Analog Electronic Circuits
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Lecture – 22
Two stage diff. Amps, op-amps

Welcome back to Analog Electronic Circuits, today's lecture number 22 and today we are going to talk about Two stage differential amplifiers and then we have going to move towards the structure of op-amps and we are going to start talking about op-amps and how to work with op-amps. So this is the plan of the lecture, let us see how far we can go before we start I think I am going to continue from where we left off in the last class.

In the last class we were talking about the folded cascode amp differential amplifier and we had worked out this mess, which if you look carefully is not very messy at all it is actually very nice right.

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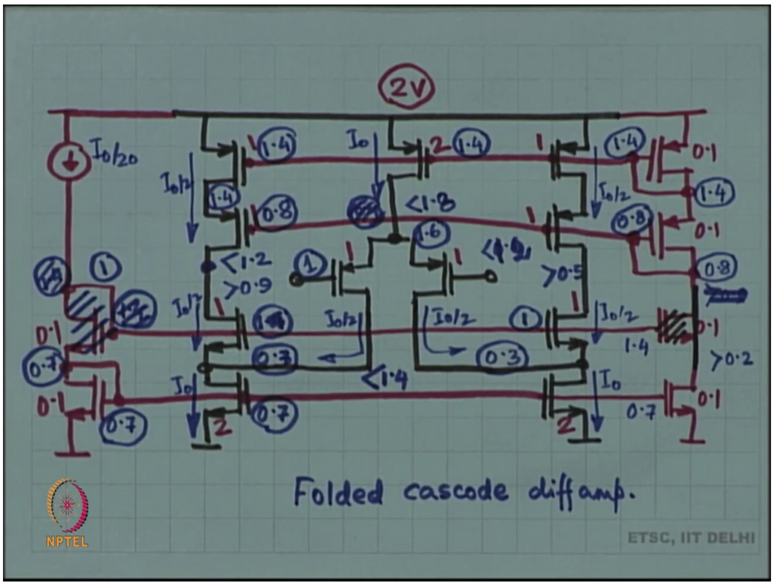

You have got so many transistors and we started from 1 transistor we have come fairly long way and I am very excited about this, because we started from 1 now we are at you know something like 20 transistors right we are we are able to comprehend and one of the important things in our being able to comprehend out of this, there are two things.

One is symmetry right this side is the same as the other side symmetry, that makes things easier and the other are these current mirrors ok. The current mirrors are really playing a very important role over here, they are setting the currents in all the different branches of the circuit so you cannot underestimate the power of these current mirrors so we spent a little time on current mirrors sometime back you know and ever since it has been a right after looking at current mirrors I am biasing only with the help of current mirrors, you know a mirroring this is the mirror of a mirror right you start with the mirror then you mirror it over here and then you said the currents here as well as here right.

You start with the mirror and then you said the currents over here right, so everything is based out of these current mirrors and it is it is actually very nice and you start with 1 transistor 1 transistor circuit and suddenly now you have built up this mesh of transistors right and if I had thrown the circuit at you know even 15 lectures back or 10 lectures back you would have immediately run away from this course right, because this looks like are big mess I through this at you 15, 10 lectures back earlier and you would be you know totally taken out I mean you would you would have run away from this course this course you would have given up immediately.

But now after all these current mirrors right this looks pretty straight forward right I naught by 20, it is going to mirror over here right that is going to mirror I naught by 2 on this side, I naught by 2 on this side, it is going to mirror I naught and I naught through these 2 devices I naught through I naught through this I naught by I naught by 2, I naught by 2 they are going to nicely add up no there is some structure inside this.

So I am very excited about this I do not know how excited you are, but I feel very excited that we have come quite a long way from 1 device to 20 devices I do not know what the count of devices here is, but and it is comprehensible it is not you know totally out of context. I have not just placed these 20 transistors randomly each transistor over here is playing a role it setting some either setting some operating point voltage or it is doing some mirroring action or it is a tail current source or it is some active load ok.

Lot of lot of different responsibilities for each of these devices now there was one little thing that we you know skipped out of in the last class because of shortage of time right and that was we wanted we needed the voltage over here to be 1 volt if I had used a regular Wilson approach then I would get 0.7 and 1.4 over here and 1.4 was a little too much because with 1.4 I was unable to do justice with this device you know I was getting exactly the same as the telescopic cascode amplifier right. Exactly the same swings as with the telescopic cascode and that was really not very nice, I want to set this to 1 volt or lower is better right can I set it you know maybe even not to 1 volt can I set it to 0.9, 0.9 is acceptable 0.9 would be optimal right.

So, can I do that and I think what you have to recollect over here so I am just reminding you once again.

