

**Circuit Analysis for Analog Designers**  
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**Lecture - 01**  
**Course Introduction and Motivation**

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Department of Electrical Engg  
Lecture 01

$P_{in}$   
 $\approx -100 \text{ dBm}$

Power in dBm =  $10 \log \left( \frac{P}{1\text{mW}} \right)$       Example:  $0 \text{ dBm} \rightarrow 1\text{mW}$

$\therefore -100 \text{ dBm} = 10^{-10} \text{ mW} = 0.1 \text{ pW}$

So, let us get started. The motivation for this course is the following any electronic system that you see today right and the common example I mean one example that is affecting our daily lives in more ways than we can imagine is perhaps a mobile phone and the front end of a mobile phone is basically the all the electronics that is necessary to sense or sniff the air waves and result in you know and finally, after a lot of digital processing we get the information that is basically writing on those waves.

And so, the front end is basically the radio and as you can imagine you know you have an antenna and the amount of power that is received by the antenna is can be extremely small. For example, in the GSM radio the smallest signal that the radio is, supposed to be able to make sense off right is the power in is of the order of  $-100 \text{ dBm}$  right.  $\text{dBm}$  is a unit of power used in by the RF community.

Simply because the range of powers when you talk when you talk about the powers at that are encountered in practice can vary over several orders of magnitude and which is why it

makes sense to use a logarithmic scale and power in *dBm* is basically 10 log of the power the actual power in watts; obviously, divided by 1 milliwatt ok.

$$\text{Power in dBm} = 10 \log\left(\frac{P}{1\text{mW}}\right)$$

So, that is the that is how things are defined and for example, what is 0 *dBm*?

Student: (Refer Time: 02:22).

Please feel free to stop and ask questions you know just like in any regular class right. We will our friendly staff at NPTEL will edit out everything that is in appropriate right. So, for example, 0 *dBm* is therefore, 1 milliwatt power. So, let us try to figure out what  $-100$  *dBm* is.

Student:  $-100$  *dBm* =  $10^{-10}$  *mW* = 0.1 *pW*

And you know given that this light probably produces few 10s of watts right you can imagine that the amount of RF energy that your actually your cell phone is receiving and actually making sense of what is of the information that is riding on that on that RF signal.

You can see that the power that is being received is actually a very small quantity it is compared to the light in the room we are talking about powers which are of about you know 14 orders of magnitude smaller than for instance than for instance the amount of visual the amount of power of light that is floating around this room right.

So, and to make matters worse it also turns out that you know as you can imagine that you know you are not the only one who is using a phone you and your neighbour and his brother and everybody else is also using the phone and most of the time at the same time right.

So, it is not merely enough to be able to detect you know a very small signal, it is also important to be able to detect this very small signal in the presence of in the presence of other signals which can be potentially very within quote within quotes allow right.

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$10^{-10} \text{ W}$

$1 \text{ W}$

$10^{-15} \text{ W} \leftarrow \text{Desired}$   
 $10^{-3} \text{ W} \leftarrow \text{Undesired}$

For example, right this is the wireless base station which is located several 100 meters away and you are here and you have your phone here and now your friend is close by and of course, this friend is not talking to you. So, he is here. So, because of, simply, because of distance the amount of power that is actually getting from the base station to you is actually very small, as I again as I said to give you an order of magnitude estimate it is roughly  $10^{-13} \text{ W}$  right.

On the other hand, your friend basically wants to talk to somebody. So, his cell phone signal must actually reach the base station and if the base station has to make sense of what is coming in from your other friend what comment can you make about the amount of power that he transmits, can he transmit you know a pico watt of power. It turns out that you know if he transmits the pico watt of power I mean what is going to get to the base station is going to be 12 orders of magnitude smaller. So, evidently that is going to be too small to discern.

