Digital System Design
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Lecture No. 02
Analog vs Digital

Hello everyone. In our previous lecture, we have understood what is the meaning of a digital logic and a digital system and we also understood that a digital signal is essentially a discrete signal in values as well as in time.

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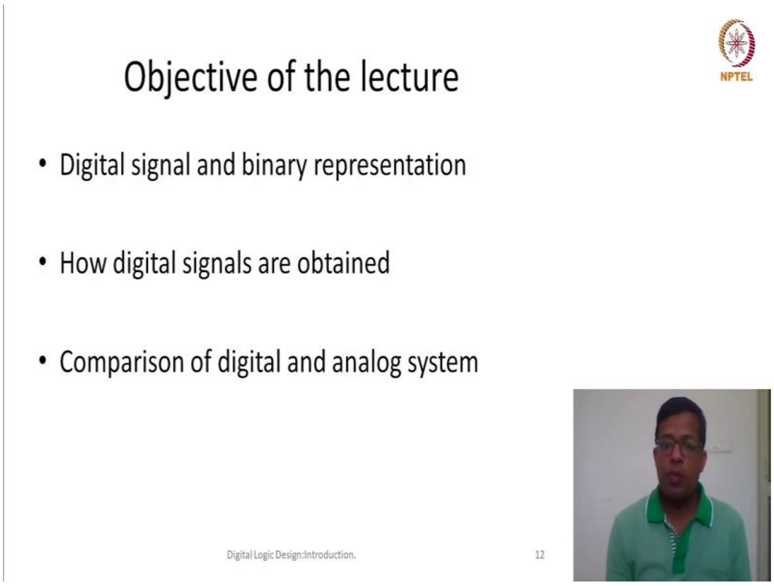

So, in today's lecture, we will see how this digital signal is obtained and how to do binary representation using digital signals and then we will also compare digital system with the analogue system. So, in yesterday's lecture we have observed that we are intuitively our systems our senses they are intuitively analog, but why we are using digital system we will try to answer this question in this lecture.

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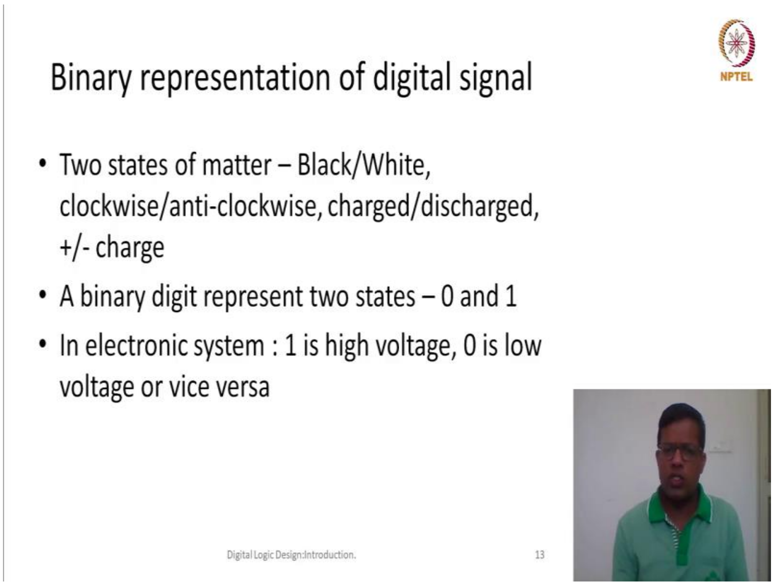

So, first thing what we observe what we see around the world that almost all the matters have at least two states. So, for example, if we see all the colours we can classify them into black and white although there could be various shades of grey, but yes black and white could be one broad classification. Similarly, in electrons or protons, they either rotate clockwise or they rotate anti clockwise.

Similarly, if we see charged particles either they are positively charged or negatively charged and magnetic also there are two poles either north pole and south pole or all the materials can also be divided into two classes magnetic material or non-magnetic material. So, this way this two state classification is most easy thing to classify and we can broadly classify anything into two classes.

From there, we can see, if we can represent all of these states into two states, we can call it binary, binary means either the value would be 0 or value would be 1. So, from taking clue from there, we can represent any particular state, any particular value using this binary representation. So, in this binary representation one digit would represent one binary number which means, either it is 0 or 1. Now, digital systems are essentially electronic systems because digital systems are electronic system, so they will talk in terms of voltages or currents.

