Digital Circuits and Systems

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Module – 01

Dear students, welcome to this course called Digital Circuits and Systems. So, first of all, I want to wish you all a happy new year, welcome to this course, my name is Shankar Balachandran and I am an associate professor at IIT, Madras, I am in the Computer Science department, currently I am visiting IIT, Bombay. So, in this course probably one of the first courses that, you are taking as a MOOC or Massive Open Online Course.

And for those of you taken this before you probably know, how such courses run, for others, who are new to this format, so this is a very different format from what you are used to. So, in this you have a remote teacher, who is going to deliver lectures. So, I as a teacher, do not get to see you at all, you probably get to see me in the video, I do not get to see you at all, we will have weekly assignments and so on are given. At the end of the course, we will also have a final exam.

So, this is unlike other courses, where you have personal interaction with your teachers and the teachers also know, what exactly to expect from the students, they also correct mistakes that you make really quickly. So, if you are new to this kind of learning, it is a bit of a learning curve that you have to go through to get the best out of this course. I will try and make that as simple as possible for you and I will try to give you an experience as though you are in a real class as much as possible.

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So, let us get to the course, so this is a course on understanding analyzing and designing digital logic circuits. So, what we will do is, we will first learn basic logic theory and then, we will go on to what are called combinational and sequential circuits. We will try and learn how to design computer arithmetical circuits and we will also learn some advance topics in this course. So, the text book that I am going to use is called Fundamentals of Digital Logic with Verilog design.

So, you see on the right side, a picture of the cover page of the text book. So, this is an Indian edition of this book and I am using the second edition, you can see the picture there. So, the authors are Stephen Brown and Zvonko Vranesic, this is from McGraw Hill. So, last I check this is available in online stores for about 300 to 400 rupees.

So, this is the text book that I am trying to use it is, you do not have to buy this text book. But, it will be good, if some of your friends and you get together and pool your money and buy this, if in case you want to read more material. I do not expect you to buy this text book, though. It will be nice to have one copy of the text book for a couple of you, who are taking this course.

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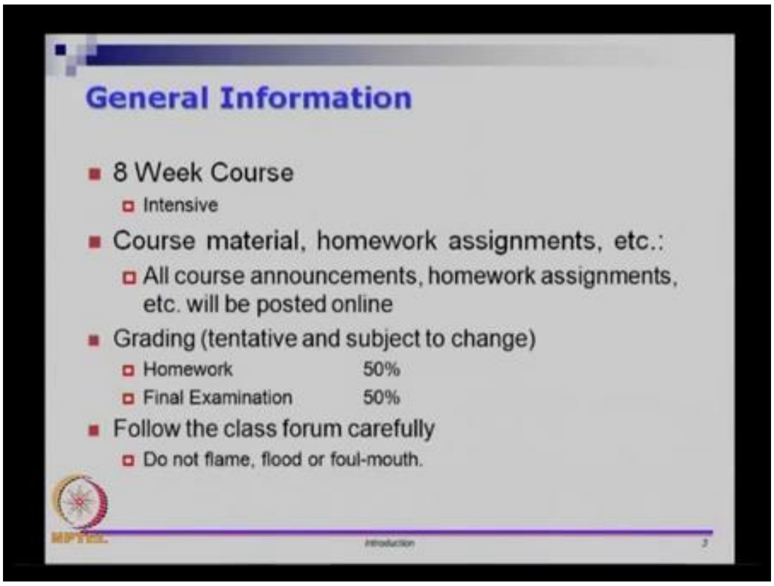

So, the general information about the course it is an 8 week course. So, unlike the regular semesters that you are used to, this will be fairly intensive course, because it is compressed into 8 weeks. So, all the course material, the homework assignments and all of those will be online and you will have to be diligent about this. So, every week we will give assignments and the assignments will be due a week from when it is assigned.

So, it is important for you to finish the assignments on time and so that you can move on to the next weeks lectures and the assignments will be strictly timed, there will be no extensions given to the, there will be no deadline extensions for this. So, you have to keep up with the phase of the course. So, the grading policy is tentatively as follows, we have at least one homework assignment every week, this will be for 8 weeks, the grade will be for 50 percent and the final exam which will be a proctored exam where you have to go to an exam center and take an exam, so this will be for 50 percent.

So, overall this is 100 percent, as of now this is tentative, this may change a little bit. So, with the final exam may go up or down a little bit based on how many assignments are given and so on. Another important thing that you have to remember for an online course is that, there is something called a forum. So, it is a mailing list that you have to be subscribe to, so you have to follow the class forum carefully.

There are several announcements that we will make, sometimes if there are any mistakes in the lectures or if you want to make any urgent announcements we make them on the forums. So, it is important to learn the etiquette of using the forums, so for example, you should not flame, you should not bad mouth other people on the forums, be it your fellow students or anyone, who is going to help you, do not fled the forums with spam or the same question repeated many, many time and so on. So, if you have participated in forums before you probably know for some of this etiquette. But, if you are new to the course as well as new to such online discussions, you have to be careful about how you use these forums.

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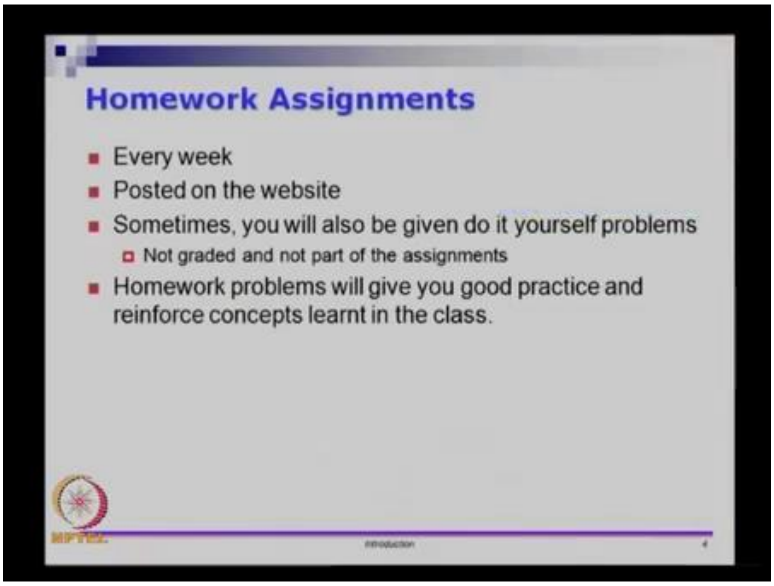

So, the homework assignments as I said will be posted every week and it is up to you to actually go and look at it, we are not going keep reminding you that there is an assignment posted, along with every lecture that we give we will also give you the assignments that go with it. And the homework problems will give you good practice and it will reinforce the concepts that you learn in this class.

Sometimes, I will also assign problems which are more like do it yourself kind of problems, where you try it for practice rather than for grade, but both kinds of things are important for your learning. In terms of the course itself, we will post every week, we will post the video lectures. So, the videos are organized roughly either a 15 minute chunk or a 20 minute chunk and you will be watching roughly 2 hours of videos every week. And the kind of work that you will need to outside the course, outside watching the video is probably about one to one and half hours of reading and doing assignments. So, you are looking at something like 4 to 5 hours a week in watching the video as well as doing the assignments.

