Digital Circuits and Systems

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Lecture - 1
Introduction to Digital Circuits

This course is on digital circuits and digital systems. We have this, signals. A signal is a variation in a physical parameter, temperature variation is a signal, speech as I speak now it's a signal, video is a signal, light intensity variation. Now any of these signals that you get need to be may be processed to be available to the other end may be stored so you do lot of processing of signals in real life. For example, if you take a microphone the speech signal that you give into the microphone if necessary it needs to be amplified and then given out as a signal out of the speaker, the sound signal out of the speaker. So it is a typical signal processing scenario.

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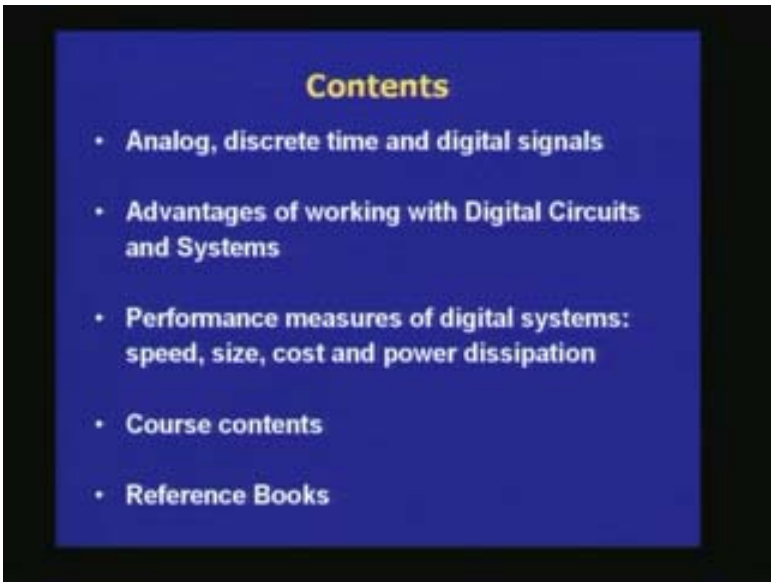

We are in the electrical engineering domain we talk about only electrical signals that means variation of an electrical quantity a voltage or a current as a function of time. A signal is defined as a variation of electrical quantity usually a voltage or a current with time. Of course you can also a signal which does not change with time then it is not called a signal any more it is the DC value we say. For example, if you know that the value is not going to change there is no need for processing so you know the value so you can use the value wherever you want to use it.

Now, once you have this variation any signal that naturally occurs the speech or temperature variation or as I said the illumination changes in the television or a seismic earthquake activity any signal first you need to convert it into electrical variations some

other are mechanical so other physical parameters so there is a transducer a sort of a device this device which converts non electrical quantity into an electrical quantity electrical signal known as the transducer. So the output of the transducers in electrical signal is where we define the signal as the variation of the parameter of interests the voltage or current with time.

Normally a signal can take any value of course within given limits and different instance of time a signal varies continuously. For example you have a time variation of signal voltage level of a signal as a function of time, if I plot like this then any number of values this signal can take as a function of time

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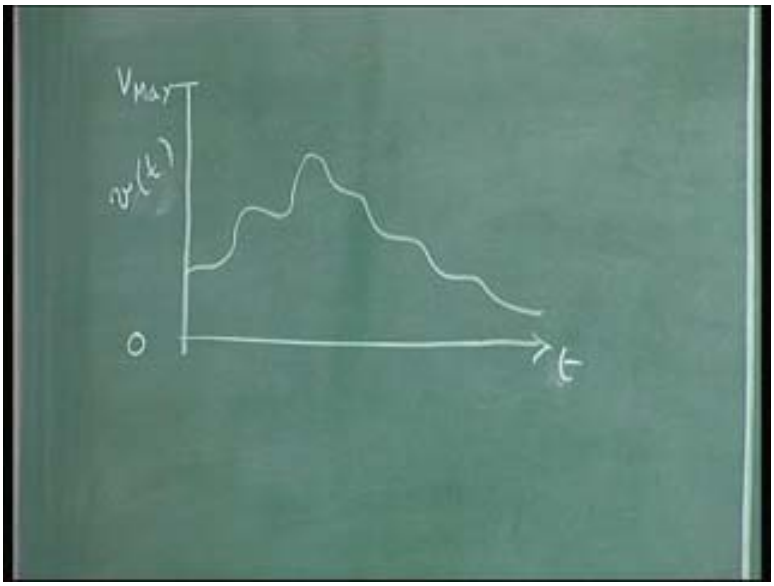

But of course there is always a limit, what is the minimum, let us call this minimum value as 0 and maximum value as Vmax. With two different values we define and say that signal always varies within this range, this is the range of the signal. And at any instant of time it can take any value and what is the instant of time is also not defined, I can make a measurement here and immediately at very next instant of time or I can do a measurement here and measure much later here nothing is remaining here. This variation of signal which can take any value between these two limits and such a signal is called analog signal. Analog signal or analog quantity can take any value at any instant of time within of course the limit defined within the range specified.

