Implementation Aspects of Quantum Computing
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Lecture – 01
Introduction: Motivation and Overview

This is a course on quantum computing where we are going to have the basics of many subjects been covered together. So, in the first week we will be looking at your backgrounds.

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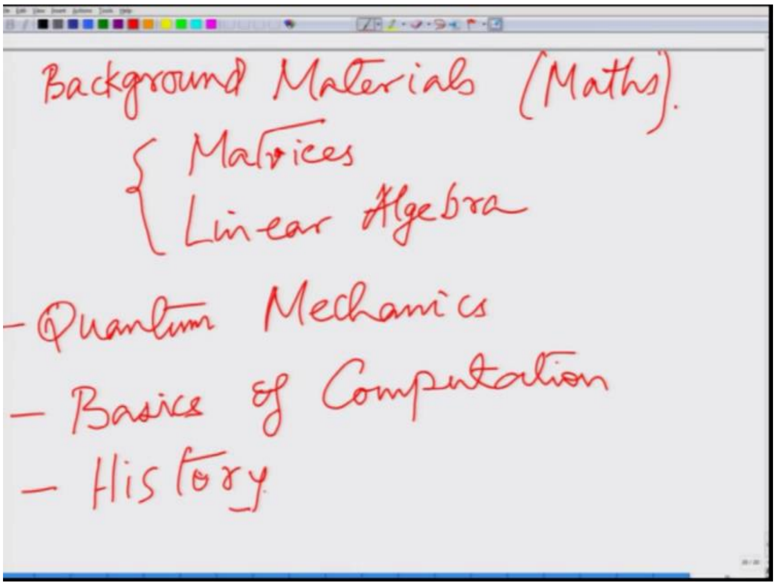

So, your background materials would involve mathematics which you must be familiar with matrices, then there is linear algebra. Once we have gone through these basics then we will look into main part which is quantum mechanics. And most of you have been exposed to the idea of quantum mechanics before. So, what we will do here is we will go ahead and go through the backgrounds of quantum mechanics in its own way.

The reason why quantum computing has become interesting is because there are many places where it is important for the ideas of quantum mechanics to come into competition. So, we will have to deal with the basics of competition also; basics of competition. Each of these we will do one at a time and then link them together. For this particular course we expect you to know most of the background materials in terms of mathematics already, because that was essentially used by you earlier and some of the newer concepts that you would be needing will be treated while we are doing our work. So, the main important part this is that we first go over a little bit of history which led to the idea of the quantum computing and then we go from there.

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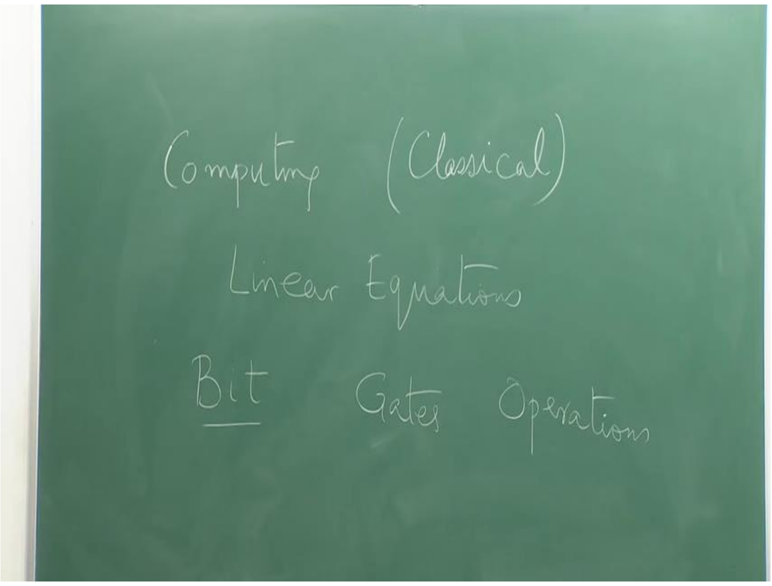

So, one part of the computing which will be done here is completely based on the idea of the classical one. And in this classical concept what happens is you are going to have lots of equation which will be solved and they are mostly linear equations. The smallest step in all of these involve computers which use something called a bit, that is your point where you use your computing device from. And they will be utilizing gates and operations. This is how the very basics will start.