So, let us say because, because of the technology mostly whatever, we can safely classify them into voltage signals let us say from now onwards. So, we can say either a high voltage means it is 1 and low voltage means it is 0 or it could be vice versa also. So, essentially there are two states either a voltage is high or it is full voltage let us say the supply voltage is 10 volts. So, this 10 volt would represent 1 and ground represent 0 or it could be vice versa that ground represent 1 and supply voltage represents 0.

So, the idea is that we have two states the system one will classify as 1, another state will classify as 0. So, what I would like to emphasise here that it actually does not matter which state you classify as 1 or which state you classify as 0. So, now if each digit represent only these two states 0 and 1.

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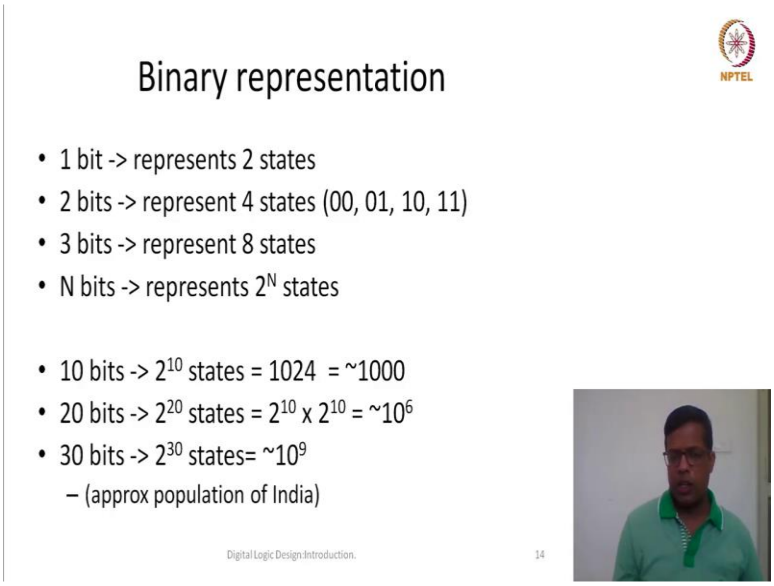

If we combine multiple of such digits, if you combine multiple such digits, for example, if we combine two digits, so they can essentially represent 4 states 00 01 10 11, we are also considering here, permutations not combinations essentially the position of 0 and 1 is important or each bits position is also important. So, that means if you want to say how many number of states or how many number of possible values are possible using 3 bits, then it would be 2 is to power 3, because at any position there could be 0 and 1. Similarly, there are three such positions, or 2 is to 4, 3 would be the total number of possibilities for 3 bit combination.

So, let us say if the group of bits are n bits, then those n bits can represent similarly 2 is to power n states. So, this is pretty much straightforward. So, let us say if we try to define this n, let us say we want to see how many states or how many possible values could be represented using 10 bits. So, we will do with the same formula 2s power n so 2 is power to 10 possible values or 10s, 2 to power 10 possible states could be represented. Now, if you compute to power 10, then it will come out to be 1024. So for sake of simplicity, I am trying to simplify it into 1000.

So, now, let us say if I have instead of 10 bits, one bit means one digit, one binary digit one binary digit is called one bit. So, now, let us say we have gone to bits 20 bits, 20 bits could represent 2 is to powered 20 states and 2 is to powered 20 states can also be written as 2 is to powered 10 into 2 is to powered 10. So, that means, although the number would be 1024 into 1024, but for again sake of simplicity, I can say that the number is approximately equal to 10 is 4 power 6, 1000 plus 1000.

So, 1000 when I am saying 1000 or 1024, these are in a decimal representation. So, similarly if I go for 30 bits, then for 30 bits total number of states or total number of possible values would be 2 is to power 30 exactly 2 is to power 30 and again, if I approximate then it is 10 is to power 9, 10 is for 3 1000 plus 1000 (())(7:15) 1000. So, that means 10 is for 9. 10 is for 9 means we call it 1 billion.

So, that means 20 bits could represent 1 million possibilities and 30 bits can be used to represent 1 billion possibilities and what is the population of India? Currently it is 1.3 billion. So, if I want to represent all the population of India then what I would require is essentially 31 bits, 31 bits would be sufficient to identify to have an identification mark for each and every individual of India.