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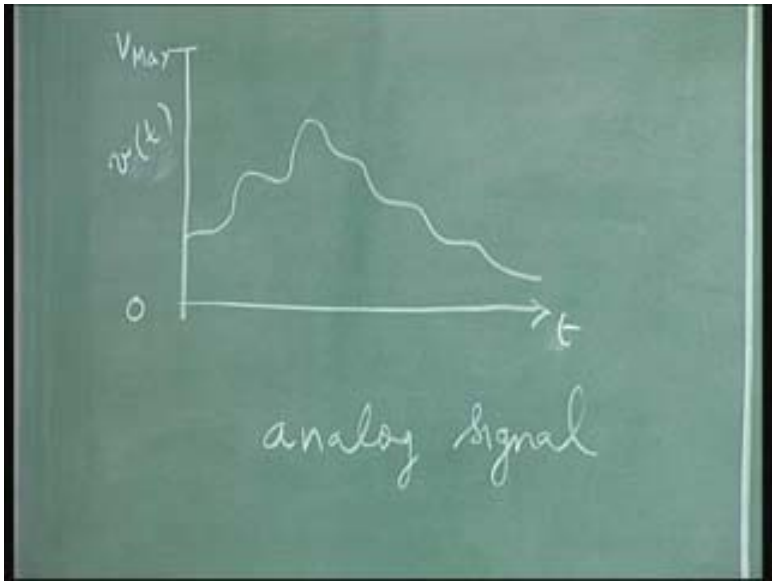

And on the other one I want to process the signal only at discrete instance of time. Suppose I want to monitor the temperature of a system every minute or every hour or every thirty minutes or whatever you discretize the time at which you look at the value of the signal the signal will vary continuously all the time and you are looking only at the discrete instance of time at a definite instance of time only there you are looking at and such a signal suppose I put this value I will have equal intervals of time so call this t_0 the starting point then t_1 t_2 need not be equal but just to explain it little easier I make it at equal intervals of time so I will monitor the value of the signal v(t) at instance of time t_0 t_1 t_2 t_3 t_4 as long as I want or as long as I am interested in the parameter so such a signal is called as the discrete time signal. The signal still continuously varies.

An analog signal is a signal which takes any value between the two defined limits as a function of time. But even though the signal varies I am only interested in looking at specific intervals of time and such a signal is a subset of the analog signal that is called a discrete time signal. The problem in these two cases whether you want to continuously monitor what is continuous finally it has to be discrete. Even it is a one micro second then what happens between one microseconds even one nanosecond can change in between these.

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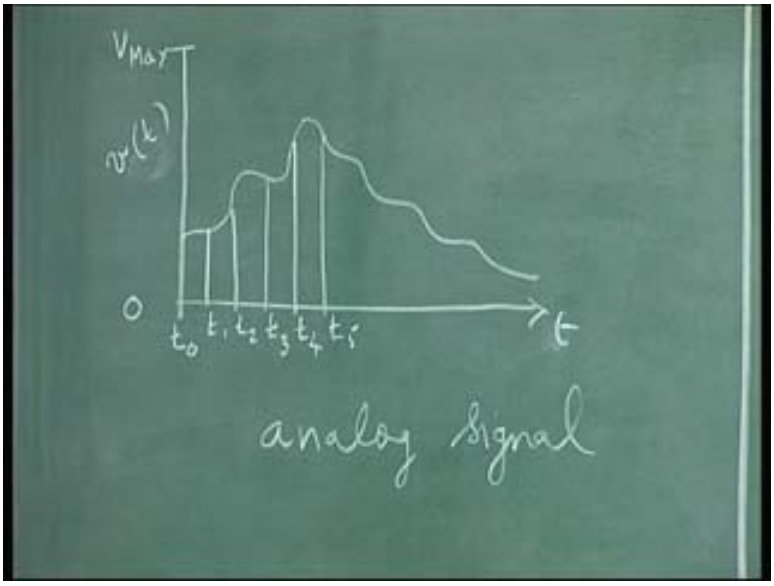

Finally we can only observe. Physical parameter will vary with input and output but if you become an observer the observation can only be discrete.

But whether it is a discrete time signal or analog time signal the variation of the signals between these two limits is a continuous variation there is no defined points by which it can vary. What I am saying is supposing my initial value is 0V and Vmax is 5V as an example, as an example I make this 5V I am only allowing this signal to change from 0 to 5V and within this 0 to 5V it can take any value.