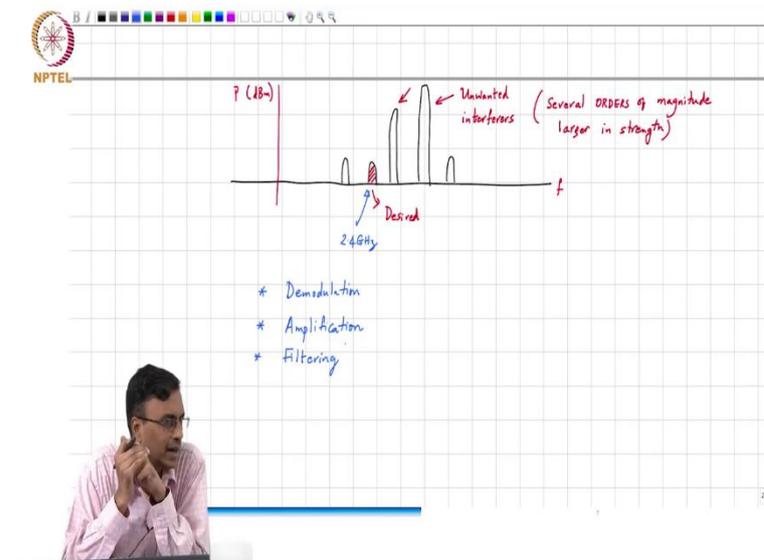
So, this the cell phone on this end must be blasting out several 100 milliwatts of power if not more right. So, in other words this is let us just make you know our life easy and let us just call this a watt right ok. So, now, the friend cell phone is blasting out a watt of course, not all that watt is going to go to the base station, most of the time you know it is it radiates isotropically.

So, you know out of this and because you are so standing so close to your friend right, a big portion of this unintended signal right. Let us assume you have a milliwatt here ok. So, and eventually you know a small amount of this 1 watt reaches the base station ok. So, let us call this again in let us say,  $10^{-10}W$  just to put some numbers in place right.

So, as you can see your instrument which you are holding is suppose to distinguish. So, you have two signals one signal has a power of about  $10^{-13}W$ . This is the desired signal and one signal has a power of  $10^{-3}W$  and this is undesired ok and the ratio of the power of the desired signal to the undesired signal is as you can see can be as large as 10 orders of magnitude right. And as a radio receiver what is your job, I mean what are you supposed to take in, what are you supposed to reject?

Yeah. So, basically what we would like is the desired signal which is very small and the undesired signal which even though it is several orders of magnitude larger it has to be reject right. And it is not necessary that you have just you know 2 people you know talking at the same time, you have as you know can imagine there are several 100 people and therefore the RF spectrum is a very crowded place.

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So, this is the very common scenario where if this is an example of the RF spectrum right. So, you have different people talking and they are all talking at slightly different frequencies and the desired signal is this guy here. The y axis is power in dBm ok and the

x axis is frequency and this is the desired signal and these are all unwanted interferers and all these interferers are several orders of magnitude large in strength.

So, the question now is you know where we are supposed to do two things. One is the we have to take the small signal which is you know which is riding at on a carrier frequency which is very very large. You know this for an example carrier frequency could be say 2.4 giga hertz or thereabouts right. There are several bands as you all know, there is the 1.8 giga hertz band, there is the 2.4 plus giga hertz band, there is the 5 giga hertz band any number of bands right.

But the point is that the RF signal is being modulated and so there are two things that three things that we would like to do. Basically, we need to bring the information which is riding on the carrier right down to down to.

Base band right. So, what is that process called?

Student: Demodulation.

Demodulation, the next thing is that well you move the spectrum from RF to base band and it does not help if the base band signal is very very small right, what you do eventually you need to hear something right. So, whatever information signal is riding on that RF signal must be within quotes amplified to power levels that our ear can discern right and typically that is about you know of the order of a milli watt right.

So, the information varying signal which is of the order of several 10s of a pico watt right needs to be amplified to a level of milliwatt. So, after demodulation so, there is basically amplification right and well it is a well the desired signal is very small and therefore, it makes sense that we put an amplifier right, but the signal that which is being received by the antenna is not merely the desired signal, there is also a whole bunch of extras right as you can see in the picture.