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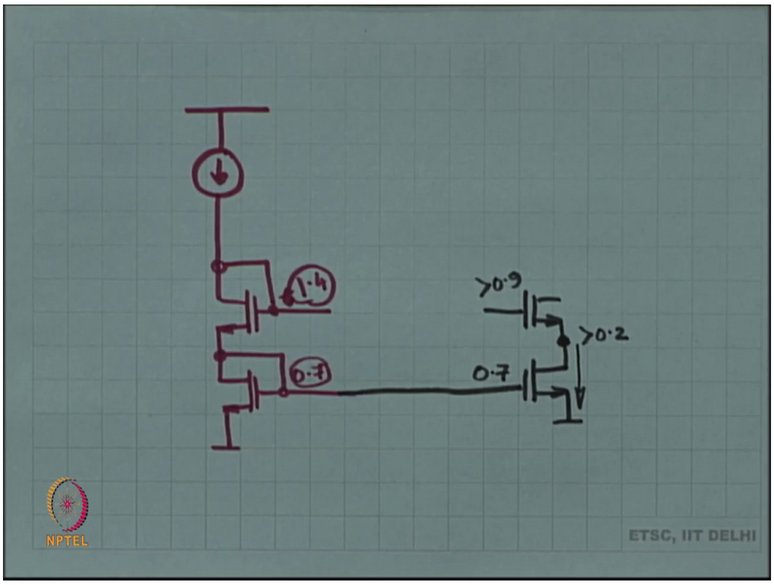

So, I am just drawing this branch all right just this portion. If I do the regular Wilson, this is the regular Wilson I was getting 0.5 plus 0.2 so 0.7 over here and 0.7 plus 0.5 plus 0.2 so 1.4 over here and that was too much ok. We need to change the structure any voltage over here within some bounds is all right what are those bounds?

What are those bounds, can I have; so here it is one point I mean in this structure 1.4 is absolute, but let us say I am copying this if this is 0.7 you do not have a choice in the matter this has to be 0.7 for it to conduct the same amount of current, but the voltage here is flexible ok. It has a lower limit of 0.2 which means the voltage at this gate can be anything above 0.9. So it does not have to be this is 1.4 volts can I pick you know like 1 volt over here is it possible and the answer is yes it is possible to do that right you do not have to employee the structure, you can employee any anything else for example.

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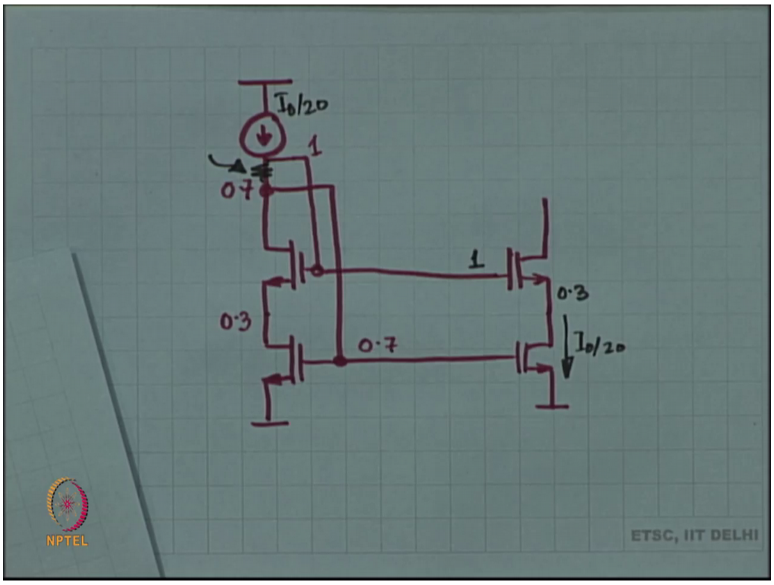

This is an alternate instead of a Wilson current mirror you can do something like, that you could have done something like this, what will happen this is at 0.7 you are forcing a current through it so this is 0.7 ok. And then this is something more than 0.7 let us keep it at 1 volt, so let us make sure that this resistor is such that the voltage here is at 1 volt then this we will automatically drop to 0.3 is that ok, so this will be at 1 volt automatically this is at 0.3 which is nice this is at 0.7 now you copy it.

So, all you have to do is choose a value of resistor over here such that the drop across that registered for the given amount of current I naught by 20 let us says is the current ok. So you choose the value of this resistor such that the drop across the resistor is 0.3 ok, in which case the voltage here will be 1 right, this is becomes 0.3 ok. So it is just a matter of choosing a resistor and now this is also an accurate correct mirror because this is 0.3 this is 1 volt right 0.7 so this tries I naught the same amount of current I naught by 20 it tries to pull I naught by 20 this is develops a voltage drop of 0.7 v gs so this becomes 0.3 which means this is 0.3, 0.7, 0, 0.3, 0.7, 0.

So, this is exactly equal to I naught by 20 as long as the mirror ratio is 1 is to 1 ok. So this is also a true replica of the current and this is also this is very nice in fact, this is a very nice current mirror then this is one strategy another strategy would be what we did some time back in class, so this was another strategy that we had studied.

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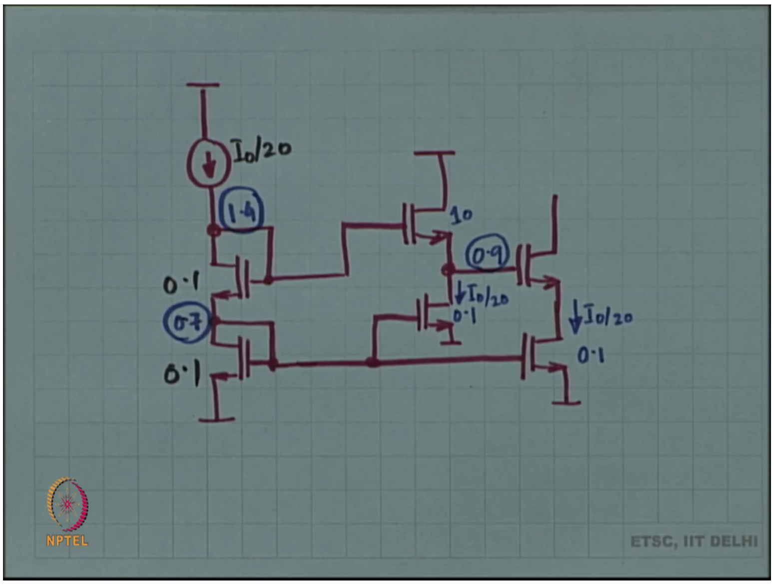

By the way these 0.5, 0.2 these are just numbers that I have picked up from my head in reality it would not be 0.5 and 0.2, in reality you will need v gs minus v t may be of 250 millivolts, 150 millivolts something v t could be 0.5 v t could be 0.4 it could be 0.3 it could be 1 volt whatever it is right.