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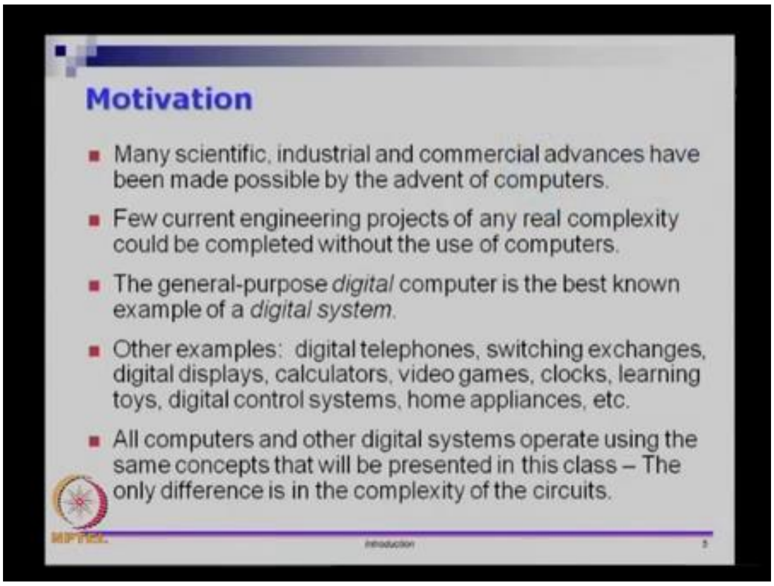

So, let see the motivation for this course itself, so the first thing is many advances in the industry as well as scientific advances have been possible, because of the use of computation. So, computers are ubiquitous you can see it as everywhere now and this is actually made many, many fields leap frog or improve quite a bit. There are very few projects which are complex and yet not use computers.

So, another way to put that is almost every real world project out there uses computers, be it from designing a bicycle or an airplane to designing cloths, pretty much everything uses computers now a days. And the general purpose computer is probably the best example for a digital system. So, we have used this in various forms your PC's, your laptops and so on are all general purpose computers, this is probably the best example of a digital system.

So, the course is titled digital circuits and digital systems, so we will learn both the circuit side of it, as well as the system side of it. So, there are several other examples as I mentioned. For example, digital telephones, switching exchanges, displays, calculators, video games pretty much everything that you see around you is does have some digital component or the other. All these computers use the same concepts that we will present in the class.

So, the fundamentals for a digital system is something that you will learn in this course, we may not reach the level of complexity of designing a complete chip or computer in this course. But, the fundamentals that you learn here will help you understand, how the systems are built.

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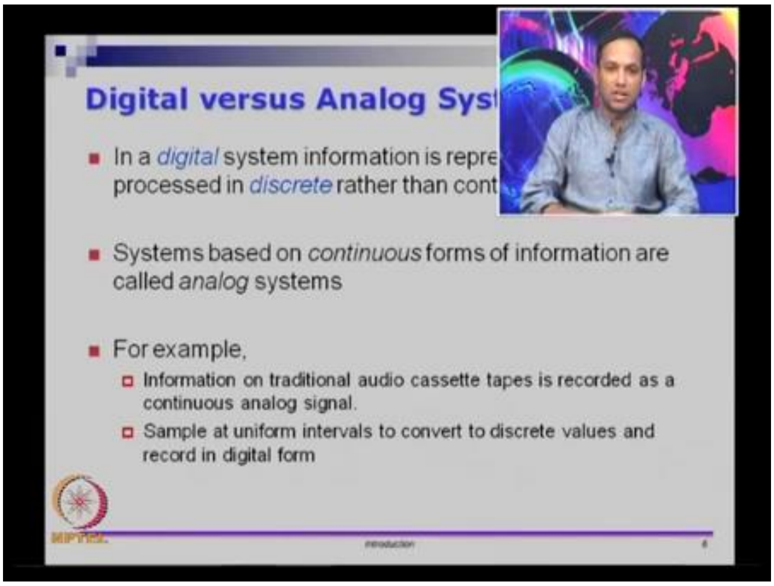

So, let us take a small look at what a digital system is as opposed to what an analog system is. So, first thing is in a digital system information is represented in some discrete form rather than continuous form, you will see this as we go along. But, in some sense, the discrete nature will tell you that, we will look at logic value 0 and 1 as opposed to a voltage which is 0 volts to 5 volts or 0 volts to 3 volts and so on or any range in between will usually strict to 2 values 0 and 1. So, that is a form of discretization. We will see several other forms of discretization as we go along.

One thing is the analog systems are usually based on continuous forms, there is something continuously happening in an analog system. So, if you take for example, audio cassettes, so probably you have seen this some of you may have used it. So, the audio cassette is an classical example of an analog system. So, it records a continuous analog signal and you can however, take this continuous analog signal and sample it at frequent intervals or at regular intervals and get discrete forms.

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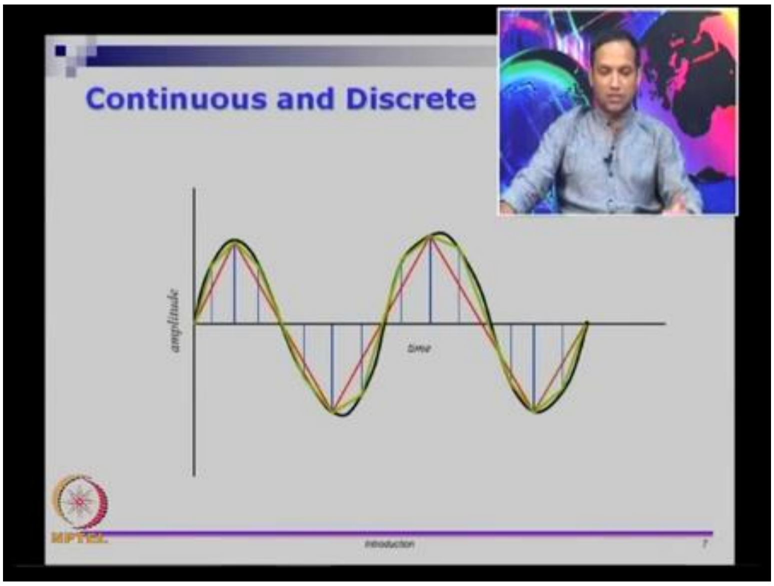

So, this is an example of sinusoid, where I want to show, what a continuous system is versus what a discrete system is. So, in the x axis you see time and in the y axis, you see amplitude and a continuous waveform at every time point you will see that, there is a certain voltage or amplitude for the signal. In a discrete world, what you would do is, you will sample this at regular intervals.

So, for example, let us say I sample this waveform only at these intervals at this location, at this location and this location and so on. I will have only four values. So, when I have 4 values it is not good enough though when I... So, if I sample here this is let us say plus 2.5, I sample here it is let us say it is minus 2.5. So, it will come to me as though I have only 4 values plus 2.5, minus 2.5, plus 2.5 and minus 2.5, so many times this is not enough.

So, one thing that you can do is actually interpolate between these times, so this red waveform that you see here is an interpolation of between these points. So, if I sampled here and sampled here and interpolated the values in between, similarly between this sample and this sample, I have interpolated the value in between and so on. So, what you get is a triangular waveform which is a very, very crude approximation to the sinusoid that we saw.