You may have difficulty in representing because you have limitations in the digits you are having in your calculator or I cannot represent any number beyond a particular number of digits to be meaningful. But theoretically it can have number of levels between 0V and 5V. Now when you are trying to transmit a signal because after the entire signal itself as no meaning unless you use it somewhere.

As a change in the speech, when I speak my speech is picked up in the microphone and it gets converted into electrical signals and the electrical signal is amplified by the amplifier and then is put out on the speaker which brings it out as a speech signal. So there is a processing involved in any signal and if there is no processing then we are not interested in any signal. We are not interested in looking at a signal just for the variation sake. We don't want to stare at a signal just because it's nice to see, it keeps changing it's nice to watch so I am sitting and watching it, it is like a wave in the ocean. When you go to the beach and sit there and watch the waves I like to do that myself because that's only for fun, for relaxation.

But when you have a signal you have to use that signal somewhere. You transmit it or you store it for later use, one of the two things. I pick up the signal and process it and give it as an output to the another system another transducer which will convert this

signal into the physical parameter like a sound or a light or whatever or I may even store it for later use.

Suppose I want to know yesterday's temperature variation over today's temperature at 11 O'clock yesterday what was the temperature and at 11 O' clock today I want to know what is the temperature and at 11 O'clock take the temperature reading store it, today I take the 11 O'clock temperature and say that today is hotter than yesterday.

So either you store or transmit it when I do that how accurately can I represent my variations within these limits of 0V and 5V as I said I can take infinite number of values I may not be limited by the channel, how accurately can I send the signal, I can directly send it or the output I can receive which will be an analog signal. But if you want to store it and reproduce it I would like to be limited by the number of digits I want to use. That way I can safely say this is within that and within that limit I will define various levels the signals can take and I will say the signal is in this level tomorrow in this level sot there is a change of so many levels.

So if I further discretize it I discretize the time to start with. originally I had a signal with continuous time and continuous amplitude variation then I let the amplitude continuously vary but discretize the time, I am going to introduce one more discretization in the amplitude I will say I will only let the signal take a specific amount of level specific number of discrete levels so 0 to 5V even though signals allow to vary I have no control over the input signal, the temperature variation and when I record it I only record it as discrete levels or when I process it I only process those discrete levels, when I transmit it I only transmit those discrete levels.

Of course how accurately I want the reproduction depend upon how many levels I want to have, I have only two levels, it is 0 or 1, 0V or 5V is the signal present or not present that is too crude or I can have four levels 0 to 1.25, 1.25 to 2.5, 2.5 to 3.75 and 3.75 to 5. I can say if signal is less than 1.25 then it is level 1, between 1.25 to 2.5 I will say it is level 2, 2.5 to 3.75 I will say level 3 signal and 3.75 to 5 I will say level 4 signal then you know that the signal is in this range. Therefore more and more levels are introduced and I can introduce more and more accuracy in transmission and reproduction but still it is a discrete level. So when I discretize the amplitude in addition to discretize the time I get what is known as digital signal. That means I will only allow this variations let us called this level 1 or this I write as 0, I will say L_0, it will be level I, L_2, L_3, L_4 etc.

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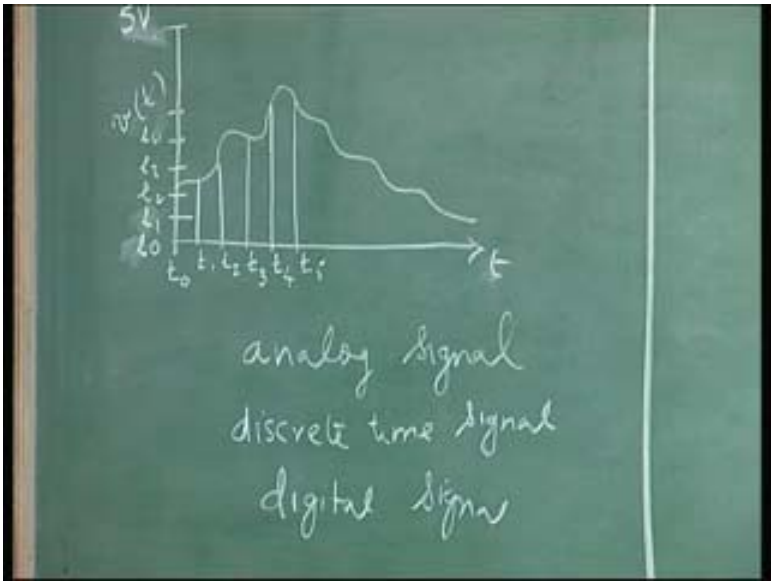

Depending on how narrow or broad these ranges are the total number of steps will be decided. The total number of steps to be decided depending on the level of each of these steps I am going to take.