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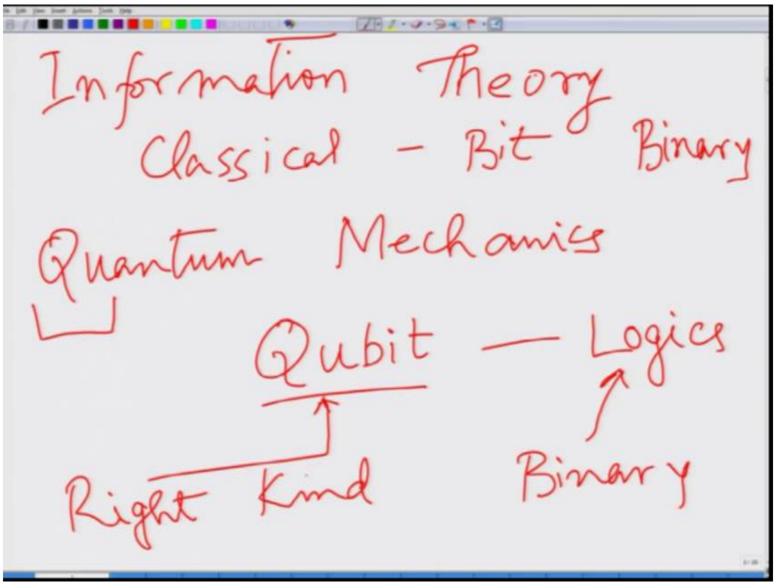

Now, once we are done with that then we will go more into the information theoretical principles. And then we will be dealing with whatever are the issues that have made information being stored in a larger form. So, currently in the classical form all the information will be stored as bit, whereas when we move over to quantum mechanics we will borrow the word ‘qu’ from quantum and make this as ‘qubit’.

Part of the problem which remains in quantum computing is to first find the right kind of qubit. So, that is one of the first challenges that you have. If you want to build a proper parallel then since bits are dealing with binary objects in qubits also you will be looking for logics which will follow binary principle.

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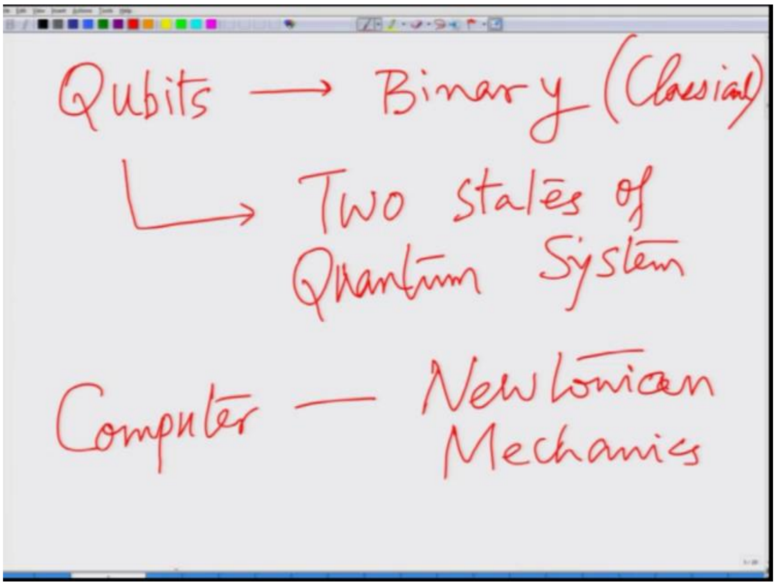

So, the idea therefore lies in coming up with qubits which can be looked at in a binary manner. So, very common qubit can be something like two states of a quantum system, just to follow the binary principle in the classical system.

Once we are aware of these very simple principles to start with we start asking some of the questions which make quantum mechanics and classical mechanics to be different. So, currently we have all the computers which are built follow Newtonian Mechanics, which means that we will be able to predict the pathway as well as the progress.

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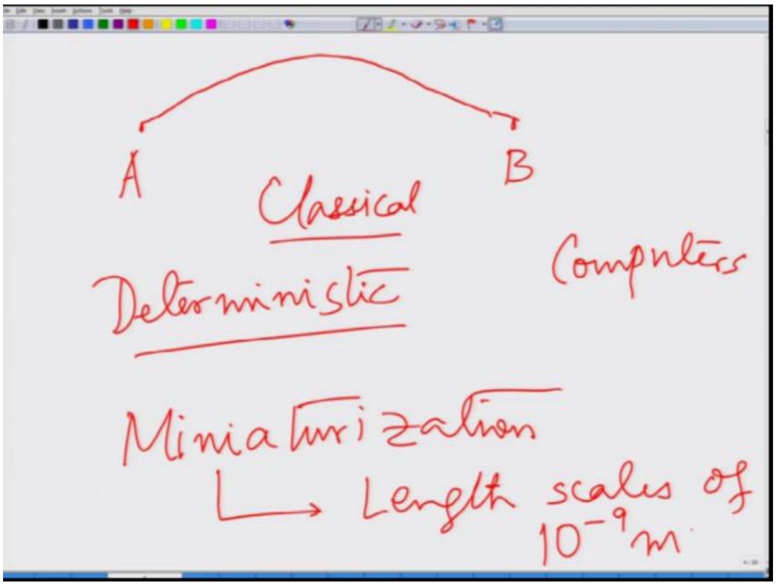

For instance, if we have a point A and if we have a point B then we can follow the trajectory as well as we can tell how they will reach each other. So, this is the classical mechanics principle, and it gives a very important determinism. So, this is deterministic. This is the principle in on which computers are now.