So, this is an example of discretization, we can do better. If we take more samples and interpolate between those and connect it. So, for example, here the green waveform is like that. We have taken more samples, between the samples we have interpolated and what we get is this green waveform, we can see that it is already closer to the blue waveform rather than the red waveform, so this is how discretization works.

You do not have to really know the voltage levels at each and every time point from here to here. Instead, we need to know the voltage levels, let us say at these points alone and everywhere in between, we can interpolate and say this is the value. So, this is one way in which an analog signal can be sampled. So, you capture the input or which is an analog input and save it as a discrete set of values and if you want to reproduce it, you do interpolation or some such thing.

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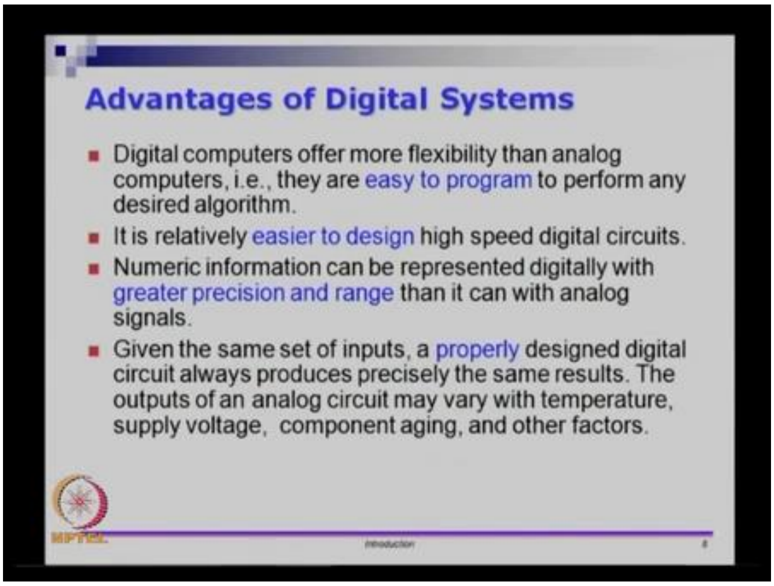

So, let us look at the advantages of digital systems, digital computers actually offer a lot of flexibility than analog computers. So, the programmability of digital computers is quite good and this is one of the main reasons why digital computers took off starting from the 50s or 60s. Then, there are several other important aspects of digital systems; it is relatively easier to design high speed digital circuits than, designing analog circuits.

Analog circuits, it still a bit of a black magic that goes in sometimes into analog circuits and to be an experience analog designer. You have to do a lot of courses; you have to get a lot of experience before you can even start producing anything which is useful in a lab, let alone, commercially viable product. Whereas, in a digital circuit, it is fairly easy to understand the fundamentals and fairly easy to do many of these exercises in your lab or build a system yourself.

Then, the third bullet is the numeric information that you have is usually represented with a much higher precision and range with digital circuits then with analog signals. And in terms of reproducibility digital signals if you design a circuit properly given the same inputs it will produce the same output every single time, as opposed to analog circuits where there are other external factors which can influence how they work.

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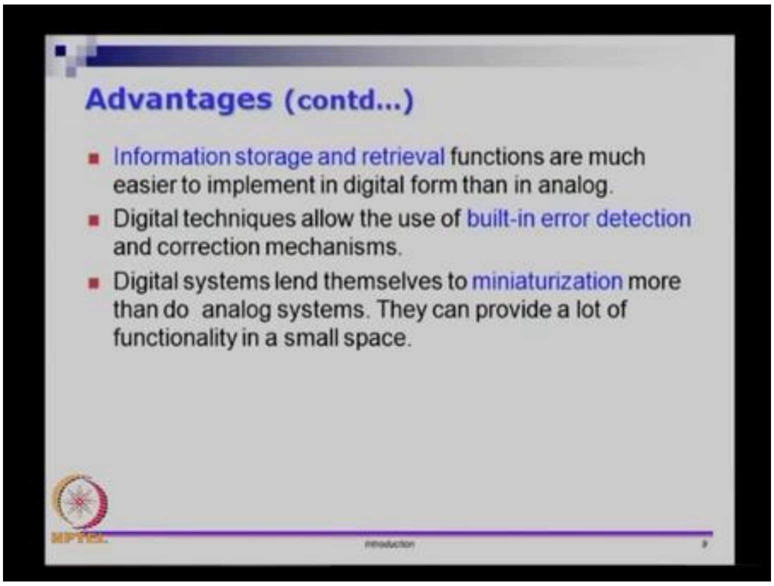

So, you might have seen that over time and old radio, may start behaving in a different way, or even cassettes, if you play over and over, they start decaying and so on. So, some of these aging and other things are problems with analog circuits, whereas with digital circuit, you do not really have a problem like that usually.

Then a few more bullet points in favor of digital circuits. So, information storage and retrieval are much easier to do with digital circuits, many of these circuits have built in error protection. So, these circuits can have errors, but there are various mechanisms to detect, if there are errors and even correct them and this is a very useful thing to have in digital circuits. Miniaturization is easier with digital circuits than with analog circuits, what that means is, you can make smaller and smaller chips which can provide a lot of functionality by using digital techniques.

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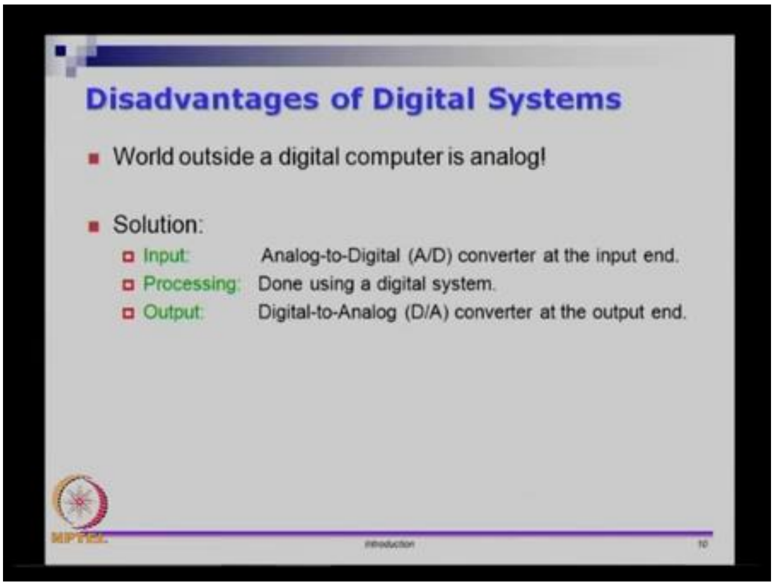

All of these, however come with a catch it is not the digital circuits is everything and you can do everything in a digital world itself. The biggest problem is the world is not discrete, it is an analog world, what you see as my video or what you hear as my speech or anything that you perceive touch, smell, sense and so on or all continuous signals. Whereas, the computer is a digital system or the circuit that we design may be digital systems.

So, one way to deal with this problem is to design inputs which will convert the analog input signal into a digital signal, then process the whole thing digitally and when you produce output you convert the digital signal back into analog signal. So, this is a very nice and interesting way to look at real world things. So, you deal with a analog signals in the external world, but you capture them as a digital signals, process all of them using digital systems and when you produce the output back convert it to analog systems.