Now I will say suppose I want to represent the signal value at t1 it is between L_2 and L_3. I cannot say it is between L_2 and L_3 it is not possible to store between L_2 and L_3 or it is not possible to transmit between L_2 and L_3 I have to either transmit between L_2 and L_3, I have to make a prior understanding I will always round it of to the nearest lower level or nearest upper level.

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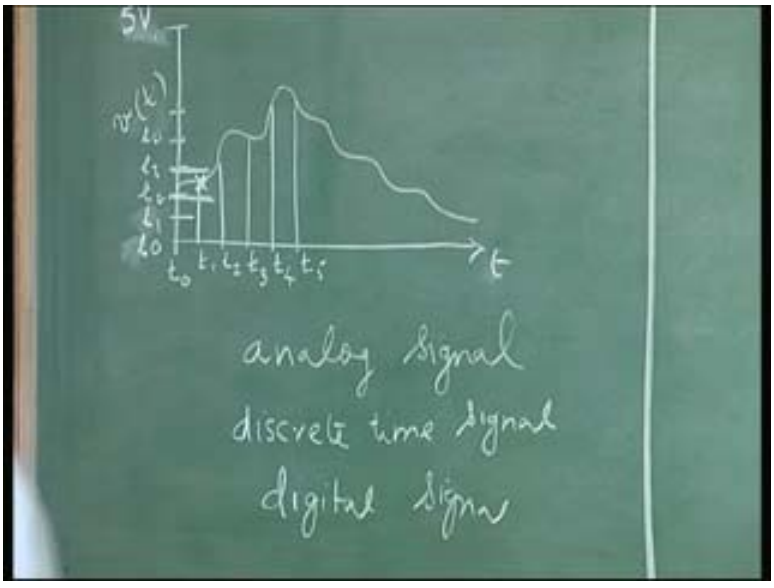

So for our example in this case let us always round it of to the nearest lower level I will say at t0 the signal is L_2, at t1 also the signal is L_2, at t2 the signal is L_3 because here it has become between L_3 and L_4 at t2, at t3 it is L_4 at t4 it may be L_5 and so forth.

Hence each of these levels can be stored or represented by a smaller number of digits than originally it had intended to be. Suppose I have infinite number of levels I need infinite number of digits to represent it. Now each of these levels is going to have discrete levels so I will have fewer digits to represent, fewer for storing and fewer levels to transmit in the case of transmission.

Now let us say there are only a total of eight steps, between 0 and 5V I divide this range into only eight steps, I don't expect much variation in temperature or I am not interested to find a variation, or I am not interested to find whether it is too hot today or too cool today it is all like if know where the temperature is in this range of 0 to 5V in eight levels you tell me and if I tell you that then I will use eight levels so these eight levels can be represented by eight different values so it is easy to store eight different values and transmit eight different values rather than having to store infinite, supposing the signal can be anywhere from 0 to 5V if is 4.7392481 I should have so many digits to represent it or so many digits to transmit it, I am now removing myself from it, the accuracy that much is not required. On the other had I have the flexibility of increasing the accuracy by increasing the number of levels.

If I am willing to store more levels and transmit more levels we improve our accuracy. If you are not interested in storing more levels and transmitting more levels then your application can now decide the accuracy that you want. So there is flexibility in this digital domain which is not there in the analog domain. In analog domain if you make a measurement, suppose if you go to a physics lab make a measurement of current or voltage the representation is analog the needle moves, it stays somewhere between 3.2 and 3.3 but you will only interpret it is 3.2 or 3.3 or say 3.25 or 3.275 like that you will make a guess. But really if you want to be very accurate I should be in a very large meter with minor sub-divisions of each of those and then keep on doing it till you can get accuracy.

There is an accuracy built in analog also because of our observation power and because of the limitations we are using for measurement, now I am legalizing it that's all I am making it official. So I am now saying I am going to tell you these are the levels permitted always represent your signal within these limits. But if you give an analog meter I approximate it, here I approximate it in a systematic way so now this is the digital domain we will be talking about.

Now why do we go for digital because even though there is inaccuracy built in analog also if you want to improve the accuracy of analog what will you do you will do a more precise meter with a large range and each range subdivided into many sub regions so that you will not make a mistake. Supposing you know the current always have to be between 2.5 and 2.7 I will make a reading of 2.5 to 2.7 so large and between that I will divide into smaller and smaller sub-divisions. This possibility improves the accuracy of the meter by

any amount by putting more and more of precise instrumentation. By making a precise instrument for measuring current or voltage or any other quantity you are trying to measure I can always improve the measurements of analog signals. Likewise I can always improve the accuracy of my digital instruments also by having more and more levels because I need to store more and more levels or to transmit more and more levels.