When we go from this idea of being classical or deterministic to something where our problem becomes much much smaller; so we are looking at miniaturization. Then this idea of classical may confront lengths scales where classical mechanics will not work. So, in this miniaturization when we talk about length scales in nanometers 10 to the power minus 9 meter then we are getting to a point where we are questioning validity of classical principles.

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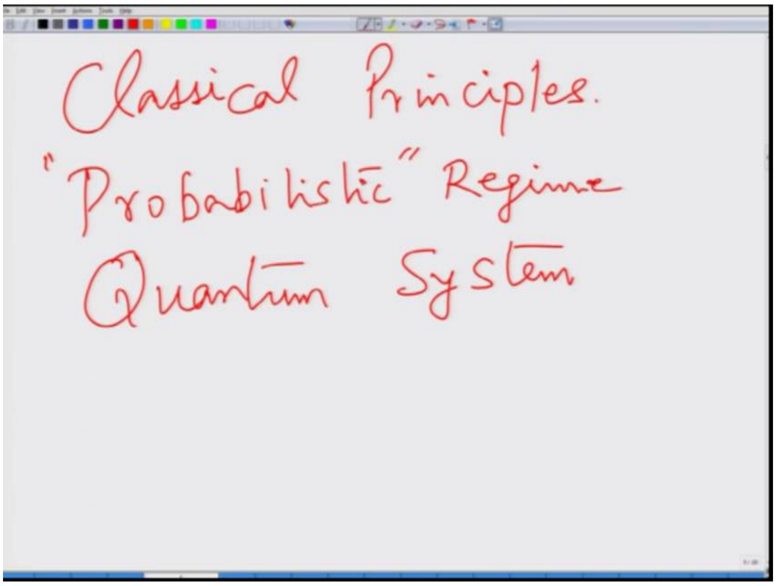

So, that is the time when we have to go away from our ideas of determinism to go into probabilistic regime. Now when we go to the probabilistic regime that is where we are talking about quantum systems. You could have probabilistic regime also in other cases; for example, in case of waves. So, you can look at classical objects which can show probabilistic regimes and you can study that also, but the reason quantum mechanics is important is the idea of miniaturization. As we want to go and build smaller and smaller systems and more efficient systems then we would be confronted with quantum mechanical issues.

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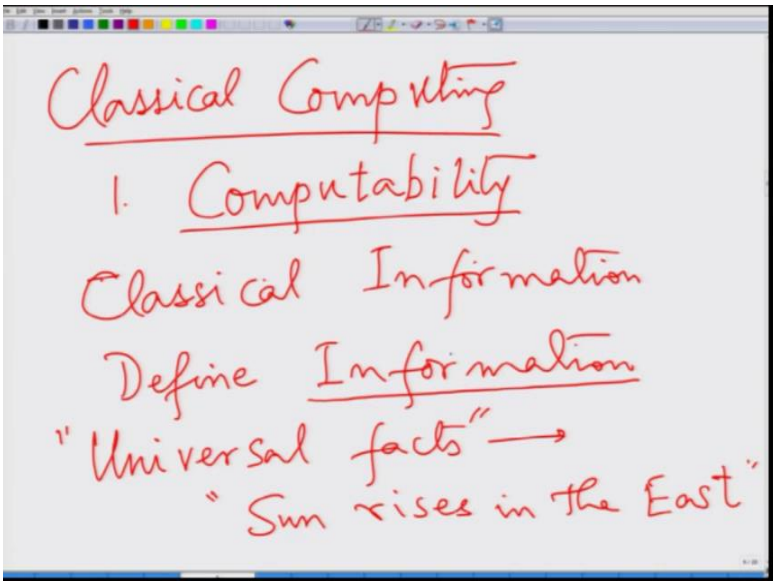

So let us see; what are the new things which appear as a result of going away from classical nature. So, what is it that is important in the classical system? Let us revisit classical computing, because if we want to learn about the new thing first we have to see; what are the most important aspects of the part that we are already using. In the classical computing first issue is to understand what is computability, can all problems be computable. That is one of the questions which is often confronted in this. Can you think of a situation which is not possible to be computed, can you come up with the problem which cannot be thought of a computable problem for instance.

Student: Any case where there is a one to many (Refer Time: 11:38) solution of a (Refer Time: 11:42).