So, for the inputs to be converted to digital form we use what are called ADC's or Analog to Digital Converters and when we produce the outputs we use what are called DACKs or Digital to Analog Converters. So, digital DAC's and ADC's are not in the scope of this course, you will probably learn it elsewhere if you are an electronic student or a double e student or even CSE students learn it in other courses.

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So, let us see where the digital systems are used, they are used everywhere. I said the word I used is ubiquitous, it is used everywhere. You see them in cell phones and rockets and televisions, toasters, ovens, f 1 cars what not. In everything that you see around, you see some form of digital circuit or the other, even if you do not see them from the external world they have electronic components inside.

So, if you go and ask your parents what kind of watch they had when they were in there teens in probably tell you that their watches to completely analog and so on. However, now a days we have digital watches which is more common, even the analog display that we have in this watches is only the display the underline circuits are many times digital, unlike your grandparents their watches would have been mechanical watches with gears which they were winding and so on.

So, digital systems are quite a ubiquitous and that is why this course is interesting. So, many of you probably have this course as a 2nd year or 2nd year 3rd semester or 2nd year 4th semester course and this online course is also placed exactly at that.

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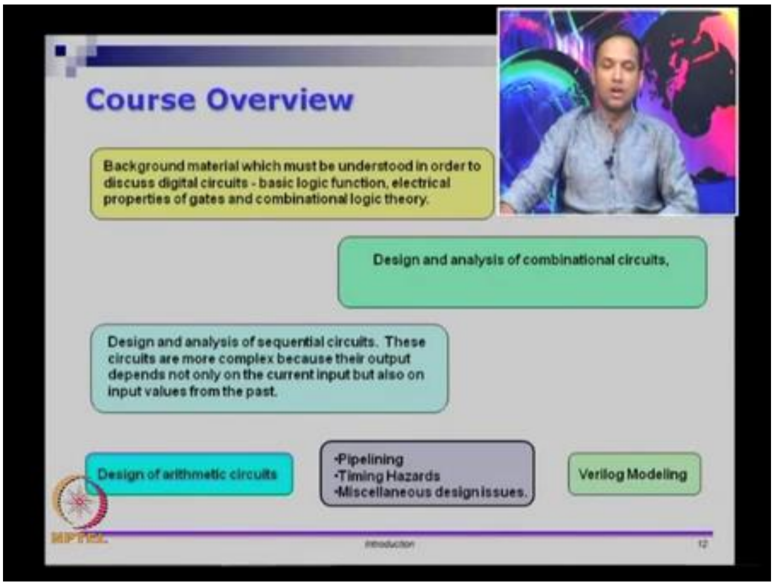

So, the course overviews is as follows, we will start with back ground material which must be understood in order to discuss other things. So, we will learn the basics of gates and basics of combinational logic theory, we will design and analyze basic combinational circuits. We will then move on to what are called sequential circuits, these are circuits in which the system has some kind of memory or history.

So, the system produces outputs which are not just in terms of the current inputs, but also in terms of what state it has been earlier. Those are called sequential circuits, we will learn them next and after that we will learn basic arithmetic circuits, how do you design a components like adders and multipliers and so on, we will learn those we will learn some techniques for high speed design of digital circuits. So, we will learn the notion of timing a digital circuit and what are the different techniques used for timing a circuit. And finally, we will also learn how to write Verilog code. So, Verilog is a hardware description language, we will learn how to write Verilog code for the digital systems that we write.

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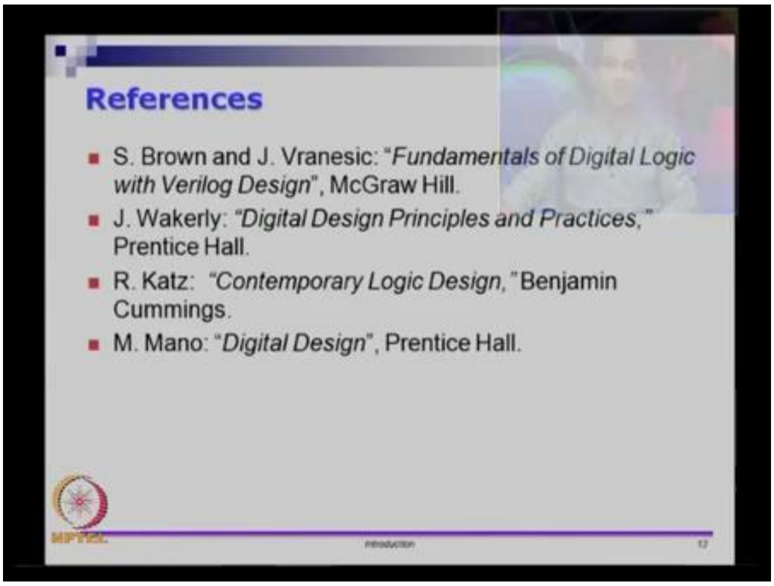

So, the references for this or these text books, so primarily I am going to follow this text book by Brown and Vranesic it is called fundamentals of digital logic with Verilog design. But, time to time I have also use material from these other books that I have mentioned here, probably many of you use this last text book here by Moris Mano, this is probably prescribed as a text for your university syllabus and what not, how over I will be using the first book mostly.

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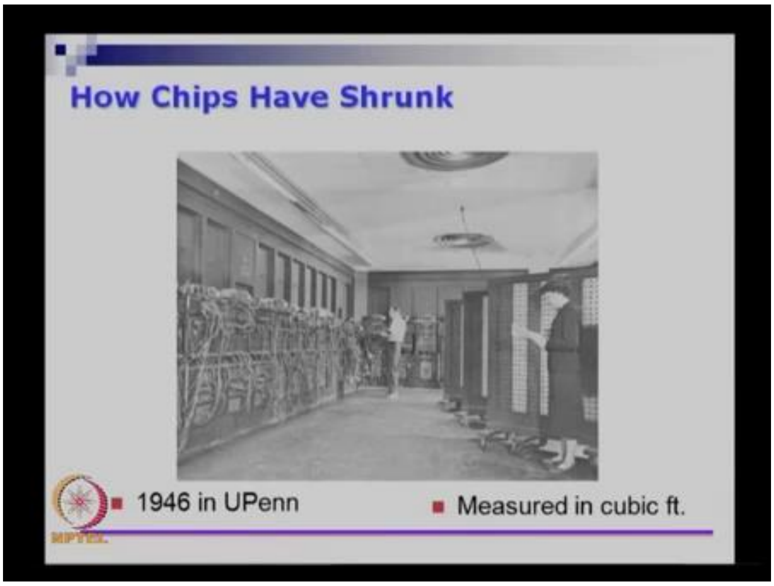

So, to get an understanding of why this course is interesting and where we are it is always to know the history of how the systems where design. So, unless we know the history we can potentially repeat the mistakes that were done. So, that is the reason why we learn history to learn what happened in the context of the time at which it happened and to not repeat mistakes. So, to make you get a feel of history I have few pictures that I want to show in this very first module.

So, I want to show you how chips are shrunk, so let see this picture here what you see here is actually a digital computer that was built in the year 1946, this was built in the at the university of Pennsylvania, this was around world war time and this was measured in cubic feet. So, clearly what you see here is a mesh of wires and a various connectors and so on.