So accuracy can be decided based on the application required. Then what is the advantage of going digital. Analog also has the potential inaccuracy which can be improved depending on the need by extra hardware, I will call it hardware or extra precise instruments. What I mean by hardware put more money in other words. If you put more money you will get better system is it not? Anything if you put more money you may get a better system, more money you get a better car right? That is what it is.

In digital also I have a potential of improving the accuracy by putting more and more levels which means more and more levels means more and more hardware then I should have some way of representing more digits more levels, earlier I had fewer levels now I have more levels so now I should have some other hardware to represent this so here also it is going to cost a little more in terms of instrument implementation.

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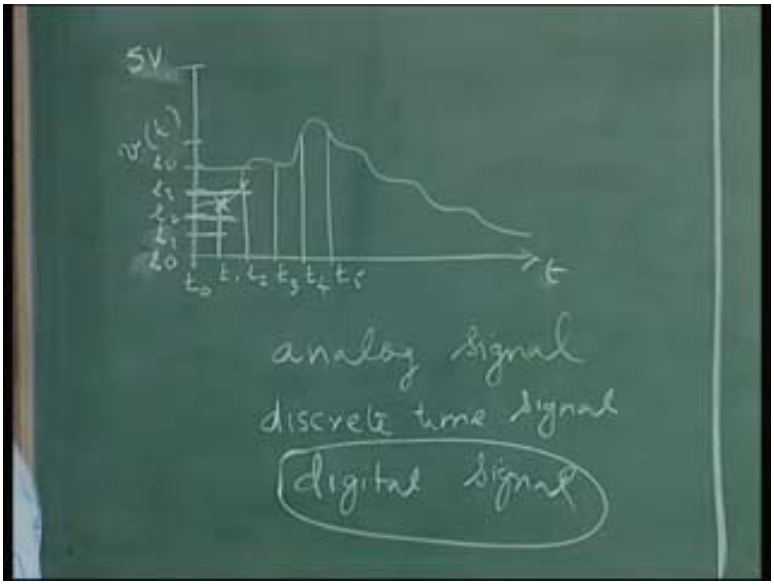

But now why analog why digital? So this is the difference between the analog signal, discrete time signal and digital signal so in this particular course we will be dealing with digital only, both in time and levels it will be digital. We are not talking about analog signals that is analog electronics POE Principles of Electronics, you will learn later on and discrete time you will learn some other time for some other specific applications. This course will deal with only digital signals and digital processing of signals, digital representation of signals; digitally you have to store it etc so this course is on digital circuits and digital systems.

Now, one may say that signals are basically analog in nature when it is generated. When it is generated most of the signals are analog, temperature variation is there, you can't say that temperature always jumps between one degree intervals can you say that? Today's temperature you want to measure can you say that my temperature will only jump from 31 to 32 in between it should not jump, can you force it? No, you need not take cognizance of the fact 31.2, you will say either 31 or 32 but then see temperature will change, analog, there will be infinite levels, it will only take 31.2745 also it can change you don't know.

Likewise all signals are analog similarly when you put the thing back and after processing or storing, transmitting and get this back on the other transducer reverse transducer in this case, in the case of microphone the reverse transducer is the loud speaker, the signal makes the sound possible the loud speaker the electrical signal is converted into sound, the light is picked up as an electrical signal it is processed and in your picture tube at home television receiver the electrical signal is converted back into light where you see the shadows of all these movements which you are addicted to, all the time watching TV.

So it is again a conversion of analog to digital, digital to analog and back so why do we have to go through the digital path? Why can't we take analog signals? Anyway inaccuracy is there, in digital also the accuracy can be defined by you, in analog also there is a provision to improve accuracy by spending more and more precise hardware and more and more money, in digital also I can do more and more hardware and then get better accuracy so when that is the case why suddenly make all of them learn this course digital? One thing is I am going to get salary out of this course teaching you that is the minor reason but the real reason is digital signals are easy to store and manipulate without much error, I will give you an example.

Supposing I am measuring an analog value I am storing an analog value, how do you store an analog voltage? How do you store voltage? Capacitor, you store the value in a capacitor.

Supposing I charge my capacitor to 1.27V today and tomorrow somebody else comes and measures it then it is equal to storing and retrieving it later or storing and transmitting it, you stored 1.27V and tomorrow somebody comes and measures 1.25V does that person know that you have stored 1.27 volts if he knows then there is no need for storing you can also tell him then there is no need for capacitor, if you are going to see that fellow tell him it is 1.27 he doesn't have to come and measure. So when you leave a voltage of 1.27 volts on a capacitor and measure it again you don't know how much is the last.