So, as a general knowledge thing, so you might also have heard some other notions of numbers here. So, you might have heard some people instead of bits they write bytes, bytes means 8 bits would be equal to 1 byte and when you buy memories, these memories are also written as 1 kilobyte, 1 megabyte, 1 gigabyte, 1 terabyte. So, 1 kilobyte memory means 10 is to power 2 is to power 10 elements, 2 is to power 10 bytes will be equal to, so that means it is around 1000. So, similarly, 1 megabyte would be equal to 2 is to power 20 bytes and 1 gigabyte is equal to 2 is to power 30 bytes.

So, in other words, 1 kilobyte means around 1000 bytes and one megabyte means 1 million bytes and 1 gigabyte means around 1 billion bytes. So, this is another parallel representation notions of words, which we typically use for binary representation. Now, this is the basic understanding of the binary representation.

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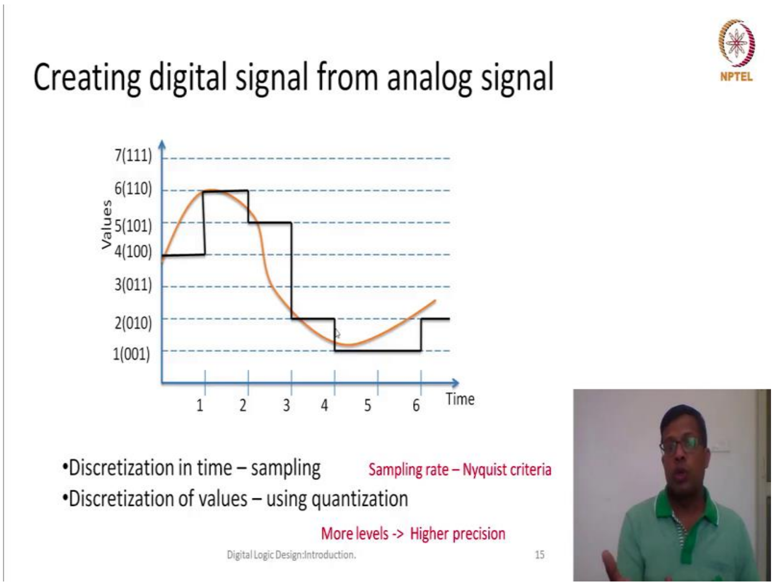

Now, the question which we would like to answer in this lecture is that if we are given, we want to create a digital signal and as we understand from the last lecture, the word is essentially analogue, analogue means it is continuous, it is continuous in values, as well as continuous in time. So, to represent to see, to understand this particular fact in little more detail, let us try to understand using this curve. So, let me see that this x axis represent the time, so 0, 1, 2, 3, 4, 5, 6, 7 are a different time units, this time could be seconds, picoseconds, millisecond whatever, but they are discrete times.

Similarly values on y axis we are representing values, values could also be continuous 1, 2, 3, 4, 5, 6, 7. So, these are the values which are there in the y direction and let us consider some particular sigma, which is given in this orange. Now, we see this particular signal is essentially continuous in value, so value is somewhere between 3 and 4, when time was 0, and it was increasing and when time was 1, it was around 6. So, it is continuously changing, continuously changing both in space, in values also the values is continuous and also with respect to time also, it is continuous.

Now, when I am talking about digital signal, they are not continuous. Neither continuous in values nor continuous in time, so they are discrete. So, discretization would happen at both places for values as well as for time. Now, for example, at let me say discretization at time is happening at one unit of time. So, at 0 unit of time, whatever was the value, closest value, so closest value is found to be 4. So this signal would be represented because it is binary, so it will be represented by this combination 100.

So after that, we checked what was the value of this continuous signal, at time equal to 1, it was close to 6, so the signal value would be now quantize at here, it is very close to 6, so we took it as 6. So similarly, at time equal to 2 again, it is sampled, it is not close, it is not 5, but it is close to 5, so it is closer to 5, then closer to 6. So, we quantized we said either it has to be 5 or 6, because it is closer to 5 so, we made this digital signal equal to 5 at time equal to 2 and at time equal to 3, now it is closer to 2, then closer to 3, it was actually between 2 and 3, but it was closer to 2. So at time equal to 3, we said the value is 2, so on so forth.

So, here we see 4, 4 as well as 4, 5 it was closer to 1, then closer to 2. So, both at 4 and 5, we said it is 1. So, it is interesting that the value was not 1 neither at 4 nor at 5 and there was a difference in value at 4 at time equal to 4 at time equal to 5, but both in digital world are considered to be same, because they are quantized.