And all these extras are actually several orders of magnitude larger than your desired signal ok. So, if you say well my desired signal is a 10th of a pico watt, I need to get it up to about a milli watt. So, why do not I put a gain you know sum amplifier with the power gain of you know whatever  $10^3$  by  $10^9$  which is  $10^{12}$  which is  $10^9$ , what you think is the problem with that approach?

Student: (Refer Time: 13:16) the desired part is also (Refer Time: 13:18).

Exactly right, I mean this the right the obvious thing you say well you know it is not while it is true that the desired part is very small and needs to be amplified right. The undesired part is several orders of magnitude larger and therefore, you know if you try to amplify the small one the large one will get amplified even more correct. And what happens I mean so, what is the problem with amplifying the undesired signal by a large factor?

Student: Saturate.

Exactly right, all of you have done some basic electronics classes and are aware that well if you amplify signals too much, eventually the signals is you know the voltages or currents or whatever will become so large that they will cause saturation right, because finally, we are operating with a limited power supply right you cannot operate with you know 3 million volt power supply.

So, since you are operating with limited power supplied you know if you amplify without thinking carefully simply based on the fact that you know my desired signal is very small you basically will have what you call saturation. So, what do you need to do, what do you need to do before you amplify, if you need to amplify which you said almost definitely need to because the desired signal is very small. It is not merely enough to say throw this into an amplifier before you throw it into an amplifier what do you need to do you need to get rid of.

Student: Undesired interferers.

The undesired interferers right and so you have signals you want something; you want you want to reject something else now what is that process called?

What is it called?

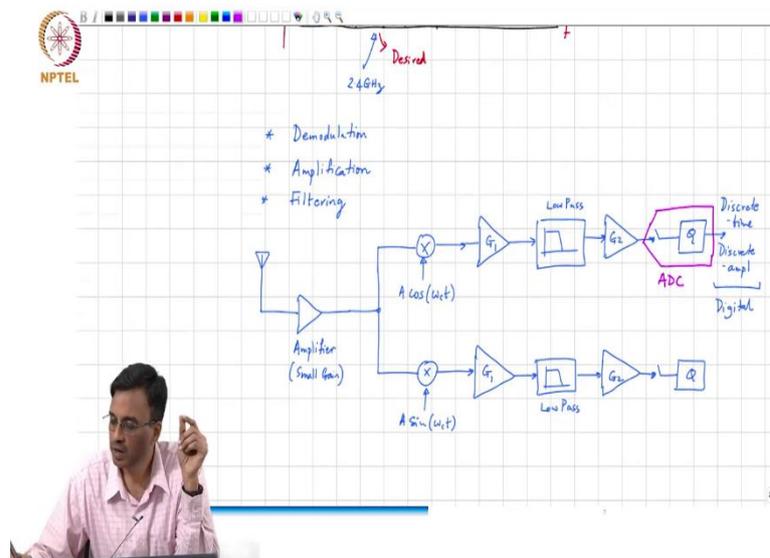
Student: Filter.

Filter. So, basically filter alright. So, I mean these are the main operations that happen in a radio right. It is not necessary to do you know these operations or perform these operations in this particular order right. People keep coming up with more and more creative ways of merging the demodulation the amplification and the filtering to result in

a radio receiver that the you know dissipates you know as low a power as possible right. And why is low power important, because all are potable electronics is running of batteries and you do not want to give a keep you know charging your phone all the time right.

And I mean alternatively I mean you could have sensor nodes and as part of IOT and you do not want to keep replacing their batteries or charging their batteries all the time. So, what you want is therefore, radio receiver, where the power dissipation is as small as possible correct. And so, people have come up over the years with a whole bunch of creative ways of performing demodulation, amplification and filtering in more and more power efficient ways ok.

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And you know the current radio architecture that is in work is basically looks something like this, I mean I will not get into the details of why this architecture for a radio is the one that is most widely adopted right, but, but just gives you a flavour and shows you that it is not necessary to do all the amplification in one place, it is not necessary to do all the filtering in one place, it is not necessary to do the demodulation in one step ok.

