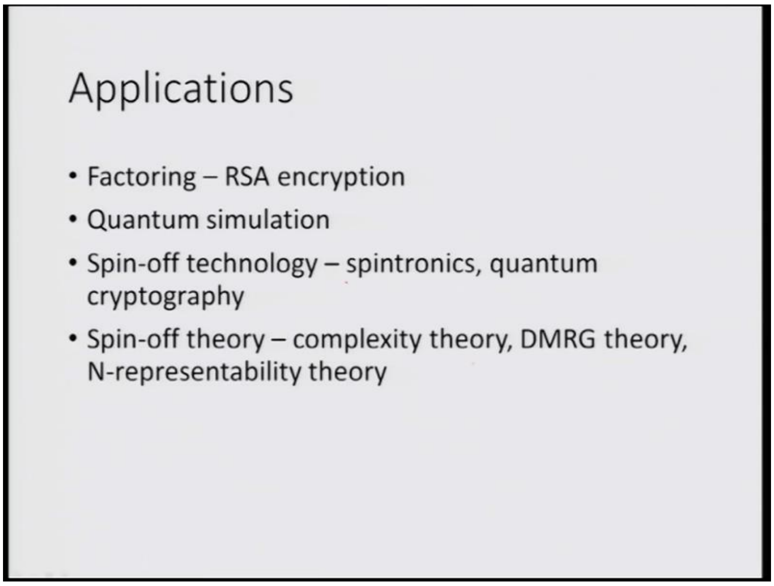

There are lots of applications of making sure that the decoherence is not going to affect the quantum computing and as far as quantum computing is concerned, the factorization as we have talked about is a major factor and that can be utilized from building quantum encryption as the current approach of RSA encryption may fail because factoring at exponential speeds can compromise the way computing or the encryption works for the classical sense.

Quantum simulation is also another very important area, where quantum computing once the decoherence properties and other things are removed can be very useful there can be spin off technology as we have discussed earlier in terms of spintronics, quantum cryptography and others which have been put through for developments. They can also be spin off theory for example, of the theory of development of density matrices and N represent ability of theories and so a lot of applications in terms of the quantum computer becomes applicable once the decoherence aspects of the problem can be looked at.

So, with this background, we will be looking at some more aspects of quantum computing wherein we address the decoherence principles so that they can become more and more practicable as we have done in this course but some of them will be highlighted in the upcoming lecture.

Thank you.