So, accordingly you figure out what these numbers are so do not blame me for the numbers all right that I am just letting you know in advance. The numbers I have picked a reasonable they are realistic however, they are not the absolute ones. So second strategy that we have discussed in class was to allow this to be exactly the same as before like the Wilson, but then we will create a voltage drop over here with the help ofone more device, what are you going to do, so for example, if this is I naught by 20 all right 0.1 size of 0.1 right. So this is at 0.7 volt this is at 1.4 volts and this is also of size 0.1 let us say so it tries to reflect I naught by 20 and I want this voltage to get 1 volt.

I start from a voltage of 1.4 I want to generate 1 volt over here suppose how will I do it all right let us try to generate 0.9 not 1 1 does not work out with this I try to generate 0.9 by dropping v t across this device. So I am going to make this device really really large, so if this is of size 0.1 if this is of size 0.1 this is also trying to take I naught by 20 current I make this device instead of size of 0.1 I make it a size of 10. So 100 times larger so w by l is 100 times larger that automatically means v gs minus v t is going to be 10 times smaller. So I started from 200 millivolts 10 time smaller is 20 millivolts it is no longer in strong inversion which means it is you know in moderate inversion it is a tiny amount of v gs minus v t that is requires almost nothing effectively the drop across v gs is going to be just v t.

So I started with a v t of 0.5 this means this is at 0.9 v t lower all right so this is also one strategy and this actually gets you 2.9, just write there all right. This one was very nice, but you have to depend on a resistor resistors are you know they change their value with temperature all kinds of funny things happen you might not get exactly the right value that you want. On an integrated circuit here there are no resistors this is just plain transistors you are just making one device much much larger than all the others and taking advantage of the situation ok. So there are multiple tricks to create this voltage.

Now, you create this voltage and applied everywhere fine ok. So this is the sum this was some leftover stuff from the last class and now what we are going to do is we are going to say that all right. Now we know how to make differential amplifiers and the ordinary differential amplifier will have again a voltage gain of let us say the intrinsic gain of the MOSFET 1 stage. The cascode amplifier will probably have more gain then that because it is output impedance is intrinsic gain times the ordinary output impedance ok, so the effective gain of the cascode amplifier will be intrinsic gain squared fine ok.

So, if I start with an intrinsic gain of 40 then maybe the cascode amplifier will have a gain of 1600 whereas, the single stage differential amplifier will have a gain of 40, 1600 is not bad for an op-amap. So a cascode differential amplifier could work as an op-amps right straight away, so this mega circuit might be able to work as an op-amp might from the gain point of view from the voltage gain point of view ok. If you do not like the cascode some people do not like the cascode differential amplifier then you can make a 2 stage differential amplifier you do 2 stages 1 stage followed by yet another stage right and that will give you enough gain to reach there.

So, it is a similar strategy or I am not really going to draw it; however, I want to oh you want me to write up ok.

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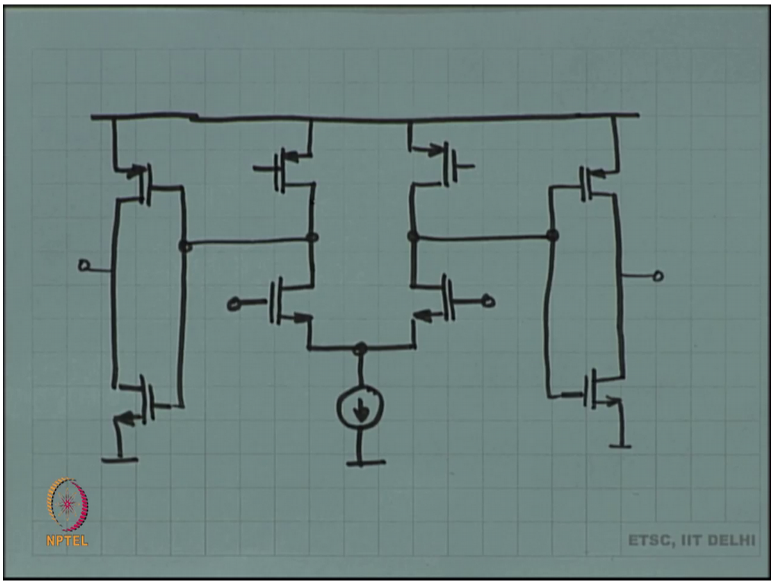

So each stage go to a place here current source or MOSFET, let us put a current source with the intention of this being a MOSFET ok. So this is my one stage the voltage over here has to be set by some current mirror which is going to mirror now you have figured that out right. I hope you a figured that much out that there was going to be a reference current and the reference current is going to be mirrored to make this current then that another there is going to be another mirror over here that is going to mirror it back and set this voltage ok, so by now I hope you have figured the strategy, figured out the strategy ok.