But it just so turns out that if this is the antenna the first stage of a you know the typical radio is basically an amplifier stage with a small gain right and those of you who have taken an RF class or those of you who are going to take an RF class you will understand why you cannot have too larger gain and the simple reason is that at the input of this

amplifier which is directly interfacing with the antenna, you still have a lot of interference right.

So, if you go crazy with the gain there then you will you know you will either saturate the LNA or make the make the LNA is so non-linear that you have trouble right. So, and after that you have mixing and the basic idea is the following well  $\omega_c$ , subscript  $c$  stands for the carrier. So, all of you know that *sin* and *cos* are orthogonal right.

So, you can have independent information writing on the sine and the cosine carrier right, this way you do not waste RF bandwidth. And then well the signal here is still small and therefore, you put in more gain here, it turns out that this multiplication also often results in a reduction in the strength of the desired signal and then you put gain and then you put what kind of filter must you put here?

Student: Low pass filter.

Low pass filter, I did not gain once you put a low pass filter then most presumably most of the interferers are knocked off, then you can actually increase the gain of the signal of the desired signal by a large factor. Is that clear people right and the output signal here is it analogue or I mean what comment can we make about the nature of the signal there.

Student: Analogue.

It is still analogue right, but I mean for a whole bunch of reasons it makes sense to process this the signal digitally and the reason being that remember that the RF spectrum is very precious right. All of you have probably seen a whole lot of controversy that goes on whenever you have spectrum options right in the press ok. So, bottom line is that you know the right to basically transmit over a certain bandwidth in the air is extremely expensive right.

So, any method by which you can convey what you want to convey right, either it is, either you know data or it is voice right or both if you are able to convey what you want to convey in a in a bandwidth which is say for example, half as large right. What commercial implication does that have, what does that mean?

Student: (Refer Time: 21:12).

I mean how why should we be excited as engineers about this stuff.

Student: (Refer Time: 21:20).

I mean basically then you know the telecom provider will basically now double the number of customers in a given area right because everybody is now occupying. I mean it is like saying you know magically if everybody every one of us was you know were shrunk to a factor of by a factor of 2 right in all dimensions. Then the airline companies would be very happy right, because now they can hold 8 times the number of passengers and then you know and charge the same money and then therefore, their revenue increases correct.

So, likewise I mean you know RF spectrum is a very very precious quantity right. So, the you know the engineers basically try to do all sorts of creative things to be able to packing as much information as possible into as little a space as possible right. So, therefore, and it makes I mean it makes sense that you know to do that you probably have to have very sophisticated algorithms which basically modulate, you know, do some magic on the data and make sure that it is within quotes as dense as possible with the information before, you know, before you launch it on this carrier alright.

So, if you want to demodulate it must follow that well if you took your information you know pulled in a mixer and like made it juice and like you know whatever right and then you throw it on the other side you know you want to get back your information it stands to reason that you must do things just as complicated to be able to unravel what has been done correct and the you know all that stuff is best done digitally right and of course, you know one more advantage of doing everything digitally is things can be stored easily right.

And another example advantage is that oh well if you messed up the algorithm do not worry you can put a patch and like you know fix the problem later right ok. Ee used that from software right. You ship something which is well you know I know it is got bugs, but do not worry about it let us ship it right, when there is a problem and customer complaints oh we will send over there update and like we will fix the algorithm right.

So, this so, all these things you know basically motivate the need for digital processing of information unfortunately the output is the radio right or the real world is still analogue and you know I do not think that is going to change any time soon. So, what we need to

do is the therefore, need to have some interface between the analogue world and the digital world and that is done by.

Student: Analogue.

Analogue to digital conversion all of you have seen you know the basic principle and the basic principle is that you know if you have a finite bandwidth signal, as Shannon has told us that well if you sample the signal at a rate higher than twice the bandwidth you can reconstruct the signal from its samples without losing any information right.