No, they are all computable problem is it not?. You are thinking mathematically, I think when we ask the question of computability we should ask the question as to how we go about the question of what is computing. And in that regard the first question which comes which is very important is all of this has to deal with classical information. As long as my information is a valid one then we can start the process of computing that is one point.

So, my classical information should have a definition. So, the first point is to have a definition of or let us say define information. I think this is the point where you would all know that not everything not every statement can be considered as information, as long as is a statement has an information that can be processed then we call that a useful information or an information which can be utilized for the processing or doing other events. So, in this regard universal fact; for example sun rises in the East. No matter how much computing do, I do a do anything with it this statement is not going to change, which means that universal facts are not information that is going to be of any use for us. So, our first definition of information comes from this kind of an idea that we cannot use statements or processes which are never going to change.

There can be situations where you reach or you achieve an answer which can remains steady, that is a different situation. Or, most often which happens is which is oscillating around the particular answer they are all allowed, but something which is never going to change irrespective of the condition imposed is not an information in our case.

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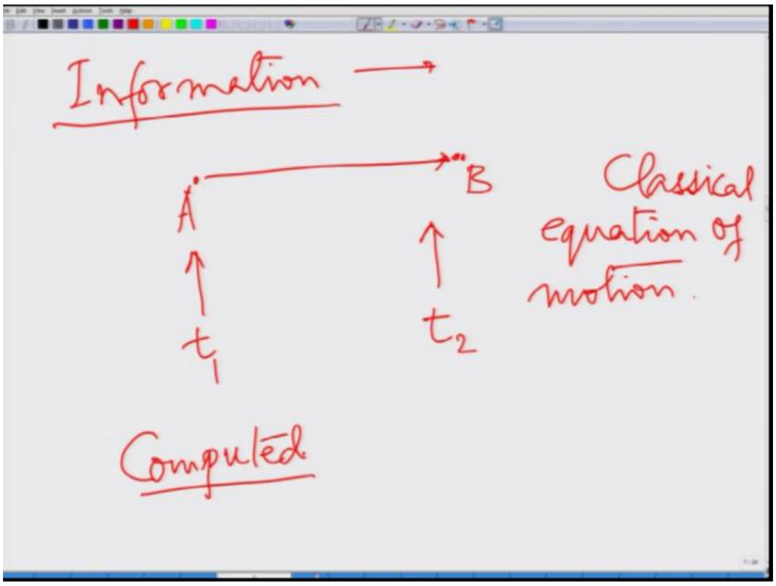

So, the information therefore is the first definition where we start with the fact that it has to be a process which on operation changes to another one; that is how we look at it. For instance, when we have a train moving from say point A to point B, so motion of the train from point A to point B that can be information; which can be specifically looked at in a way which can form equations of motion and in this particular case since we are talking about classical objects this is a classical equation of motion which will be set up.

In this particular case at what time now if I put in the parameter time, I can say that I would know the times at every point of this trajectory as to how things are happening.

So, this is the information which can then be defined in terms of equations of motions which can be then gone ahead and given at direction of computed. So, this information processing can be computed. But this is perhaps a very lame example, because you already knew that this is a very simple case where it can be done.

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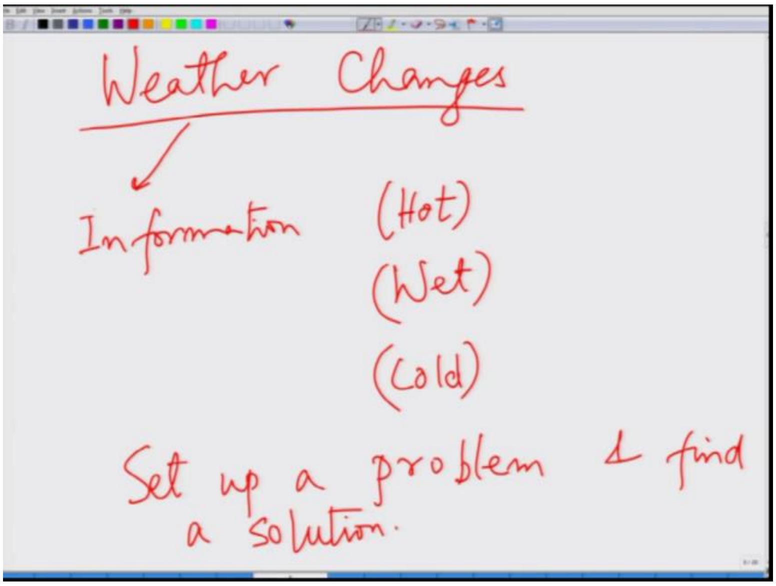

You can even do things which have much more complicated, like for instance you can come up with weather predictions, weather changes. Again, here weather can start off with the information which can be hot, can be wet, and can be cold. Now all of these are different sets, so you can make this into an information chart and you can start processing or building your problem around this concept.