Now, we are not going to stop at one stage we are we need one more stage of gain, so we are going to take these 2 outputs and apply them to a second stage. Now second stage could have an NMOS input, it could have a PMOS input. Let us you know assume then it has a PMOS input in which case oh what is it, your saying where is the tail current source ok. So you could have had a tail current source over here, but you need not also you have already got common mode rejection right, your signal to interferer ratio at the output of the first stage is much lower than the signal to interferer ratio of the input of the first stage already you have already got that benefit right.

Here in the second stage I just forget about the interfere whatever I have I just amplified both signal and interferer ok, possible. If you do not like it you place a current source on top right, some people are happy with this ok. So then again you have to work out what is the voltage over here, you can work it out with the help of the same current mirror will work for example, one more strategy is that I am applying input to PMOS who said I should apply input to PMOS I should probably apply input the NMOS and leave the PMOS as the load right one possibility is there. Another possibility is that you could apply PMOS to input to the PMOS as well as the NMOS why not apply to both and that will give you both of the gms.

So, you will get g m of this as well as g m of the second one right, we will get the sum of the gm of these two you not clear yes this looks like the CMOS inverter right, the digital inverter ok. Do not like it take this is the digital circuit the CMOS inverter is an analog circuit this is your CMOS inverter ok.

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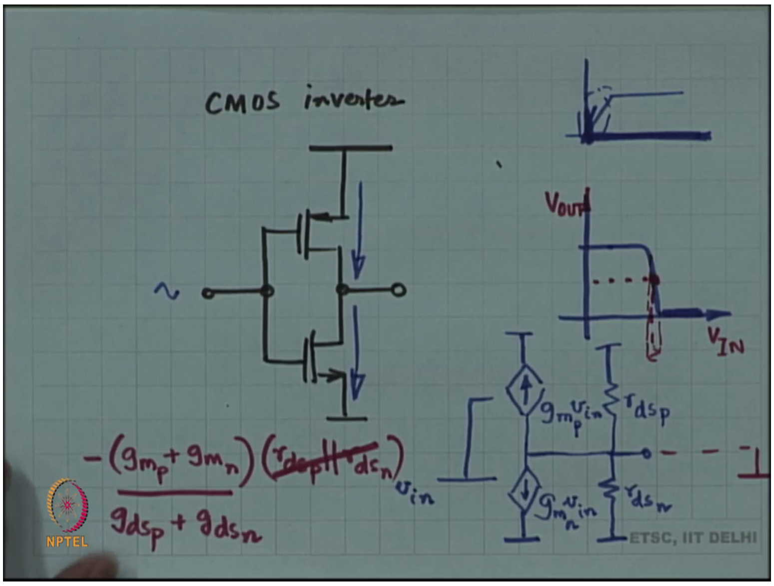

The idea is that if the voltage at the input is high then the NMOS is on, the PMOS is off and that pulls down the voltage at the output. So if the voltage at the input is high then the voltage at the input is connected to output is connected to ground. If the voltage at the input is low then the PMOS is on, the NMOS is off which means the output is connected to v dd supply voltage.

Ok, but all of this is assuming that these 2 MOSFETs are working in the triode region that is not in the flat region of the characteristics these 2 MOSFETs are either on or off there in the other region of their characteristics right. You are assuming that your operating condition is over here v ds is very small or it is very large right when it is very large I is 0 v gs is low. So in one case v gs is 0 v ds is high so you are on this x axis, in the other case you have got v ds is 0 so the MOSFET is on which means you are on at this region you are in the triode region so your operating the MOSFET as a switch all right.

So, that is the action in the CMOS inverter; however, who asked you to operate it as a switch why are you applying input as 1 input as 0 right, let us apply input as a small signal around DC operating point. So let us assume that both of the devices are in saturation are in there flat regions at the same time, so the same current will flow through both I can work out in that case the DC operating point required at the gate. So for specific value of the gate voltage this current is going to be equal to that current k into v gs minus v t the whole squared of the bottom one will be equal to k into v sg minus v t whole squared of the top one ok. And therefore, both of them will be in the flat region for that particular gate input and at that gate input let us apply a small signal riding on top of that value.

So, for example, your inverter characteristics look like this when the input voltage is low the output is high, when the input voltage is high the output is low in between you have some curve right. Let us apply exactly this voltage at the input let us apply exactly that voltage and then we will apply a small sinusoidal wave on top. The small signal writing on top of that input, so when I have exactly that input my output is in the middle right and then I apply or small sin wave I get a large sin wave at the output, because of the high slope ok. So I can use the inverter the CMOS inverter as an analog amplifier ok. What is the small signal equivalent of this? So you have got MOSFET NMOS so you have so you are input is small v in I am drawing the NMOS this is gm v in r ds g m n v in r ds n from the output to ground.

And then let us draw the PMOS also, what is the PMOS doing? For the PMOS this is the drain that is the source so it is going to be exactly the same and v in is exactly the same in this node is at ground in the small signal all right. So effectively you have got g m of the NMOS plus g m of the PMOS times v in that is going to be your short circuit transconductance. So if I a put a short circuit over here short circuit experiment the transconductance will be g m of v in g m n times v in plus gmp times v in. So g m n plus g m p times v in is the transconductance short circuit output impedance v in is 0.