So, basically what is happening there is you know equivalently we have sampling. So, that is converted a signal which is continuous in time to something which is discrete in time right. But what common can we make our amplitude I mean well the time is discrete, but amplitude is still continuous that basically means can we represent this digitally or we cannot.

Student: Cannot.

If you have continuous levels, you know you need an infinite number of numbers to be able to represent the signal properly right. So, if you want to be able to represent a signal digitally remember a digital state machine understand signals only at clock edges right which means time is quantized. It also only understands a finite number of levels because register withs in a digital system or finite, you can have as many as you want 32 bit, 64 bit whatever, but the fact remains that the number of levels is finite.

So, you need to convert this discrete time signal also into a discrete amplitude signal. What do you I mean what do you think we can do to do to force this? What do you think we can do? You quantize right which is equivalent to say I am going to round off the signal to the nearest integer I mean that is what it means in right. And the hope is that I mean with quantisation are we losing information or you know or we are preserving the information of the signal that is coming in.

Student: (Refer Time: 26:04).

We are.

Student: Losing

Losing information right, but then the engineering argument is that well if I make the level sufficiently close right, in other words if I have you know a signal and if I round off in the 8th decimal place you know which stands to reason that that there is virtually and it probably does not matter right ok. We have accepted that even in a grading system you know we know that there is no information in the even in the first decimal place right because there are typically you are all bunched by 10 max right ok.

And eventually it does not matter. So, there is so, instead of working with continuous time signal now we are able to work with a signal here which is both discrete in time and discrete amplitude and therefore, this is a digital signal, does make sense forks. So, so this is what is called, this box is what is called an analogue to digital converter or ADC alright.

And that is ok. So, one thing nobody asked me was I mean why are we, why is it that we are limited to only being able to detect some number as small as say a 10th of a pico watt, you know what prevents us from saying ok if I made this 10 power minus 13 watts, let us say if my electronics was able to detect say 10 per minus 17 watts. So, what implication would that have? Whenever we will detect a smaller and smaller signal what practical implication do you think that would have?

Student: (Refer Time: 28:08) we need to amplified (Refer Time: 28:10).

That is ok right, I mean what is the commercial implication that you think that would have?

Student: (Refer Time: 28:16).

Oh well, remember why is this I mean the base station is transmitting a lot of power right and you are picking up only a fraction of it where is all that other power going.

Student: (Refer Time: 28:27) disturbance in (Refer Time: 28:33).

Why is only a fraction of that power reaching us?

Student: (Refer Time: 28:39).

Pardon.

Student: (Refer Time: 28:41).

Ok well, I mean even if there is no attenuation, I mean the fact that you know let us say the base station is the center of a sphere and you know you are at the edge on the surface of the sphere how much power is going to reach you, there is nothing to attenuate in the middle what is going to happen.

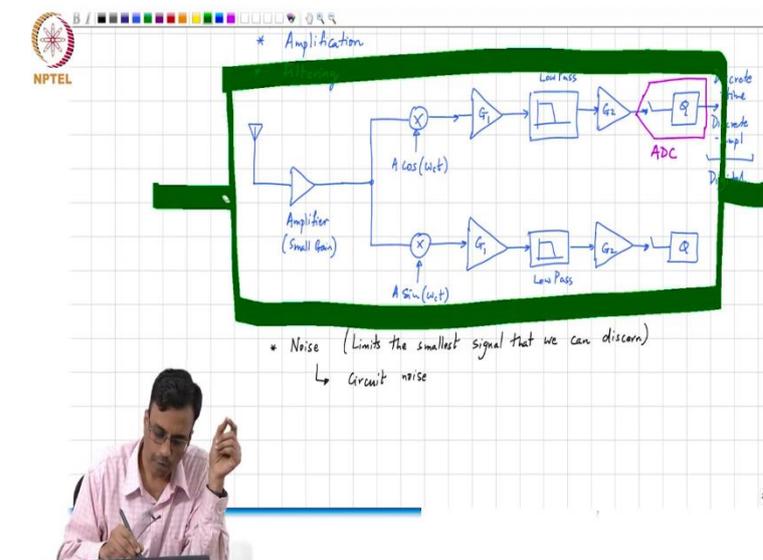
Student: it will be I mean density will be (Refer Time: 29:01).