For analog value because 1.27 is only our limitation, as I said it can be 1.27 to and in that case it can be measured as 1.27 too whatever value you put you should be able measure it accurately but there is always a leakage or I am transmitting analog signal let us say 1.72 instead of storing in a capacitor I am trying to send it across a wire to the other end as a signal so you try to send 1.72V the receiving end it is measured as 1.75V this person has no idea that you sent 1.72V and if he knows that you have sent 1.72V then there is no

need for a transmission. So the other end receives it as 1.75 volts he was not sure about what you have sent that was one point seven two volts. There is a 0.03V noise which has been added in the transmission part which itself is 1.75V but he doesn't know exactly how much is the noise added. Now there is uncertainty about the values of storage and the transmitted signal in an analog domain.

Take a digital example; I have only eight levels as I said or a minimum number of levels whatever is the level but I will take eight as an example. Between 0 and 5V I have eight levels so when you divide 5V by 8 how much is each step? It is 0.625. So if the voltage level that I want to transmit is between 0 and 0.625 I am going to send it as a 0 level that is what I told you, I am going to round if off to the lowest level. If it is between 0.625 and one point two five if it is 0.625 and 1.25 you know it is L_1 level one.

Supposing I send 0.75 let us say there is a noise added, at the same .03 a noise was added same channel I am sending so the noise is added in it so 0.75 is going to be received as 0.78 but it will still be recorded as L1. The effect of noise on a digital transmission is much lower compared to the effect of noise on the analog transmission. Since I only know that predefined levels as the possible levels I know it cannot be 0.75 it cannot be 0.78 this guy must have send 0.625. I don't care whether 0.75 became point seven eight because anyway you send only 0.625 which is level 0.

Unless there is a marginal thing where you are trying to send 1.25V you send 1.24V which is referred to as L1 and 0.2 got added so 1.24 plus 0.2 will be I will not even say 0.2 so .01 got added so 1.24 becomes 1.25 then you are not sure whether what you sent was L1 or L2 but occasionally these type of extremities are there. I am not saying it as a perfect transmission I am saying it is better than analog in noise performance. That is one of the reasons why you want to go for analog. It can store and reproduce values not more accurately but I will say more reliably than, why did I not say accurately? Accuracy depends on number of levels I use. If I am going to truncate my 0.825 as 0.625 is not accurate by any stretch of imagination but I chose to have only eight levels. If I wanted I could have had 16 levels, also if I had wanted I would have had 256 levels, if I wanted I can have 1024 levels so that case becomes more and more accurate. Accuracy depends on the number of levels but more reliably I can store and reproduce and more reliably I can transmit and receive, that is one reason. Do you think it is a valid/good reason to for digital? No? You are not convinced. I think it is a good reason.

Now second reason I will say is I will go back to accuracy a little bit more. I said accuracy can be improved by analog or digital case. In digital case it is having more number of levels and in analog it is by giving an instrument which is more accurate which can handle these lower order values better by increasing the sensitivity of the equipment. For example, a meter, how does it work? A meter works by the current carrying coil which just makes a deflection of the pointer and where it stops so if you want to make more accurate measurement I should have more sensitive coils but now the difference between having more levels and more sensitive analog is very different.

To improve the accuracy it is easier in digital because all I have to do is to increase the number of levels. So reproduction of levels is the same effort. Hardware wise it is more but then the similar hardware I have more of it. So if I have similar hardware more of it I can improve the accuracy of a digital system. In analog system to get more accurate I need to struggle more I need to slog more. Analog improvement accuracy is more difficult than digital improved accuracy. Digital improved accuracy means more levels which are identical to the earlier levels. Instead of having eight of those levels whatever it is I will have sixteen of those whereas for analog I cannot say.

For example, if I want to make a measurement of the distance from here to here if I ask you to measure and give me the feet you will very easily take your foot ruler and measure and say seven feet, eight feet and if I ask you to do in inches then you will be little more careful you need a scale with an inch, rule of an inch calibration in it and then have to be very careful and then finally if I say give me the nearest millimeter then I need an instrument with a millimeter calibration and then I have to be very careful in my measurement. So, by measuring more and more accurately in analog systems is difficult than having more and more levels and improving the accuracy or precision of a digital system, that is another reason I have given for a digital. So the cost of more accurate system is proportional to more accuracy in the case of digital whereas it increases the exponentially in the case of analog. In analog the increase in cost for most accurate systems is not proportional to the accuracy improvement but it is much more than that.

For digital I spend more money I get a similar one. If a I am happy with four levels be happy, if you want eight levels give me double the cost I will give you, in analog I can't say that so it is more difficult to make more meaningful measurements more accurate measurements in analog compared to digital or storage. When I say measurement it means storage and transmission everything. The quantity we may signal after all what did I say the signal has to be represented, stored, measured, transmitted, everything is part of signal that is called signal handling or signal processing. The signal has to be processed, you can call it handling of the signal doesn't matter to me. So these are the reasons why we go for digital. So now the effort is to convert everything that you see in the world and why can't you do everything in digital? It is not possible.