Again this is another way of thinking that you can set up a problem. So, it is very important to set up a problem and find a solution. Now had it been also simple, why is it that it has taken many many years of mathematical understanding to come up with this entire process of computing and the story associated with it.

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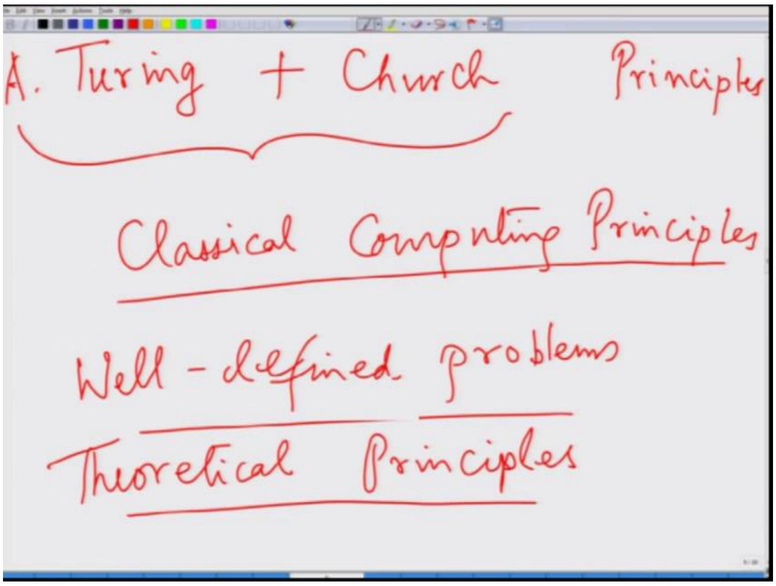

In fact, the ideas of computing started well before the first computer was ever made. This whole idea that you can actually come up with automated machine which will do the job of what you can do came from mathematical principles, purely mathematical principles well before the idea of computers ever existed. So, that was first done by Alan Turing and it was later on clarified little bit better by Church another person. And so this particular principle is known as the Church Turing Principle which almost dictates all the known Classical Computing Principles.

In these classical computing principles the problems are well defined. So, there are all these well defined problems. And these well defined problems can be settled on a computation basis. In order to learn this, what we need to do is to understand the theoretical principles which have been in existence for a very long time. So, the theoretical principles in existence for a very long time on the computational concepts give rise to the idea of the Turing Machine.

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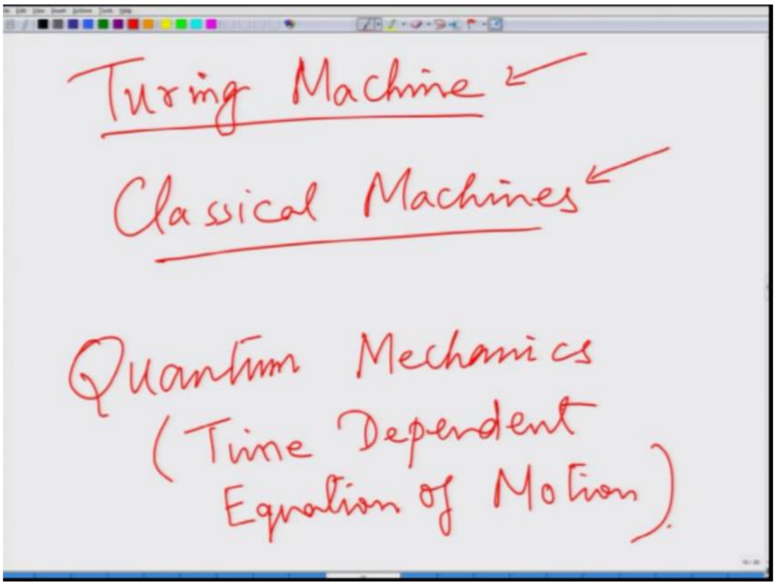

So, I will actually let you first go back and look up the books that you have to get the information about this principle of Turing machine, and then we will do this in the class so that when we are doing this you are all clear about how to develop and device a Turing machine. In fact, I will perhaps use a presentation in that case to tell you about the Turing machine