So, this is gone the other one is gone, so the output impedance is nothing but r ds of p in parallel with r ds of n and therefore, the voltage gain of this circuit is nothing but minus g m p plus g m n times r ds of p in parallel with r ds of n ok. That is going to be the voltage gain or in other words you could write this as g dsp plus g dsn fine is this ok. So if you had just one if you were amplifying just with the NMOS and this gate was connected to ground then you would have got g m n as the transconductance and the output impedance would be the same r dsp in parallel with r dsn.

Now, you have got transconductance of g m p plus g m n ok, so you have got a benefit. In fact, so you get even closer to the actual intrinsic gain of the MOSFET ok, so this is not a bad design this design is not bad not bad at all that I just speak an inverter as the second stage a CMOS inverter you can do a pretty good job sometimes all right. So this could be a 2 stage amplifier first stage, second stage, second stage does not have any common mode rejection the carrier the sorry the signal to interferer ratio at the input of the second stage is the same as the signal to interferer ratio at the output of the second stage.

However the signal to interference ratio at the input at the output of the first stage is much smaller than the signal to interferer ratio at the input of the first stage because of this tail current source right, which creates common mode rejection. How does this tail current source create common mode rejection the common mode half circuit becomes something else, the differential mode half circuit becomes the common source amplifier whereas, the common mode half circuit becomes a source degenerated common source amplifier and therefore, the common mode gain is much lower than the differential mode gain and it gives me common mode rejection.

We have talked about all of this before I am just repeating myself so that you get it ok. So I am repeating all right this is the 2 stage amplifier and this 2 stage amplifier it is far simpler than far simpler then this for example, right. Still has it has a lot of transistors right you have got 8 plus 1 9 transistors over here right and then I have not drawn the bias network you will need some biasing right you will need 1 you need a reference current source plus a mirror right and then 1 more mirror right another 2 transistors to do the PMOS and then a times you might want a cascode mirror and so on and so forth to get more accurate values ok, so this is the 2 stage amplifier.

Now, I want to ask you something whether I make a single stage amplifier or a 2 stage amplifier or a cascode amplifier right it is either this or this right whatever it is the output impedance of this amplifier is it large or is it small, you see our entire strategy from day 1 in this course not maybe not from day 1 from day 2 or day 3 in this course has been to adopt the not an equivalent method and what does that mean; that means, that we are only talking about current sources ok. So we are really playing with current sources; that means, naturally our impedances are large our source impedances are large that is why we like not in for example, the flat region of the MOSFET the output impedance is large, that is why we like the flat region of the MOSFET.

So, automatically; that means that when I am trying to make a high gain amplifier my strategy is to keep transconductance the same. So when I went from single stage to cascode I kept the transconductance the same g m remained more or less right the output impedance jacked up because of cascode ok. So the output impedance of the cascode amplifier is very large the output impedance of this amplifier which is not cascode is also large if it had not been large I would have not got good gain right. My gain is the transconductance stands the output impedance, so naturally I want large output impedance ok. So what does that mean; that means that the output impedance of my amplifier is going to be large ok.

So, if I use either of these amplifiers whether I use the cascode amplifier or the 2 stage amplifier whatever I use, the output impedance of this circuit is going to be fairly large ok. That naturally means that if I am going to think of this as the building block in a larger scheme of things, so this I want to imagine this as a building block right I want to encapsulate this in one now symbol like a triangle and think of this as the building block in a very large scheme of things, much larger scheme of things.

Then that building block is like a voltage source or a current source? It is like a current source, because it has large output impedance ok. So I want to make an op-amp and what is the property of an op-amp, do you know if it has large output impedance or small output impedance? Small right because the op-amp you think it is going to work like a voltage source yes.

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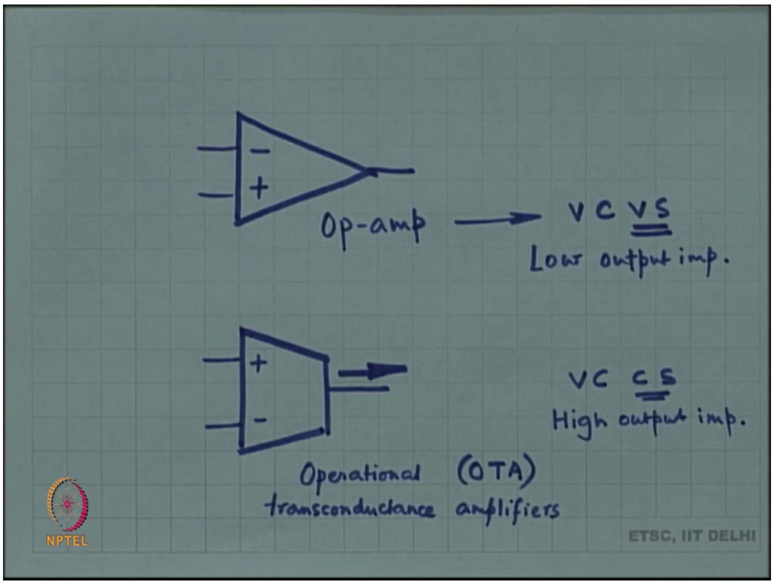

You think the op-amp is going to work like a voltage source right voltage controlled source it is going to amplify the difference between plus and minus by very large number and give you corresponding voltage at the output. So this is ordinarily what we think of as the op-amp, but does it matter if it is a voltage source or a current source.