So I told you why digital, why do we need analog? If you say so much about digital being so good can you not do away with analog altogether and have only a digital world and not have the principle of electronics course in your next semester? It is a good tempting thought but unfortunately not because all real life signals are analog signals. Be it a temperature variation of a body or a temperature variation of a parameter or anything or a speech or a light or heart rate or whatever you think of, have you seen the ECG waveforms in monitors, in hospitals, in movies? Suddenly the heart rate will come and then follows that that is how they represent a person dying in a movie is it not?

So all are analog signals unfortunately or fortunately if you look at the analog people they will say otherwise they won't have jobs. So analog signals are there and our job is to convert these analog signals to digital signals and because we live with digital people but today technology has improved so much it is easier to do digital as I said it is easier to do

digital cost of the digital becoming lower and lower so we want to do more and more of digital so what we do is we cannot do away with analog I told you, first we pick up the signal analog by a transducer as I said, sometimes the signal is so weak that you need to amplify it before you convert into digital you need to amplify it. Supposing you don't do an amplification sometimes the signal gets lost, the signal is lost completely, you get very weak signals and if the signal is not very weak you can directly convert into digital.

Therefore take an analog signal convert it to digital preprocess if necessary that is if signal is very weak, convert to digital, by process I will put anything I am not going to put separately store measure and all that I combine all of them, manipulate do whatever you want with that signal that is called processing, just storing and reproducing is also processing and then convert it back to analog this is the flow of any processing today and because the technology advances because the digital domain being so dominant today in electronics they are trying to push as much as possible digital domain and have as little as possible in analog.

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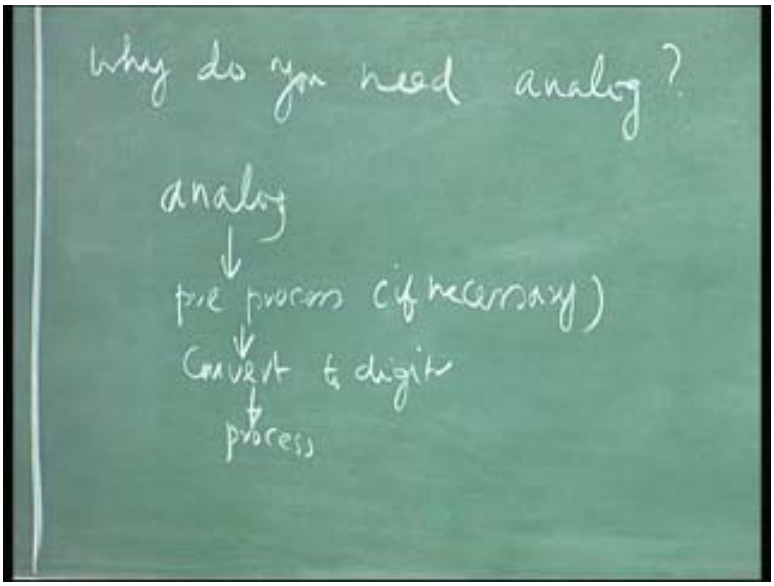

So in any system today you design ninety to ninety five percent of the activities are digital but that five ten percent of the analog is not real, without a proper signal whatever processing you try to do that is not going to help you. I am not trying to say analog is not important, I am not trying to say don't go to analog but more effort is put on digital more amount of work is done in digital domain than analog domain. But design efforts are very difficult in analog as I said. To improve the accuracy in analog is not easy but digital is easy. So effort wise it may be even equal or slightly different but then I am not saying in reality in that sense please, do not misunderstand me, do not misquote me to analog professors and pick up a fight for me with analog professors who are my colleagues here, I am not saying that but digital as lot of these applications today and what we will be seeing is only this, we are going to do this process convert to digital, convert to analog and that we will learn later on in future courses but in this particular course what is this

signal, how are these signals represented in digital, how are we going to use it in processing, what are the various things we can do, what are the various things we can do with this signal, this is the basic building blocks so what we will basically study in this course are building blocks of digital circuits and systems. There are several other things but we will not go into the details.

We will have to do from the analysis point of view we have to analyze the behavior of them, how does it work, what is a building block, how do you define the input output relationship of this, how do you analyze it, how do you use it, analysis, use and design, how do you design it to build one? That is the crux of the subject matter of this course. We will go into the details of the subject matter this is further divided into combinations circuits and sequential circuits and all that we will see them as we go along.