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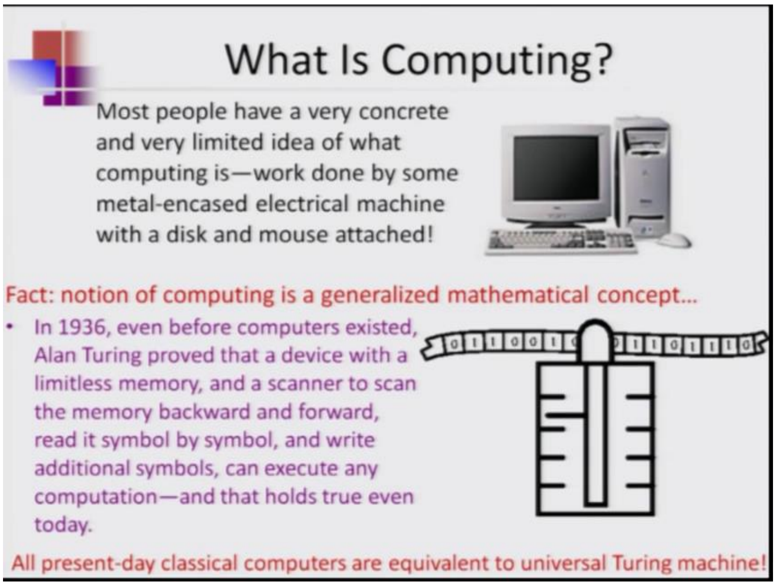

So, that notion of a computing is a very generalized mathematical concept. So, the first principle is given in 1936, even before computers existed. That the idea was very simple that if you can have a device with limit less memory and a scanner to scan the memory backward and forward, read it symbol by symbol and write additional symbols, it can execute any computation. And this principle holds true even today as a classical computer.

So, this is roughly how the imagination was that this would be like a machine where this will be the infinite tape which has all these binary digits written, and once that digits are being going through the head which reads the digit it will be able to process the information. That was the basic first principle idea of the Turing machine. And all present day classical computers are equivalent to universal Turing machine.

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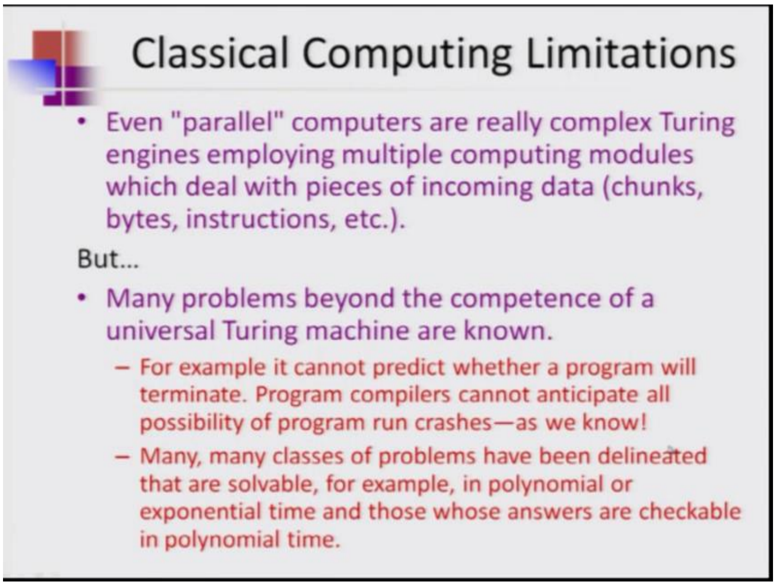

So, that is the first principle that we have understand. In fact, the massively parallel computers of today are also are nothing but really complex Turing engines employing multiple computing modules which deal with pieces of incoming data, chunks, bytes, instructions, whatever they are. But there are many problems beyond the competence of a universal Turing machine which are known. For example, it cannot predict whether a program will terminate. So, this is known as a classical halting problem. Program compilers cannot anticipate all possibility of the program run crashes and we know that, no matter how you build a computer it will always it may have that problem. Also there are many many classes of problems that have been delineated that are solvable; for example, in polynomial an exponential time and those whose answers are checkable in polynomial time.

Now, this is an important concept which introduces the idea of complexity of computation. So, the harder the computational problems becomes this principle is which is where is applied. It is sometimes for instance very difficult to find the solution, but it is much easier to check the solution. So, factorization is hard, but multiplication is easy. So, I can multiply n number of elements to get a number, but given the number to be able to find those n elements is going to be hard. So, inverse problems can be much much harder. So, this is what is, the second part of the statement, and that is true in terms of the complexity of the problem.