Now, this figure itself raised quite a significant questions for us. First question is that how can we make sure that this digital signal looks grossly inaccurate? How can how can we represent our system using digital signal it does not look good, it does not look correct. So, what should be done? So, there are some theories, most of you would be doing another course in parallel to this course that is called signal and systems.

So, in signal and system course, you will understand more about this digitalization process or discretization process. But one important formula, one important thing which is called Nyquist criteria or Nyquist rate, so this rate proves that if we sample a particular signal at a particular frequency, any signal at a particular frequency, then it can be reconstructed back whenever we convert this discrete signal into a continuous signal.

So, it has been proved that the, if the maximum frequency of a signal is F, then the and if it is sampled with the 2F frequency, then we can always regenerate without any loss of accuracy. So, if our sampling rate is fast enough, if sampling rate is fast, so basically we are not sampling, we are sampling in such a way that all minute differences are calculated or basically are captured then we would be able to reproduce that.

Similarly, a discretization of value can also give a lot of errors. So, if we can increase the number of such levels, so here number of levels were only 7. So, if we can increase this number of level from 7 to let us say 100 or let us say 1000, then we would be able to capture each and every effect and at sufficient time, sufficient number of times, if some sampling rate is good enough, then we would be able to, we will not be able to miss any particular event in this particular in analogue signal.

So, using this two important theoretical exercises, one is sampling at Nyquist rate the other using very high like number of levels, using like more number of levels would increase the precision. So, we would be more accurate. So, this is the reason that we still like, although because of quantitation there would be error because of sampling there could be some error, but still digital signals seems to be more accurate and that is what we seems to go.

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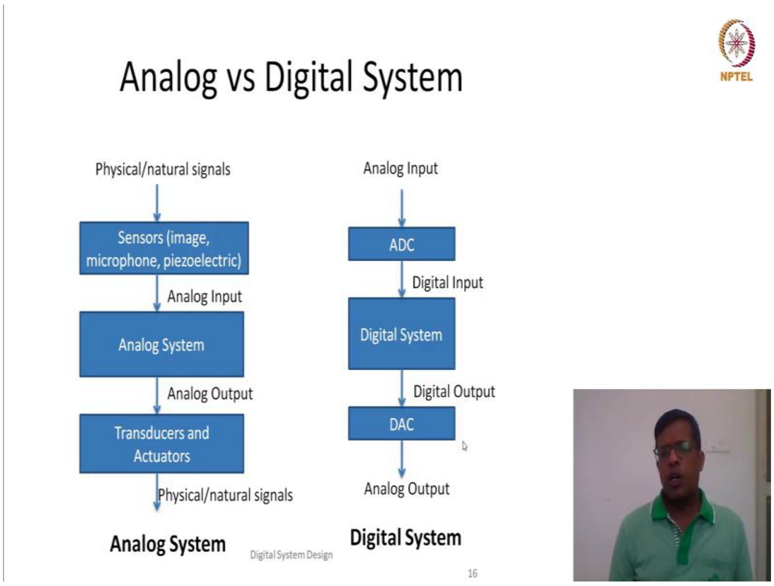

So, you see there is a good paradigm shift also from going from analogue to digital. So, let us little bit understand one more thing that intuitively when we see around word, it is not electronic, it is not electrical in nature. So, essentially, we see different physical quantities different natural signals around us, these natural signals could be like, we see things in terms of wavelengths or light and we can measure lengths or there are some kind of a pressure or frequency which we feel, as your sound waves are also different.

So, this is natural or physical signals, whenever we do any kind of electronic processing first all of these signals are converted into analogue signals. So, there are various kinds of sensors which are present, you have image sensors, like you might have heard of CMOS sensors, which are present in your mobile phones or which are present in digital cameras. So, the CMOS sensor will convert the light intensity even RGB signals of each and every light wavelength, they formulate a corresponding electrical signals for that.

Similarly, these microphones also have a diaphragm kind of a structure which convert the sound waves which are essentially mechanical in nature the sound waves into electrical signals. Pressure can be converted into by using peso electric signals, peso electric sensors to electrical signals. Similarly, there are 1000s of sensors which are around us and even in your mobile phone there are many sensors which are present which are tried to measure the position or GPS or orientation, your speed, all of those things are finally converted into electrical signals and these electrical signals are essentially analogue in nature means continuous in space as well as continuous in time.