And this whole room was actually just one single computer, these were not multiple computers that are connected together, this whole thing was just one computer and this computer was called the ENIAC, this was the very first digital computer that was ever built.

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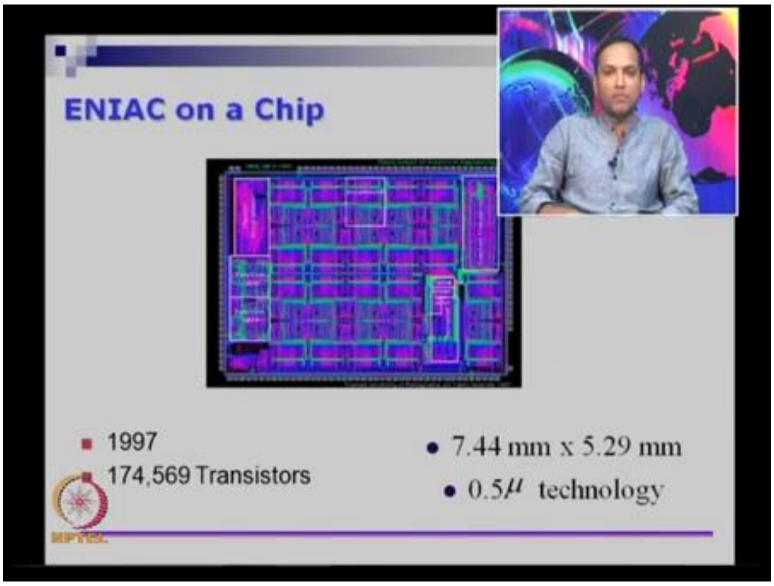

And what you see here is a micro photograph of ENIAC the same system, but done in a single chip this was done in the year 1997 by under graduate students like you at Pen state. So, they wanted to commemorate 50 years of digital computer and this is given as an assignment in a course, designing this whole ENIAC system on a chip, this was done in the year 1997 by under graduate students like you.

This had about 1800 transistors in the chips dimensions are actually 7.44 milli meters by 5.29 milli meters. So, it is hardly some 40 milli meter square, so it is much smaller than the picture that you seeing here, it is only a photograph zoomed quite well and this was designed with what is called 0.5 micron technology. What; that means, is the wires that are connecting the gates or the logical elements inside, as well as the logical elements inside or all designed with 0.5 or all of dimensions 0.5 micron or so.

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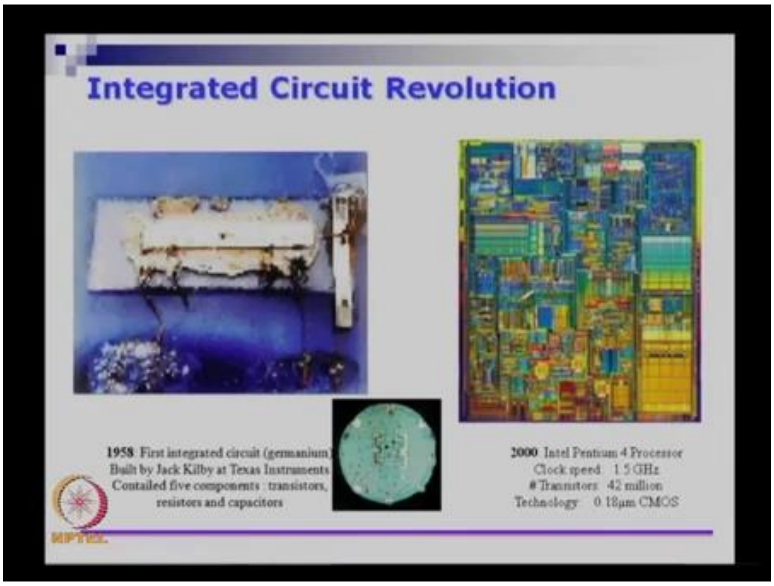

So, to understand how this huge jump from 1947 to 1997 how that happened, we need understand what is called the Integrated Circuit revolution or what is called the IC revolution. So, what you see here on the left side is the very first integrated circuit that was built and it was built by this Nobel Laurette Jack Kilby. So, he received the noble prize for designing this integrated circuit, what it had was a few active components and a few passive components that is all for few passive and few active components.

So, active components like transistors and passive components like resistors and capacitors that is all it was. And this is quite bulky for something very, very simple from there we went to a place where we have a complete processor. So, this is a micro photograph of a CPU which was designed by this company called Intel, it is called the Intel Pentium 4 processor.

So, the time at which it was released you were probably still kindergarten kids, this was in year 2000. And this was able to run at 1.5 Giga hertz what; that means, is it can do 1.5 billion operations per second, it had 42 million transistors and it was designed at 0.18 micron technology. So, which means the basic components are all of size 0.18 microns.

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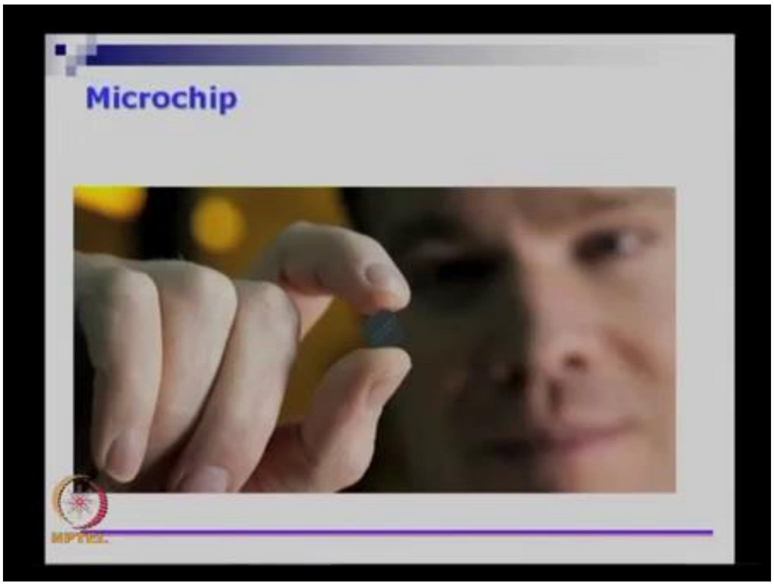

So, this is a picture of a small microchip and this goes into systems and so on. So, what we see here is a micro photograph and then it goes through what is called packaging and once it goes through packaging it comes to a few centimeter square in size and this a picture of a microchip.