I mean there is simply 1 by r square loss correct right. If you go close to the light you know you pick up a lot of energy if you go you know 100 feet away I mean the amount of light that falls on you is very very small is 1 by r square loss right. On top of it there is a other loss because the reflections and all these other stuff right, but if you are able to detect signals which are say two orders of magnitude smaller right, in principle you can go much farther away from the base station before you cannot make any sense of what is coming correct ok.

So, there is definitely an implication I mean there is the definitely a motivation you try and make that minimum received power as small as possible to achieve a given performance correct. So, what therefore, the question I am asking you is what is limiting the smallest power that I can receive, why is it that you know for in the example that we took is at 10 power minus 13 watts what is so holly about 10 power minus 13 watts.

Student: (Refer Time: 30:04)

(Refer Slide Time: 30:13)



So, the issues at as an engineer we have to worry about are basically noise and this limits the smallest signal that we can discern alright and where is this noise coming from? There is some noise which is coming from the antenna, there is nothing you can do about it right, but you know where else is all these other noise coming from?

Student: (Refer Time: 30:52).

Right, I mean remember that I mean if you have taken an analogue IC or an RF class you know already that transistor right does a great job of amplifying the input signal, but in that process also adds noise of its own right. So, the output not only consists of.

Student: (Refer Time: 31:16)

Basically, the amplified desired signal, but also noise.

Student: Noise

So, it is basically like a rumour you know right. If your you know for sure from you know prior experience that you know if you hear something that you know a friend told you and I mean then we ask him you know how did you know he says no my friend told me and then you know his friend is heard from you know 3 other friends in cascade.

You know that each time you know and the next time you tell the story what is going to be, you will tell that within quotes truth plus add some masala right ok and therefore, you know what the next person hears basically I mean it is pretty much like our like our press ok, what you read in the newspaper all that you know you can probably say without making an error you say something happened to someone somewhere right.

What really happened unless you are there you do not know right ok and probably you do not know even when you are there ok alright, but, so, basically you know any anytime somebody amplifies something you know this is always not. So, we have a very conscientious you know journalist or a very conscientious person then you know all that you can hope is that the noise added is as small as possible right ok.

So, this is basically when we say noise what we are worried about is we are worried about circuit noise right, if you amplify a lot, but add a lot of noise ok I mean it does not help ok,

if you amplify very little, but you know do not add noise that does not help either. So, we can see that you know there must be some switch part somewhere ok.

So, all that this is saying is that you know we need to study noise and circuits at you know a sufficiently deep level to be able to understand what it does to signals, how do I calculate noise right in a circuit ok and then you tell the communication designer and then so, as far as the communication designer is concerned this whole thing is a black box actually it is a green box, but does not matter right.

So, you know in your communication those if you have taken advanced electronics and communication, you say you know there is what is this IID channel with you know output which is you know  $N(0, \sigma^2)$  you know the output noise is  $N(0, \sigma^2)$  right AWGN right. You know what all that those guys are saying is that oh well I do not know right you are putting in some channel you know some information what is coming out is information plus noise right.

I we really do not really care about what you guys do in the radio right as far as I am concerned the box behaves like this right ok and then you know you do all the stuff of you know you know how much SNR I need to get this filter away and all that stuff right and what we are doing a circuit designer is basically worrying about what goes inside the box alright.

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\* Amplification

\* Filtering

\* Noise (Limits the smallest signal that we can discern)  
↳ Circuit noise and methods of calculating noise

\* Nonlinearity → Next nonlinearity

\* Filtering \* Linear Time Varying circuits and systems

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21

So, on the lower end of the spectrum therefore, we for very small signals you know what limits performance is noise. So, we need to study noise carefully right. So, we need to study circuit noise and circuit noise and methods of calculating noise alright.