Now, if we process these analogue signals directly and give analogue as a output and then there could be a transducers and actuators which will finally convert into again back to natural signals. So, for example, your speakers will again convert electrical signals into sound waves or when we see in a monitor or television, so this each LED pixels will have different colour and intensity which will again reproduce the effect of visual effect of whatever we would like to see.

And in mechanical, so basically again you can have stepper motors or different kind of motors which can convert which can put things into motion. So, all of those things are again putting things into natural signals. So, this is the overall view of an analog system which, in which we are interacting with nature or we are interacting with the real world.

Now, as we said we are moving from analog system to digital systems because they looks like more accurate. So, in there would be additional steps involved here in there would be another component called this analog input would be given to analog to digital converter. So, analog to diesel converter what it is, what it will do is, it will do quantitation, it will do sampling and when then for each signal, for each sample it will produce, it will give let us say a multi group or multiple digits or group or multiple bits as a digital output.

So, this digital input after like after ADC conversion, so this digital input would be discrete in time and values. Now digital system will process this digital input and again using DSP means digital to analog converter will again generate an analog output and this analog output would be again using transducers and actuators, would be given back to physical and natural signals. So, this is what your digital signal is.

So, essentially there would be two layers involved one there will be sensors which are converting physical quantity into electrical quantity and then there will be an ADC which would be involved then only we will get a digital input. So, now again multiple questions arises here that we are doing so much, analog system seems to be straightforward and they are also processing the analog which is, which looks more correct, because it is continuous in space and time.

But why we are reading why we are understanding this digital system, is there any use is there any application? So, to understand this question, instead of giving a theoretical answer, so first we will see around us.

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So, what we see that there is a paradigm shift in last 20 years. So, this in last 20 years, we have seen when all of you were kids, we used to have the CRT TV at our homes, but nowadays all the CRT TVs, first they have been replaced to LCD TV, now LED TV and now most of us whenever a new TV is being purchased, we are purchasing Smart TV.

Similarly 20 years back, we used to have these analogue cameras. So, these analogue cameras they used to click photo and the photo would be, now I will not say these were analog electronic signal, but it was still an analog signal because each photo was captured and then it was developed on a photographic film and then you were creating from negative to your actual image. But now all these cameras are obsolete, nobody know, you will not be able to see any analog camera these days, all the cameras have become digital cameras.

Similarly, telephones have this dialling telephones where you used to dial each and everything and there used to be connect using coaxial cable. Now, instead of coaxial cable now they are connected using FTTH fibre optics cable which is transmitting a digital signal instead of an analog signal. So, not only this but all other things for example, we used to listen to FM radio, AM radios so all these radios also become digital in nature, all the mobile phones, they are the best example now they are all completely digital.

So, when we see around there are, so many digital products and all the analogue products, they have been (())(23:41) to a very small market and a very small segment. Why it is happening? If it is so natural to grab to catch or to read an analogue signal, why we are again processing into digital and then processing it completely in digital. So, there are multiple reasons for that.

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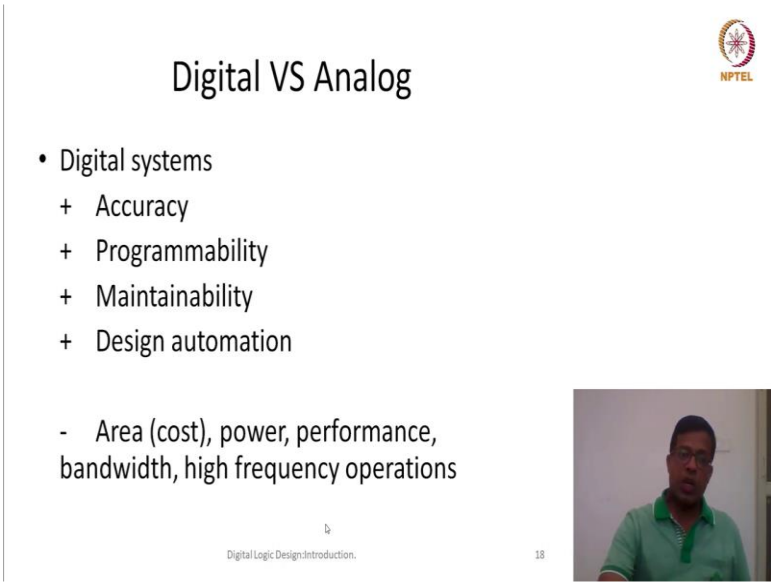

One of the reasons is my digital system will give me very very high accuracy, so let us give it take an example, so let us say my analogue signal is between 0 and 5 volts, let us the value, let us say the value is 3.5 volts, now is 3.5 volts, if I convert this five volt signal into a digital signal which is represented by a 10 bits value. So, that means I would have an accuracy or precision of 5 millivolts and there is a very less probability that my 0 will become 1.

