Course name- Analog VLSI Design (108104193)
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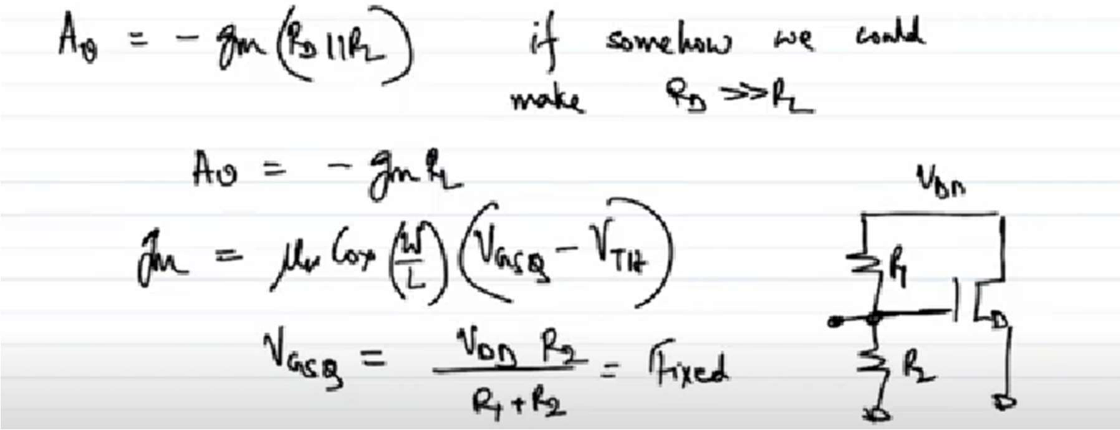
Week- 6
Lecture- 16, Module-2

Welcome back. So, up until now we have been discussing the architecture of common source amplifier and what did we see? We saw that we after lots of discussion and soul searching we came up with this architecture which was able to give us some gain. What was the value of the gain? The value of the gain is supposed to be minus gm times. So, the value of the gain is supposed to be minus gm times Rd parallel RL under ideal condition right. What is what I mean by ideal condition? What I essentially mean by that is when C1 and C2 are acting like infinite capacitors at signal frequencies when R1 parallel R2 combination is not loading your input right. If these conditions are met then the maximum gain that you can get out of this configuration is gm minus gm times Rd parallel RL ok.

So now this we saw. So what so now the issue is so the gain that I am getting out of this common source amplifier the voltage gain is minus gm times Rd parallel RL right. If we could make if somehow we could make Rd be much much greater than RL then the gain for a common source amplifier would have been minus gm times RL and that makes sense because if you look at the incremental network what we see in the incremental network the current I0 right the current I0 that was getting divided between the branch on the top in Rd and the branch on the right that current would prefer to go to the branch on the right if Rd was much much greater than RL. I am obviously assuming C2 is infinitely larger right.

So the current always tries to go towards the path of minimum resistance if Rd is much much larger than RL then the current would definitely prefer to go to the right and hence the output would have been minus gm times Vg times RL and hence the gain would have been minus gm times RL right. So this is the maximum possible gain that we could get from the common source amplifier ok. So now how does this gain relate to our quiescent point right because ultimately the incremental characteristics of an amplifier always depends on where you have bias the transistor how you have bias the transistor right ultimately it all depends on that. In this case clearly gm is the incremental parameter that depends on that depends on our quiescent point right. So what is gm? gm is mu n Cox W over L VgsQ minus threshold voltage right.

If I sketch only the input side right. So what is VgsQ? VgsQ is R1 R2 Vdd. So VgsQ is equal to Vdd times R2 by R1 plus R2 correct and this is fixed. Why do I say this is fixed? This is fixed because once you have decided the power supply you have chosen the power supply once you have biased R2 and R1 R2 and R1 then whatever you do the value of VgsQ is not going to change correct. The value of VgsQ is not going to change then clearly the VgsQ is fixed.