The next thing that we would be worried about is remember that the desired signal is also accompanied by signals that are very very large right. So, if the signals become too large what can potentially happen in amplifiers or any electronic system or any system for that matter if signals become too large.

Student: Saturation.

Saturation which is an example of you know is it a linear effect or a non-linear effect.

Student: Non-linear effect.

It is a non-linear effect right. So, on the low end we need to worry about noise, on the, when the signals become too large then you need to worry about saturation or nonlinearity. And remember as engineers you know this already right it is not that you know the system goes suddenly from being linear to something which saturates right everything happens.

I mean it is not like you remain a youth you know all the way until you are 70 and suddenly you pop off. Right, that does not happen correct. What happens, you know well you know first you start you know first you develop a part belly then you develop a bald head then you know then you cannot walk then you know this thing that thing then you are gone right ok. So, like that it is not that suddenly the amplifier is all so linear for signals which are the small and then once the signal becomes beyond a certain range, suddenly it becomes starts to saturate, you know most nonlinearities is in real life.

And what are called you know there is a progression right, when the signals are very small the nonlinearities you know is so small that it can be ignored right, when the signal start to become larger and larger well you know the effect of nonlinearity is still small, but it is not small enough that it can be ignored right. So, this is you know. So, therefore, we will study we need to study what we call weak nonlinearity. Ok of course, if the signal becomes too strong then you know there is clipping and you know that is nasty and we most likely want to make sure that we never operate in those regions right.

So, this is basically so, we not only this is the region between signals which are so small that we do not have to worry about nonlinearity at all versus signals that are so large that cause that cause clip right. So, this is the regime which is practically I am which basically is the one in which we operate most of the time right where nonlinearity cannot be is not small enough to be ignored and not large enough to be catastrophic alright.

So, you know as you know as circuit designers, we need to basically what you call equip parcels with tools that allow us to understand noise and to understand nonlinearity. Well, the next thing that I would like to draw your attention to is we also need to understand the process of filtering right, because remember we cannot simply take the small signal and stick it into an amplifier and hope that oh well, all will be well. You are going to call saturation.

So, before you go into a high gain amplifier you want to make sure that you have removed as much of the interferer as possible right and again you know if you are doing a communication class we just say basically there could have a brick wall filter and say right well you know I put the ideal low pass filter and I removes all the stuff that I do not want in the sense the stuff that is that is desired and you know as engineers you know that well this ideal situation does not exist right there is no brick wall filter ok.

You have to you have to live with, all that you can say is well the filter that you know is practical, we will have a high gain for signals that are needed and a not so high gain for signals that you do not want right. So, there is you know and you know it also stands to reason that if you want to have, if you want to reject signals that you do not want by a larger amount it will be sounds reasonable that you need to do more work right, becomes the filters become more complicated. So, what we are going to do therefore, we also need to understand this whole process of filtering right.

The topics that we are going to study in this course not necessarily in this order, but these are the topics that we will study and I hope we are now convinced about the reasons why we need to study these topics right. And typically, in the past what we would do is you know some of these topics you would kind of learn you know along the job right, you did you know, if you those of you who have taken analogue IC design, you know you would kind of learn noise you know there at some level.

A nonlinearity is something that we usually I have no time to talk about and likewise with filtering and of course, time varying circuits and systems is something that is never touched upon right, simply because there is no time to talk about all these things in courses dedicated to you know to other subjects. So, the idea behind this course is to basically give you an introduction to the tool set needed to become you know a competent you know analogue mix signal IC design right ok.

And so, in that sense unlike in other analogue classes where there is a clean flow from topic to topic, here you might at sometimes wonder you know oh this guy was talking about noise today, suddenly he is talking about nonlinearity right the I mean you know that is how this course is going to be. So, you can think of it as somewhat separate topics, but all these topics are needed, you know, they come together when you make a system that is, you know, real world practical system does not make sense ok.