So, because 0 would represent 0 volt and 1 would represent 5 volts so even though there is some noise or there is some environmental impact chances that 1 will become 0 or 0 will become 1 is very very minimal, but chances because of this noise environment conditions or transferring the value from one place to another place, because of stray resistances, capacitances there is a good possibility that this 3.5 volt will become 3.6 volts or 3.2 volt.

So, because of all of these things because of all these stray electrical circuits, stray resistances capacitances because of this noise, there is a good possibility that electrical signal or analog signal will change its value but a digital signal will not. The other thing on top of that is that let us say our digital signal is being transmitted from one place and travelling to the other place, in a channel or in a basically in a wire.

Now, if we see that there is a possibility of changing from 1 to 0 within this particular wire, then there could be some system called error control codes, error correction code, so we can we can identify if there is some bits flipped from 0 to 1 or 1 to 0 and we can even correct them. So, those encoding can be associated with binary so that means, even though there is a possibility of inaccuracy we can again correct them. The other biggest thing is programmability.

Now, your analogue signals or analogue systems when they are created, they are created for one particular use case, one particular using the fundamental registers capacitance and there value of resistance and capacitance also matter. But digital systems they are created using generic gates. So, once they have been created, there could be various mechanism using them, they can be reprogrammed. Now reprogramming is a very important thing for today's world, when we are changing very fast.

So, for example, you get this Android updates once in 6 months, so because you would like to get new features every time and also there is a possibility that there are some bugs in your system. So, there is a possibility of patching. So, there could be a like, you can even programme or as the functionality will change, you would be able to change yourself. So, this programmability in this ever changing world and this ever changing world is more changing, dynamically changing these days, then it was in past.

The other thing is like you see, there is a effect of environment. So, for example the temperature is increasing, humid is increasing because of that electrical properties of your basic circuit like resistance, capacitance, inductance, they will also change, but my digital systems are digital bits are essentially more robust to change. So, that is why they are more maintainable. So, after 20 years after 10 years also they will function correctly, they will not give some error, but there is a possibility that your analog system will not run for that long.

So, if there are so, many advantages, there must be some disadvantage also. Your analog design are usually very small with respect to digital design. So, let us say if I want to do multiplication in analogue, it could require only 20 transistors, but you want to do see multiplication in a digital domain then I might require 10,000 transistors. So, the cost could be 100 X or 200 X in case of digital. So, because more number of transistors are required, it would be costly, it would be slower, it would consume more power. But, it is going to be accurate it is always going to reproduce the same value, whatever be the case. It is you can change you can programme it over the time.

So, even though digital signals are slower, they consume more power are less area efficient, but still, they are more prominent, because they are reproducible, because they are more accurate because they are programmable and most importantly over all of them design automation gives another cherry on the cake that we can automate so we can design digital logic using thousands or millions of, billions of gates. So, we will see that in the next slide.

So, the conclusion of this slide is essentially although most of the systems are going towards digital, but if I require very area efficient and very high frequency, very high bandwidth requirement operation, then it is still done using analog circuits. So, for example, your amplifiers your input output circuits and plus your radio, RF receivers. So, they are all will be analogue they are analog in nature and will remain analog in future also. So, Design Automation or like huge quantity we will see.