Well to some it matters and what we do is instead of so this is called the op-amp. So the op-amp is technically voltage source which means that it should have low output impedance not high right the ones that we have designed and not a op-amps. Why because the ones that we have designed have very high output impedance all right, so the ones that we have designed we call them operational transconductance amplifiers and the property of the operational transconductance amplifier in short this is called OTA, the property of the OTA is that it has high output impedance.

So, it is a voltage controlled current source ok. So it amplifies the difference between plus and minus and then puts out a correct, that is what we have made that is actually what you have made we have made over here right not this all right. We have made an operational transconductance amplifier for example, if we shot this then it is going to push g m times the difference between the 2 inputs; however, if we leave it open then it is going to try to push the current, but it will end up making a voltage ok. If we do not allow it to push the current it is going to try to push the current right, but instead of pushing it through the output node it is going to push it through it is own output impedance and it will create a large voltage.

So, it will end up producing a large voltage right, so it will have a high voltage gain if the output is left open, but if the output is not left open if you connect the load to the output then it is going to push that current through the load and create whatever voltage it creates all right. So this is what we have made if we wanted to make an op-amp what needs to be done you have to buffer this up right.

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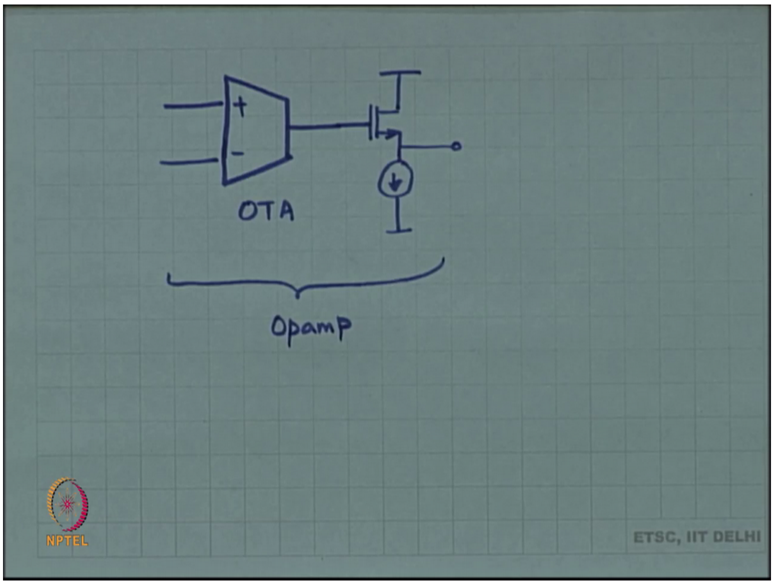

So, you take this OTA which is what we have made and then if you wanted to make an op-amp then we need to have a buffer stage which has a low output impedance. What is a buffer stage? Something like a common drain amplifier, where is this common drain amplifier coming from.

It is a source follower it does not take any current, the gate is not taking any current ok, so no current is going in. So this is voltage is going to be very high because it is though OTA is trying to push a current it cannot push a current it pushes the current through it is internal output impedance, so you get g m of the OTA times the output impedance of the OTA, which is the large voltage gain of the OTA right. And then there is a buffer this common drain stage has a voltage gain of approximately 1 it is actually less than 1 in this case right and therefore, you get a large voltage gain and the output impedance of the common gate stage is low or high, it is low. So a common so and OTA that we have made if I follow it up with a common drain stage then I manage to make an op-amp.

So, thing is an op-amp if I do not then it is not an op-amp it remains an OTA all right. So let us keep this understanding in the background, so there is a certain difference between a real op-amp and what we have made. So far what we have made is this, if you actually want to make an op-amp then you have to follow it up with a common drain stage buffer right to give the low output impedance that an op-amp desorbs. Otherwise the OTA has very high voltage gain, but that is not enough ok, all right. Now let us let us just think it through a little bit, so you have a favorite op-amp circuit you have done some op-amps in the past I presume.

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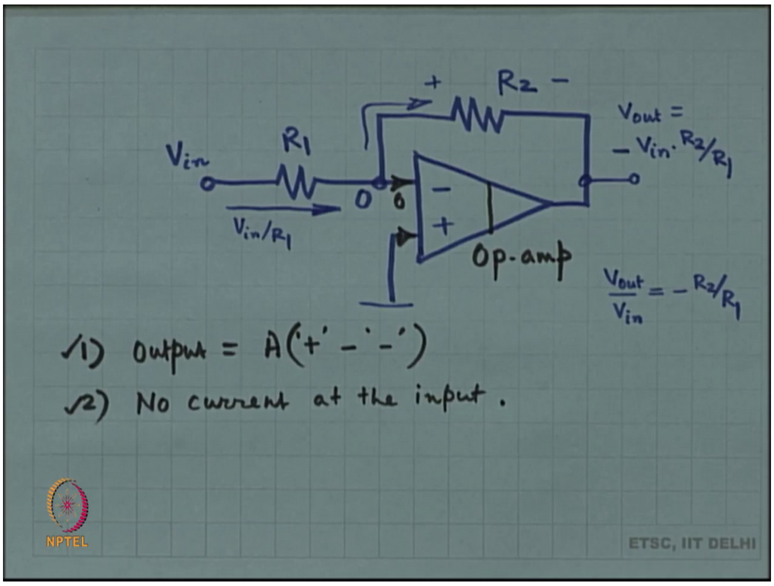

You have done this circuit, you have done this circuit some of you seem to have done this circuit, many of you have not done this circuit all right. So we will do this circuit as a recap, so this triangle is the op-amp this triangle with the plus and minus sins this op-amp contains a very high gain amplifier, voltage controlled voltage source insight, such that the output voltage is that very high gain times the difference this difference plus minus at the inputs of the op-amp ok. So the op-amp has 2 properties, number 1 the output is equal to some high gain times the plus voltage minus the minus voltage at the inputs.