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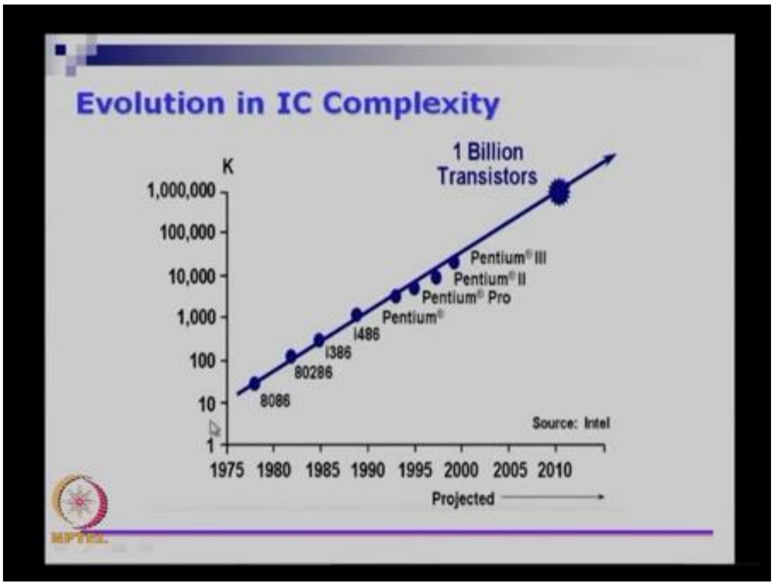

So, all of this happen because of the evolution in the integrated circuit industry or the IC industry. So, in this picture what you are seeing is the x axis you see years and in the y axis you see the number of transistors and the basic units used is K. So, which means this point here is 100 K or 100,000 this point or this line would mean 10,000 K or 10 million this is 100 million, this is 1 billion and so on.

So, this is the kind of the growth that the number of transistors inside a computer went through. In year 1978 or so 80, 86 was designed with somewhere like 20,000 to 30,000 transistors. I 386 was a computer that was designed in 1982 to 1983 time frame, this had a few more than 100,000 transistors. Pentium which is slightly before the time we were born probably was designed in 1995 it had about 1 million transistors. Pentium 3 and Pentium 4 was probably the time at which you are born and this already had about 100 million transistors. So, 42 to 100 million transistors before had 42 million and so on.

And current day chips are much more than 1 billion transistors in a single processor, so we are already hitting 1 billion transistors in a chip. And if you notice even though, this shows just a line the scale on the y axis is logarithmic which means this growth is actually exponential. The number of transistors is not just the linear increase from year 1968 to 1982 and so on it is actually an exponential increase.

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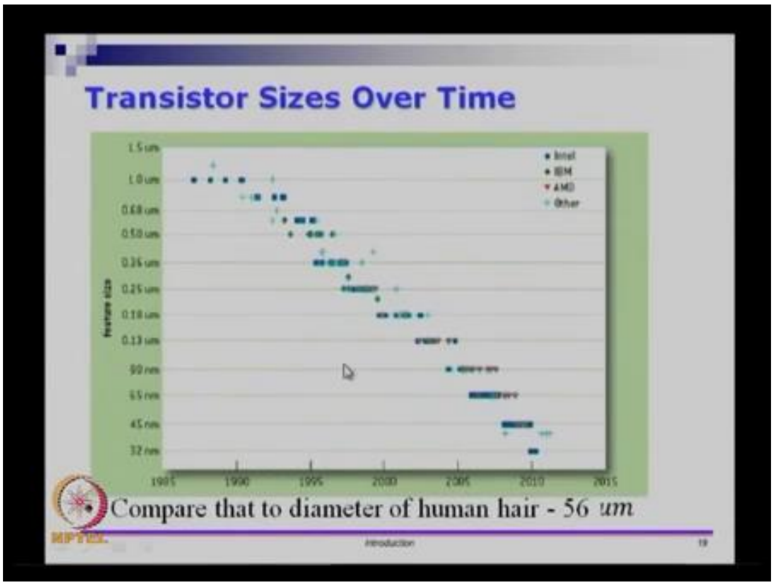

So, the transistors increased in number how over the transistor size is reduced. So, what you see here is again years in the y axis and the size of the transistor in the x axis, size per transistor shrunk exponentially down as years progressed. So, what you see is for every, so called generation. So, the generation in a integrated circuit is usually about 2 years for every generation or so it went down by one technology node.

So, one technology node means, so in this example there is something at 1 micron and if we go to 0.5 micron it is probably already two technology nodes. So, 0.5 to 0.35 and 0.25 and so on, these were the different sizes at which chips were made. So, each transistor or each logic element was 0.25 micron in size and it had millions and billions of these things inside a chip. So, across different companies, across years we can see that the transistor size or just one single logical element shrunk in size exponentially.

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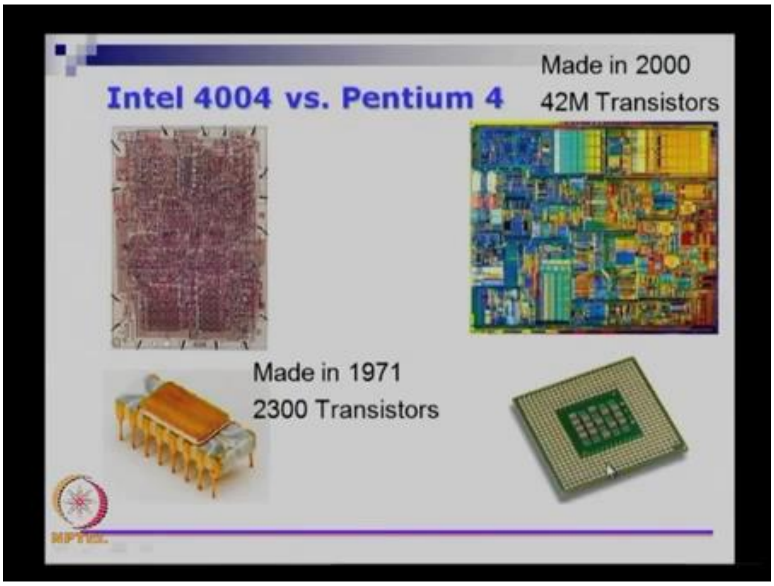

So, in the picture on the left we see Intel 4004 which was the very first microprocessor that was made, it was used inside a calculator it had only 2300 transistors, this was even before the time I was born. And this is micro photograph of Intel Pentium 4 which was made in year 2000 which already had 42 million transistors. So, this one you can see the package here it probably has about 20 or so external connections whereas, a Pentium 4 has 100's of connections for input and output to the external world.

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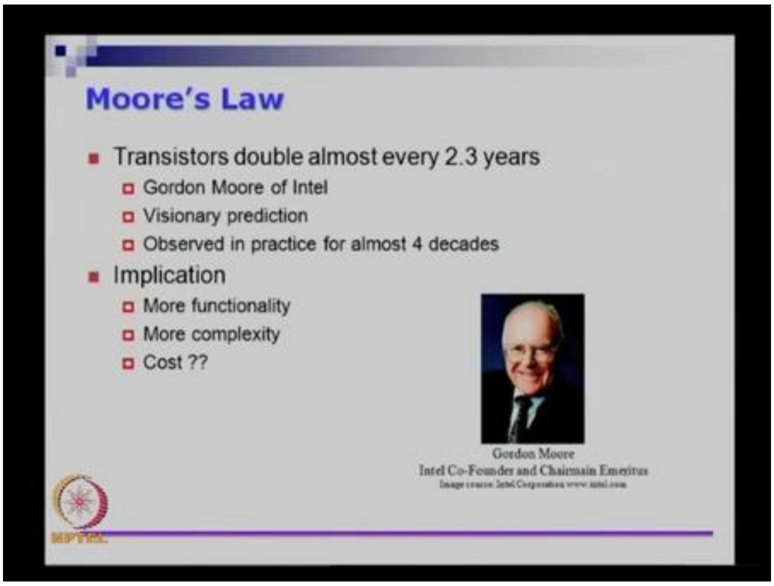

So, all of this was possible because of what is called Moore's law, so Moore's law essentially says, the number of transistors double almost every 2.3 years. This is not like a natural law like Newton's physics, Newton's laws of motion and so on, this is more of an empirical observation, it was made by Gordon Moore of Intel he was the founder of Intel a co-founder in fact of Intel and the implication of this law is that you get a lot of functionality.