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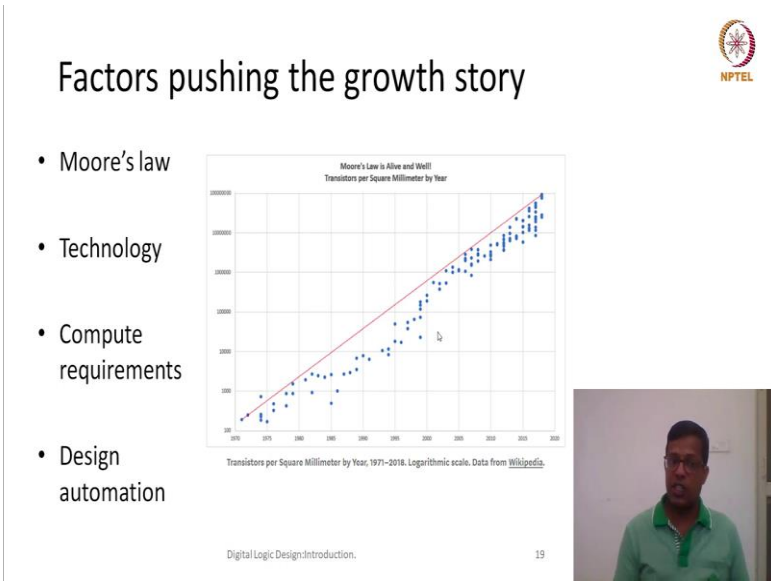

So, another important thing we see that, so there is one particular law which is pushing the growth. So, we call it Moore's Law, according to Moore's Law every 18 months, number of transistors on an integrated circuit will double. So, your area remains same, but the number of transistors within the same area would be doubled after every 18 months. All of you know that anything which is exponential in nature will not work, but this particular law this particular Moore's law is stable it is working at least for last 20, last 40 years.

So, if we see our first integrated circuit in 1970 so till 1920, we see that all of this blue dot represents some of the production assets. So, transition, number of transistors are doubling every 18 months and this doubling is happening because of technology because of compute requirements. So, because of marketing requirements. So, every time we would require a newer circuit or a circuit with a new functionality, so because of this requirements, technology is also pushing itself that we will bring all these transistors more transistors into same area.

So, it is shrinking, you might have heard that now our latest transistors or the latest chips are fabricated on 14 nanometre previously, it used to be 28-22 nanometre. So, every time they are shrinking by a newer technology or a shrink smaller technology. So, because of that now more transistors can fit into this and the other side effect is that now we need to design a chip which would have billions of transistors onto the same chip and that could happen because of design automation.

So, because of all these 3-4 things that compute requirements keep on changing keep on we always acquire new smartphones with new features more features and because technology is improving itself and because now we have techniques, which partially we will study during this course, that can be automate given a specification can we design our digital system automatically.

So, because these techniques are there, now we can even scale up we can design even or ever complex chips, because of this particular dynamics, that design could be automated. Now, we can fabricate more complex chips and this is also one of the reason that digital revolution is replacing all the analog products and this digital revolution as we discussed in our previous lecture also, this this digital revolution is also pushing the boundaries and is or will be causing fourth industrial revolution that means due to your machine learning, artificial intelligence and IoTs.

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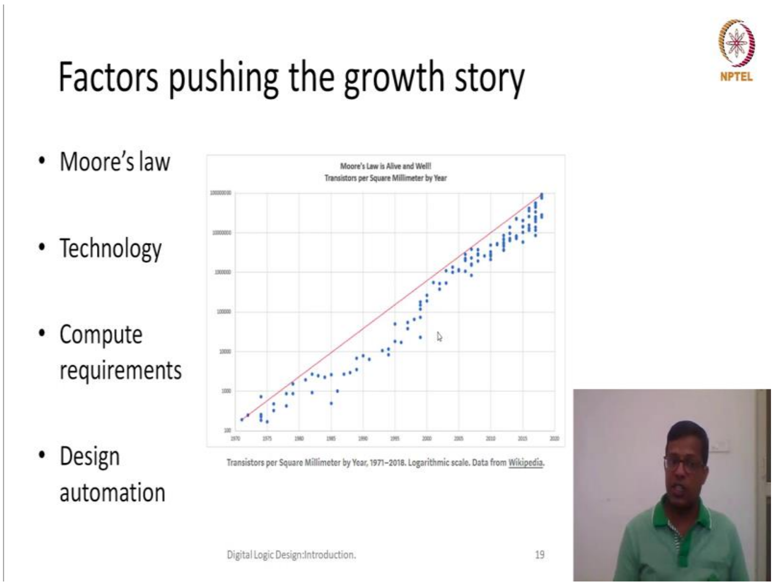

So, with this I would summarise the lecture that so in today's lecture, we have we have understood, how do how we sample digital signals and how we quantize them or how we actually get digital signals from analog signals and we have also over we have seen the overview of analog and digital systems, what are their input output comparison, why digital systems are more robust, then then low counterparts. So with this, I would like to close and we will see you in the next lecture. Thank you very much.