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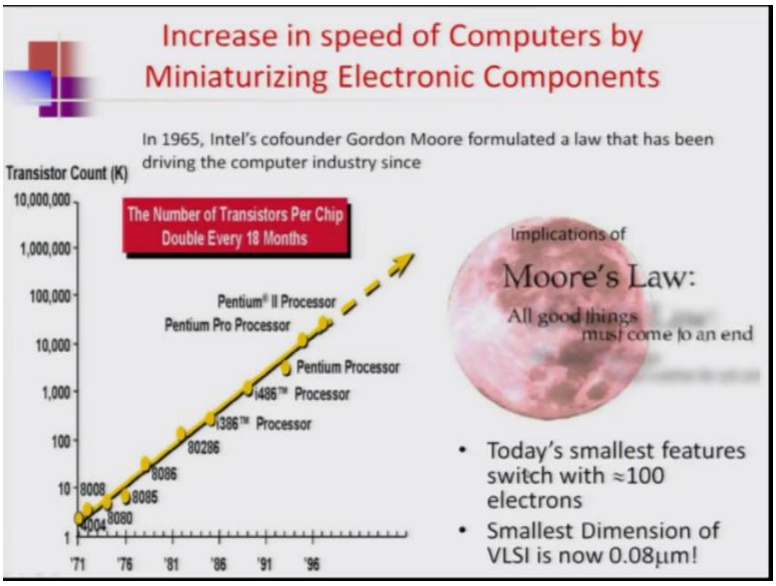

The reason why the story as we unfolded today started with the idea that we want to miniaturized because we want to increase the speed of the computers, and this is the famous law which was given by Gordon Moore, the is a cofounder of Intel. It is an implicit observation because he had been observing how the computers where becoming or being developed over the years, the basic chips, the processors. And what he saw that they were existed, almost a linear relationship over the decades of progress.

And that was very interesting and that is the idea that he presented, that as the processors or the computers are getting faster and faster and number of processors being fact are being increased a time will come when the size dimensions that we are talking about will not allow any more classical concepts to be taken care of. And that is the reason why this was. For instance, this was done at a time when the smallest switches where switching at around hundred electrons where in actually less that that nowadays, and dimensions of the very large scale instrument devices are now in nanometers. So, that is the reason why we have this issue about quantum mechanics coming into the picture.

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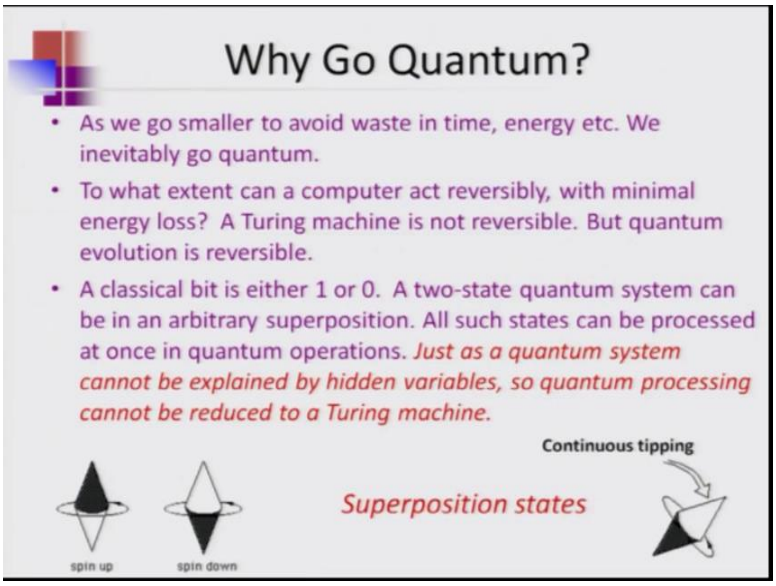

So that is what is been said here, that it is implicit we cannot really actually help us but go into this quantum world, because as we go smaller to avoid wastage in time, energy, etcetera. We essentially go into this quantum world, because we are going to smaller. And this other principle which is a thermodynamics of computing says that in order to get the best out of a computer we would like to have the computation to run in the most energy efficient way. And the most energy efficient way of any system is to have that system work in a reversible manner. And so that is the reason why it requires it in this manner that we want to be.

But a Turing machine for instance is not reversible it is a, if you saw the picture of the Turing machine as I showed you before the principle it is a particular tape which is going through the head, and its gone. Once it is read, you are not going back on it is just continuously moving in one direction, so it is not a reversible process. Also there is an expensive energy the moving of the tape, the reading of the tape, everything is expending energy. If you are only expending energy you are never going to have a reversible process. So that is one of the other reasons why you can always think that the Turing machine is not reversible.

The other implication of the classical computers which are based on Turing machine is the fact that all the computers get hot. They never remain the same temperature, with time. So, it is basically dissipating heat and whenever a system dissipates heat you know that it is no longer going to be reversible. These are the main issues that are there. On the other hand however, quantum systems are reversible. Quantum mechanical equation of motion is 100 percent reversible.

So, this particular background of the quantum mechanical part which shows the time dependent quantum mechanics for instance, which shows that its 100 percent reversible is one of the background information and backgrounds which will do a right after this introductory part, so that we are again familiar with how the evolutions that we talk about in terms quantum systems are always going to be reversible. So that is what we will do right after this.