Because, you given twice the number of transistors or logical elements, you can have more functionality with it, it gets more complex because you are dealing with much more components. But, the cost is something that roughly remains the same actually, when you go from one node to the other the cost does not change, so much. Even though every 2 years or so the number of the functionality that you get from these processes increase they are increasingly more complex, the cost of these chips roughly remain the same.

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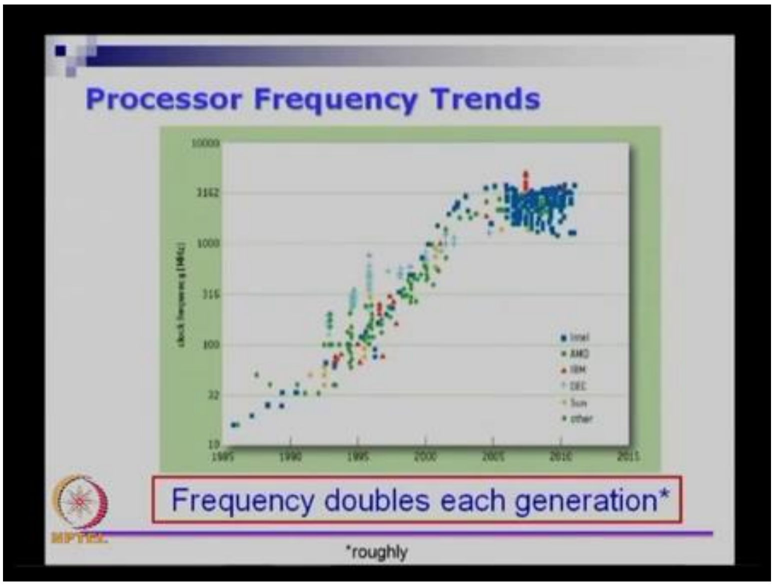

So, another trend that is useful to known and understand is the process of frequency trends. So, if we go and look at the frequency at which your processors run your desk top or laptop process is run, this is also roughly double every generation or so. So, every 2 years or so the frequency actually double, what you see here on the y axis is again not a linear scale it is actually a logarithmic scale.

So, if I go one step here it is double this number, if I go one step here it is again roughly double the number and so on. It is not going as 10, 20, 30, 40, it is going 10, 30, 100, 300 and so on, it is roughly tripling for every unit that is shown in the y axis here. So, when you see a line here what that means, is it is growing exponentially. So, process of frequencies are currently all around 3 to 4 Giga hertz and probably dipping. But, over a period of time the frequencies actually increased almost exponentially.

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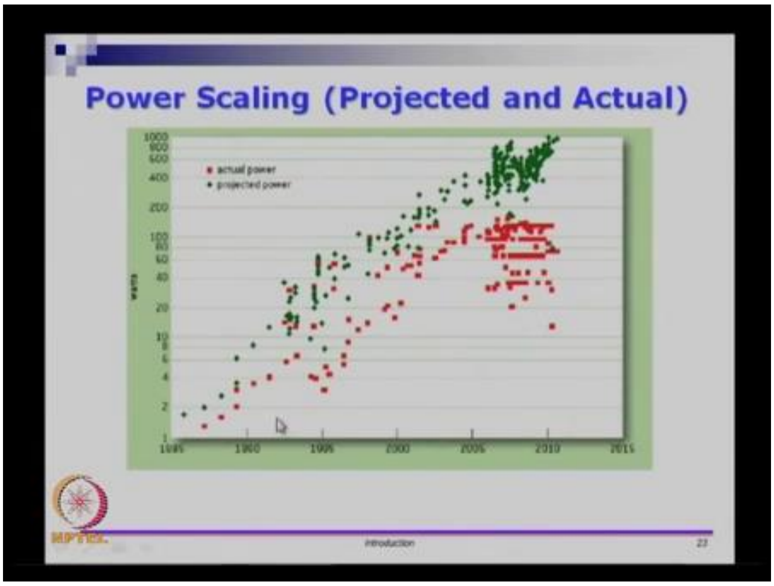

Finally, the kind of power consumption or the wattage consume by these processes also when through a phase where it went up exponentially. So, you can see that in the early 1980’s or so it consumed a few watts of power and current processes use about 100 watts of power. So, in the current in about 20 to 30 years we have increased the power consumption that is required by the chip by about 100 times.

So, this is not very surprising, because you have a lot more components inside you are doing a lot more work which will of course, require you to do lot more, you have deliver more power to the systems is just like riding having a bike a 100CC bike versus a 200CC bike and so on. You want more power a more performance from the system you have to deliver more power to the system, so power did go up exponentially.

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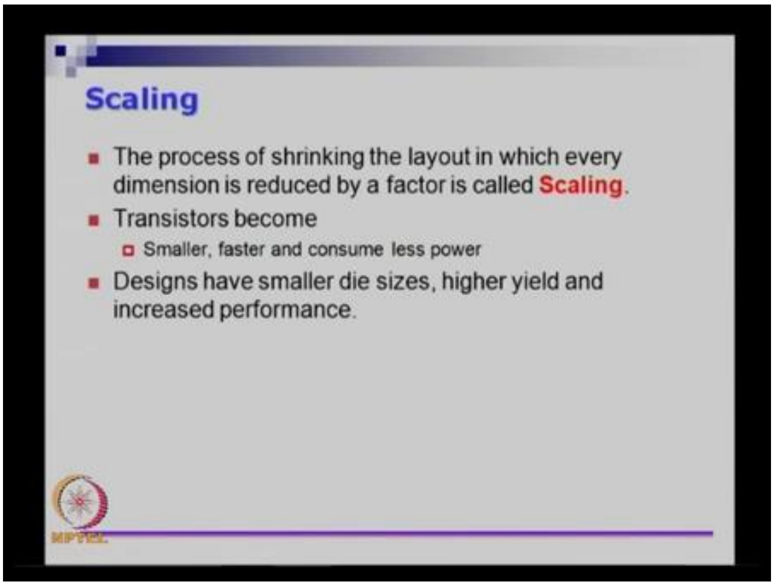

So, all of this is called scaling the process of making smaller than smaller components not necessarily chips. Smaller components which go into the chip this is called scaling and the transistors when the scale, they usually smaller, faster and they also start consuming lesser and lesser power. So, because of this, designs have much smaller sizes and they usually get better performance.