The difference of the 2 inputs times a large gain is the output and this gain is of the order of 1000, 10000 some large number ok. It has to be large for it to be an op-amp this is number 1 and number 2 is that the inputs do not take any current ok, the absolutely do not take any current which is something that we have already insured by making sure that the input is at the gates of the MOSFETs right, the gates do not take any current. So always you will see that the inputs are at the gates of the MOSFETs and therefore, they do not take any current at all.

So, we have already make sure made sure that these currents are 0 this is already taken care of. We have also taken care of the fact that when we have designed or op-amp the output voltage here there is only 1 output voltage that output voltage is some large number times the difference of the 2 inputs and how large we I mean depends on the intrinsic gain of the MOSFET, MOSFET has an intrinsic gain of let us say 100 then a 2 stage op-amp will give you 10000 for example, and that is fairly large for an op-amp ok. Now the only thing that we have not taken care of is the VCVS action.

So, this is what we have made so far is an operational transconductance amplifier which looks like this pentagon right. So this is what we have made so far and that if I follow it up with a buffer circuit that is a common drain circuit I end up making an op-amp and that op-amp will have will behave like a voltage controlled voltage source ok. So far so good how does this circuit work? Now you can make think of the circuit as working in the following fashion the output is limited in range the output of the op-amp cannot be unlimited right this a times difference of the 2 inputs this is valid only within the swing limits of the output for example, ok.

So, let us say the swing limits of the output you have made a very good op-amp the swing limits of the output are ground and power supply cannot be more than that ok. So within ground and power supply you have you know this situation, so your output is naturally within those 2 rails and therefore, the input differential voltage has to be A times smaller than the output which automatically means that the input differential voltage is very very small. For example, if the output voltage is 1 volt gain of the op-amp is 10000 then the input differential voltage is 10000 times smaller than 1 volt which is 100 microvolts all right.

So that means, that this input over here is minus 100 micro volts let us assume minus 100 micro volts a engineering approximation let us assume it is 0. So the engineering approximation that you can do is you can say that these 2 inputs are equal there are almost equal right 100 micro volts a part is almost equal ok. So engineering approximation these 2 voltages are equal, if I have an input let us say V in then this current is going to be V in by R 1 this current cannot go into the MOSFET into the gate of the op-amp, so it has to go the other way in which case the drop across R 2 is V in by R 1 times R 2 and therefore, if this is 0 volts the output voltage is going to be minus V in by R 1 times R 2 or in other words V out by V in will be minus R 2 by R 1 all right and to many of you who have seen the op-amp before this happens to be your favorite op-amp circuit is it or is it not it is not.

You have got one more this is one more favorite op-amp, this is the second favorite op-amp circuit is it ok. This is happens to be your second favourite op-amp circuit this is one more op-amp circuit that happens to be your favorite in that case this is one ok.

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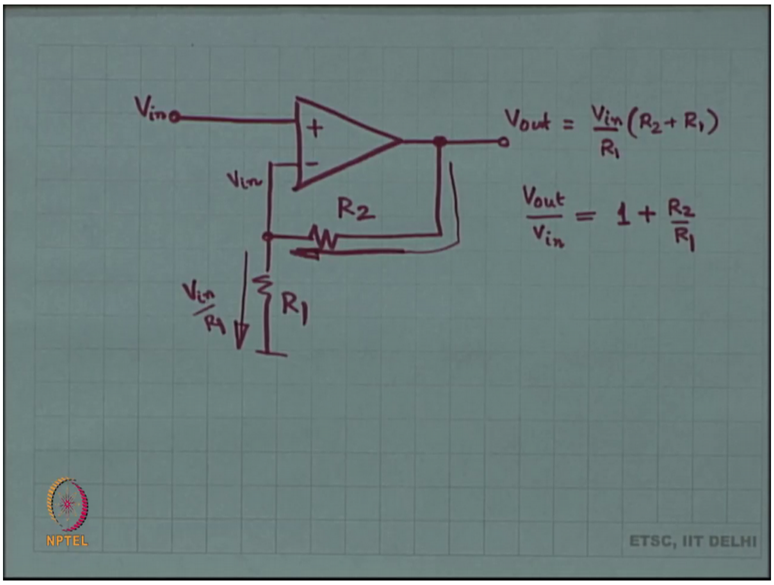

So this is your favorite op-amp circuit for those who have not seen the circuit once again let us do the same argument I have got a reasonable amount of V out which means that if the op-amp gain is very high then the input differential voltage is nothing which means that if this is V in the voltage here is also engineering approximation is also V in. That means, that this current is V in by R 1 if this current is V in by R 1 and the current in the minus terminal is 0 then that means, all of that current is coming through R 2 V in by R 1 current is coming through R 2 ok. So V in by R 1 is coming all the way from V out through a resistive network of R 2 and R 1 ok. So V out is nothing, but V in by R 1 times R 2 plus R 1 which means that V out by V in is equal to R 1 by R 1 is 1 plus R 2 by R 1. So for example, if you pick R 2 equal to 10 9 kilo ohms R 1 equal to 1 kilo ohms then you will get a gain of 1 plus 9 k by 1 k so 10 V out by V in we will come out to be 10.