Now, what I introduce in the very beginning was that we have working with binary situations which are our bits, which is essentially can have values which in terms of electronics is either high or low, basically 0 or 1, and you put them sting them together in the binary sense to create information. On the other hand, even if you come up with this kind of formalism for quantum systems which can be low line energy to high line energy, spinning in one way versus the other way, these are all quantum thoughts.

The quantum system however, will always be in an arbitrary super position. It is never going to be either one or the other; it will always be a mix of all. For example, a quantum system therefore cannot be actually explained by only looking at one of the two states. So, a quantum processing cannot be directly reduced to a Turing machine. But there is one very important thing to note, that although we are saying that the quantum system cannot be reduced to a Turing machine in the sense we cannot come up with a new way of computing just because we are using quantum mechanics which is not going follow Turing machine principles; that is also true.

So, over definition of competition still will relive on the principles led down by Church and Turing Principles, but the very fact that the machine operation will not be exactly the same is going to give us a difference between the two. So that is what the two systems have the main difference on. And will be having super position states, because it can actually have the two spinning. This is for example, a spin device; I think about a spinning topper something, and something spinning in one way versus the other way. The additional thing which happens in a quantum system is that. It not only spins one way or other way, it can also go it can tip one side versus the other. And include all other possibility which can happen versus only the two different cases of the classical.

For instance, coin toss problem you only have head or tail; that is your classical system. But if you have a spin then as long as the spin is rotating it can also prices down and hit the ground. All the possibility in that is covered when you do a quantum system that is the difference; because as long as you do not measure all possibilities are counted, because it is a probabilistic situation.

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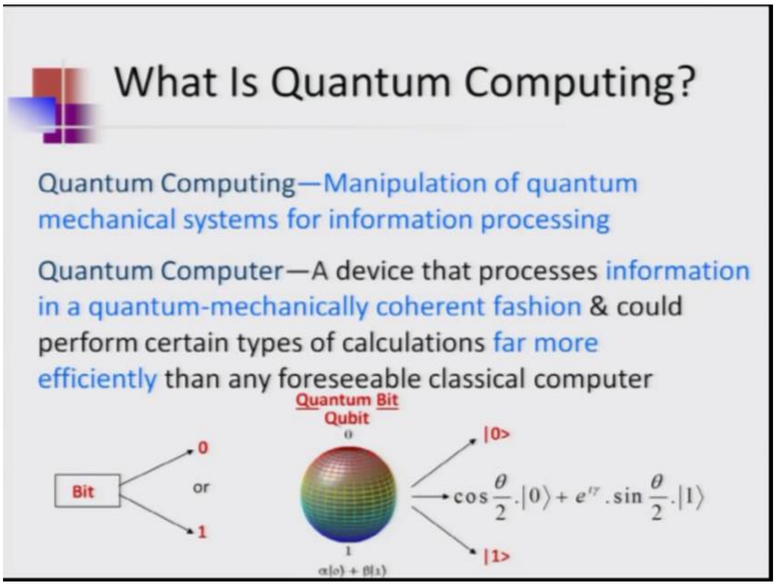

So, let us see if I can now go back or maybe I should just define quantum computing in the current sense once. So, let me actually formally defined quantum computing at this stage, because we already have an idea of classical computing and we have given enough examples on that. Quantum computing as of today is defined as something where manipulation of quantum mechanical systems for information processing. That is how quantum computing is being looked at.

And a quantum computer is a device that processes information in a quantum mechanically coherent fashion, and could perform certain types of calculation far more efficiently than any foreseeable classical computer. Now there is a question however, that it is not true universally for all types of calculation. So therefore, it is specifically mentioned here certain types of calculations, so this is how the general difference is. A bit will take only 1 or 0, whereas quantum bit or a qubit can have any of the possible combinations of the two.

However, at any point of time when you measure you will only see one of the two. So, the advantage in this computing process of the quantum computing lies in the fact that many possibilities exist which could do the computing. And if there is a way to take advantage of that then you will get advantage of quantum computing otherwise not. Otherwise it will just behave like a classical bit and so on and so forth.

So, we have gone through this idea of having something like a Turing machine. We will do a little bit more on these in terms of hand outs and exercises to understand the classical machines. So, the machines which are based on Turing which are the classical computing devices we will use some more examples and things in our assignments and homework problems. But for going ahead what we now need to do is to look at quantum mechanics, more importantly the time dependent equation of motion.

So, this time dependent equation of motion is the one which will help us understand how we can address issues which will be connected to our computing. So, this will be the main issue that will be starting on right after this step. And I think will stop here for today, we will take it on from the next day.