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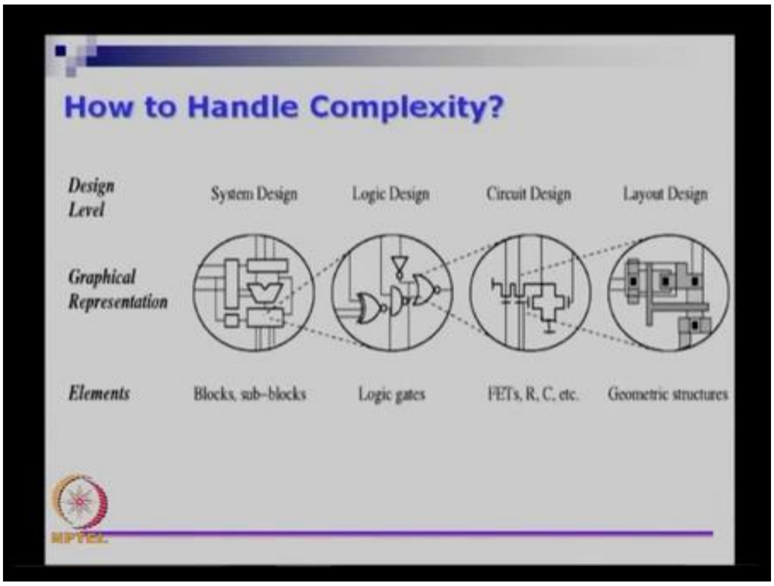

So, because we are handling a complexity which is very, very high, we have a very structured way of approaching this problem. So, in the 1950's and 1960's an under graduate student would learn how to do what is called layout of a chip directly. In the early 60's and so on people started designing transistor base things on paper and there were tools which were used to convert transistor base designs into what is called the actual layout.

What you will learn in this course is what is called logic design and system design. I presume that if you are a double e or a ECE or a CS student, you may learn this level called the circuit design course, where you learn how electronics work, how digital electronics work. If you are a ECE or a double e student, you may actually do a Cmos course where you may also learn how to do layout. In this course we are going to learn these two things, how to do logic design or how to do circuit design.

So, we are already at several levels of abstractions away from the actual chip. So the actual chip has individual components, we abstract them as transistors, we abstract them as gates, so called logic gates we are going to operate this level and above without worrying about what happens here. So, whenever you go from one component here to the right side, we are probably talking about 10 times more elements or so roughly.

If I take a simple basic block here, we are looking at tens of gates, if I take a single gate here it is probably tens of transistors, if I take a single transistor you have a 10 different kinds of rectangles with in some sense you have to over a super impose to get a layout. So, the complexity we will handle the complexity by going up in the ladder of abstraction.

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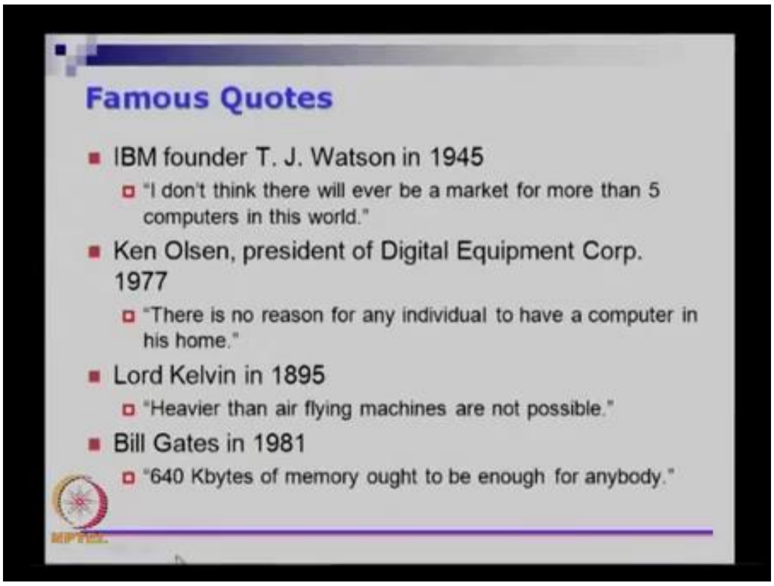

So, to conclude this module I want to give a few famous quotes that were given by people which all turned out to be incorrect. So, for example IBM form to T. J Watson in said 1945 that he hidden thing that there was a market for more than 5 computers in the world. So, this is comes completely surprising to you, because you probably have 5 computers in your own home now let alone the world.

Even if you have a let say one single cell phone, you have probably talking about 2 or 3 different processes inside. Ken Olsen was the founder of digital equipment corporation in 1977 he said there is no reason for any individual to have a computer in his phone, we have computers in our pockets now. Lord Kelvin in 1895 said heavier than air flying machines are not possible and turn off the century we had air planes, Bill gates the founder of Microsoft in 1981 said 640 kilo bytes of memory ought to be enough for anybody.

And if you have installed RAM in your desk tops or if you have bought cell phones, the first thing you ask for is how many GB of RAM or how many GB of memory you have which is internal or external clearly kilo bytes is several orders of magnitude smaller and somebody who... So, all these people where visionaries they were not ordinary people they were all in the field, they were all visionary they founded companies and so on and all of them still fell short of the revolution that is possible from the digital world.

So, this is why digital circuits in systems are really exciting and by the time you finish your under graduate program, the complexity of it should have already gone up. So, I hope that this course opens you up to these ideas and in some sense make you ready for what to expect when you graduate.

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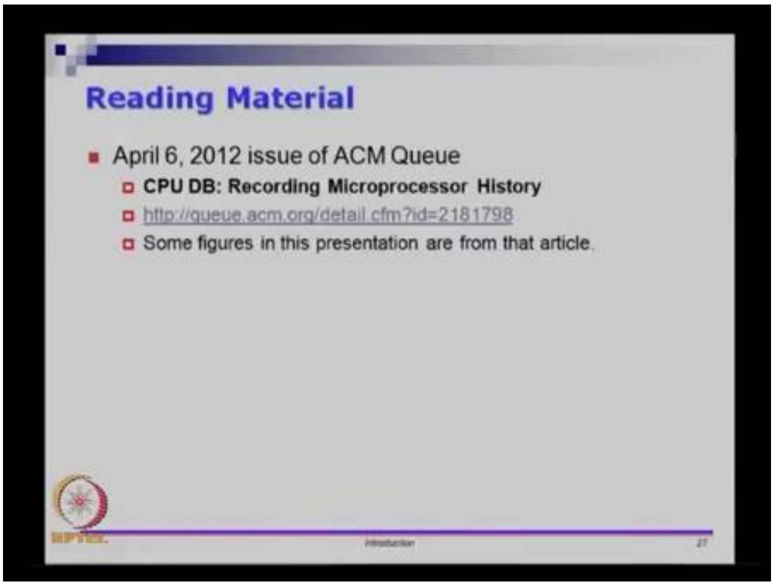

So, in terms of reading material I want to make you go and read this bit of an article, I took some pictures like the process of frequency and other things from this link. So, it is from ACM's queue April 6, 2012 issue I highly recommend you reading this article. Because, it gives you a lot of insight about what happened in the computing field and what are the different kinds of growth trends that we saw in the CPU side.

So, CPU's are not the end of the world there are several other chips which are outside CPU's, but it is a good place to start. So, with this I come to end of this module, so what we will see from now on is, we will see smaller chunks like 15 to 20 minute chunks which will introduce you to a topic. And it may actually be beneficial for you to take a break go and think about what you have learnt so far and think about some of these problems or some reading assignments that I give you, go and read those things and then come back to the next module. So, that way you will be keeping in touch with what is happening in the class, it also gives you some time to relax and see how to observe the material that is given to you.

So, thank you very much.