So these are all very nice circuits right these are very popular circuits this is you know your favorite op-amp circuit there is a reason why these are so popular. The reason is that the voltage gain comes out to be a ratio of resistors related to a ratio of resistors and these resistors can be picked to be matched to each other, so that the ratio remains constant and as a result the gain of the whole circuit is well determined there is no flexibility there is no variability in the gain of the entire circuit. So these are all very very popular circuits, so this has a gain of 1 plus R 2 by R 1 all you have to do is pick the right values of resistors and you will get begin and then this circuit has a gain of minus R 2 by R 1. So if you pick R 2 equal to 10 k and R 1 equal to 1 k then you will get a gain of minus 10 so on and so forth.

All right now my argument so far I made one argument that if the output is reasonable then the input is 0, if the output is reasonable then the input differential is 0 which means this is V in right. This argument is a little specious it is it is filled with fallacies and we will see later on how to go around these fallacies how to give the right argument. As of now let it remain let this argument this is the poor argument that I have made I acknowledge that this argument is poor. However, let us keep it at that we will sort out that argument later on all right. Now what is going to happen if in this if in my favorite op-amp circuits the op-amp is not an op-amp, but an OTA is something bad going to happen.

So, suppose I forget to put the buffer there is an OTA and usually for an op-amp I need a buffer, suppose I do not have a buffer over there what is going to happen is it very bad, can we check, let us check ok, let us check.

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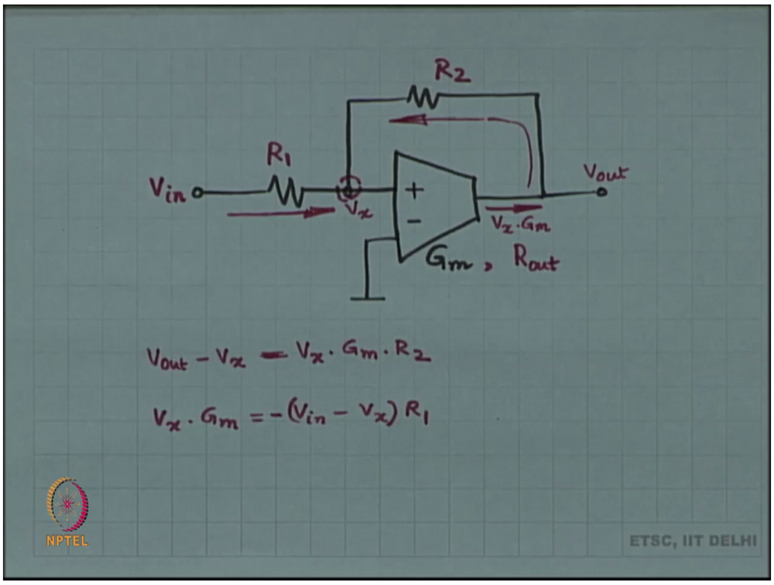

So this is an OTA and let us say the transconductance of the OTA is capital G m ok, if it is an cascode amplifier this capital G m is approximately equal to small g m. If it is single stage differential amplifier then this capital G m is equal to small g m and so on and so forth ok. So this is my circuit all right and let us say in addition to capital G m this transconductance amplifier has an output impedance of R out and the product of G m and R out is very large G m times R out is very large number of the order of let us say 10000 ok.

That is the only think that I have in hand R out is large G m is something right accordingly G m times R out happens to be let us say 10000 and I have R 1 and R 2 all right. What is going to happen? How is this circuit going to respond first of all some current is going to come this way, can this current go in, so if I have V in over here if this voltage is 0 volts suppose this is voltage is 0 volts then immediately all V in by R 1 current comes all of it goes this way and reaches the output and automatically I have the output voltage as minus R 2 by R 1 times V in ok.

So, the only thing is what is the voltage over here, if this voltage happens to be 0 if these 2 voltages happen to be equal then immediately the output voltage is going to be minus R 2 by R 1 times V in and the circuit is going to behave exactly the same way as before no difference with the ordinary op-map ok. What is this voltage? Let us say this voltage is not 0 let us say it is some V x in that case what is this current, the difference is V x. So the current is V x times G m it is trying to push that current out all right and where is that current going to go that current has to flow this way fine. So whatever my output voltage is V out minus V x is V x times G m times R 2 all right and this V this current V x times G m this current flows like this, but this has to be exactly the opposite of V in minus V x by R 1.

All right so you have got two relationships you are unknown is V out and V x these are unknowns two unknowns two equations we should be able to solve for them and work out what is V x what is V out ok. So we are going to do all of this in the next class; however, let me summarize what we did today so first we figured out leftovers from the last class some important information about how to bias the cascode amplifier, then we briefly did the 2 stage amplifier and then we transition from the 2 stage amplifier to see what is an op-amp oh by the way we briefly discussed the CMOS inverter as well ok.

And you can also use the CMOS inverter as an amplifier that is also something that we discussed today, then we transition from the 2 stage amplifier to an operational transconductance amplifier and then now you are trying to see what is the difference between an OTA and an actual op-amp all right and then we are now trying to play around with some with a few op-amp circuits right we have not really done justice to them, but we will continue with them in the next class.

Thank you.