So basically we will look at the basic building blocks of the digital systems and digital circuits find out their behavior how they are built and how to use them in known applications and in a reverse mode given a requirement in a digital system how do you go about designing the requirements or what are the building blocks you need and how to connect them in properly and so on, that is why we call it the design phase. Design is given the specifications of the circuit how are you going to choose the proper building blocks, how are you going to connect them together, how are you going to make it work to give you the satisfactory results.

There are two types of circuits basically; one is called combinational and the other is sequential, both come under the same digital category. I will define the difference between these two a little later on.

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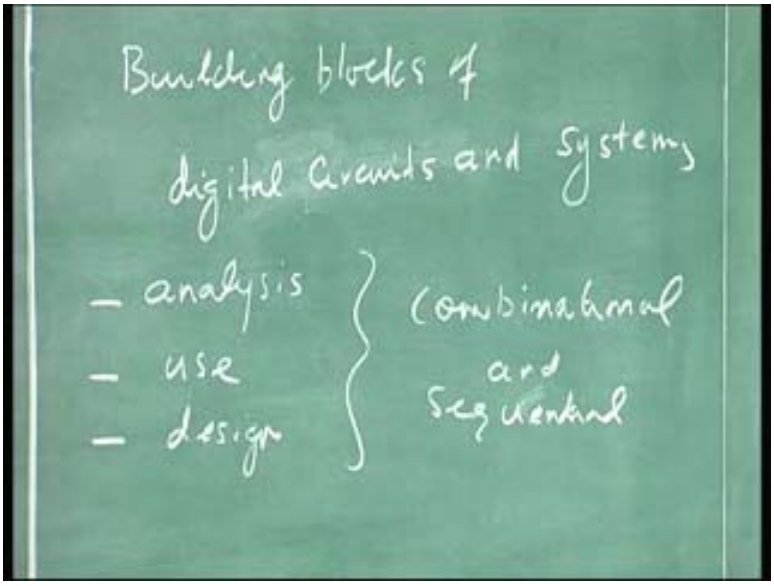

So, in a nut shell you want to know the course content of this course we will be doing the analysis use and design of combinational sequential building blocks which are required

for digital circuits and systems, one sentence course formulation and what are the books we will be using? A very good book is called “Digital Design” by Moris Mano M. M Mano he is called as Moris M. Mano this print is all book I think, it has come in cheap edition it is available, I think it is available in our book stores.

This Moris Mano has come through several iterations, it has been there for a while for the last twenty years this person has been writing books and updating and improving the contents, this one is the latest version called as the third edition, digital design edition 3. Then we have Roth Junior C. H. Roth “Fundamentals of Logic Design” by Jaico Publishers, I don’t know what it is Jaico Publishers 1998, there are two typical but there are so many books.

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Any book which as title like digital design, logic design, digital and logic design digital circuits, good enough because these are all very basic stuff we are talking about, the basics, the first introductory material and digital there are scores of books at least about 15 to 20 good books you can see in any library and I will not be following one book strictly, I would like to teach you everything you need to know in your first level course but does not mean that we will be following the book that cover to cover it is not necessary because this is such an interesting course we have been teaching this course for a while so some books doesn’t cover one topic very well, some book does not cover a topic at all properly so in that case I will go on, I don’t even have to follow books because I am teaching this course so many times so I will just sort of give an essence of my experience of teaching this course over years, might as well has been a good practice I have been doing it for a while without any much complaints. So that’s what we will do but you need to have a book so that you need to follow the material and do more studies, sometimes we are not spending enough time in the classroom we want to do further studies, sometimes something is not very clearly explained in the class you want to go back and refer to a book so please have a book, I am not saying you should not have a

book but do not expect me to follow a book from page to page and it always nice to have a basic digital because book because this is a first course lot of other things are done.

As I said today digital world is technologically a very advanced world so lots of opportunities are there for you to do digital, there may be an advanced course in digital that you may do, you may be doing some mini project, you may be doing even a major project in digital area so it is always nice to have a reference book with you instead of always having to borrow or copy somebody else's book and all that.

So if you are thinking of buying a book you can buy one of these two books, there are so many others also. If you are doubtful about a particular book and if you want to know if it is good or not you can always ask me, you can browse through and that will tell you. So these are the various things we need to know and as we go on we develop a material and for homework I may have to prescribe some of these books so that may be a good idea that way to have, at least there must be enough for books available so that you know what problems are there for the class.

This is where we will stop today and in the next lectures we will start with the detailed subject matter as I said levels and all that, we will be more specific how to present levels, what do you mean by level and what are digital signals and how do you represent digital signals and then we will start with the simple gates and then go on. It is a good idea to have a book and follow the book read the book sometimes it is better to read ahead of the class if possible so that way you can understand this topic better.

I will prescribe homework from the book so that you can start also working out problems, okay we will stop here today.