So I mean you might be wondering why am I harping on this? The reason I am harping on this is the following as it turns out mu n and threshold voltage are temperature dependent variables right. So what is mu n? Mu n is a mobility, mobility of the electron in the channel. In plain English, mu n essentially gives an estimate of how easily an electron is moving through, moving through, moving through the channel and clearly if you raise the temperature of the device right all the lattice structures and all the stuffs that you learn in your device physics courses will tell you that the mobility of the electron changes. Most likely the mobility of the electron goes down. Similarly the threshold voltage of the device also as it turns out is a function of temperature it also changes with temperature which means what? This essentially means that the value of gm right will change with temperature which essentially means the gain that you have obtained right the gain that you have obtained will also change with temperature right.

So this is something that we do not want because ultimately when you want to deploy an amplifier in the field right in any product and you say that I guarantee a gain of 10 right minus 10 or minus 2 or whatever you want to guarantee you should it should not be such that I guarantee you a gain of minus 10 when you make your temperature equal to 27 degree centigrade right it should not be that. It should be you should be able to guarantee the gain of minus 10 regardless of I mean not even not I mean over a range of temperature right. Let us say you take your cell phone from Kashmir to the thar desert right. So it should I mean it your amplifier should still work which means that it should work from let us say minus 20, 30 degree centigrade to almost plus 50 degree centigrade it should work. If you are designing something for automotive applications where electronics goes inside the inside the car depending on where you are putting your automotive chips the temperature can go as high as 150 degree centigrade right.

So in a sense you will have to ensure that your electronics right the devices that you are designing should be working for a wide temperature range. But clearly we see that if we design an amplifier like the way we have done this common source amplifier it seems like it has it will have a lot of temperature variable right. So A V the since mu n and threshold voltage at temperature dependent variable A V that is minus g m times R L will be changing with temperature. So this is something that will not be acceptable given to us when we buy a product right we want reliability. So what is g m? So again g m is mu n C ox W over L V g s q minus threshold voltage correct ok.

So how much does I mean let us quantify the change of g m with respect to change in mobility and threshold voltage right. So how much we g m will change? So if mobility mu n changes from mu n 0 to mu n 0 plus delta mu n right. How much g m will change? The delta g m will clearly be equal to del g m del mu n times del mu n correct. So this is this is equal to delta mu n C ox W by L V g s q minus threshold voltage correct. So this is equivalent to if I write in terms of g m this will be terms delta mu n by g m sorry delta mu n by mu n naught times g m correct.

So this will be the change in change in g m when the mobility changes by a certain amount correct and clearly this change will get reflected in your in the change in gain. Finally what will be your change in g m if the threshold voltage changes? So if so again let us write down the g m expression gm is mu n Cox W/ L Vgsq minus threshold voltage. So if threshold voltage changes from some nominal V th 0 to V th 0 plus delta V th right. What will be the change in g m? Del g m will be again to g m del V th times delta V th which will be minus mu n C ox W over L times Vth right. So why minus? Because if threshold voltage increases the g m the value of the g m decreases right some I mean negative sign essentially is testament to that.

So del g m essentially becomes if I write again in terms of g m so if I multiply with V th q minus threshold voltage so this becomes voltage by the overdrive times the original g m right ok. So one might argue one might argue that if I want to reduce if I want to reduce the effect of change of g m due to change in threshold voltage what should I do? I should bias the transistor with as high overdrive as possible right. But now we know that what are the side effects of biasing a transistor with high overdrive? The bias we already know we already saw in one of the earlier lectures that if you bias your transistor with a high overdrive then you lose on the available swing at the output right because you would also want to ensure that the voltage at the drain the quiescent voltage of the drain is not very close to the overdrive of the transistor because otherwise you will you will lose the available signal swing right. So there is a tradeoff, but if I say that if I have I mean what can I do to reduce the L g m I mean change in g m because of change in mobility seems like we cannot do anything because nu n 0 is first place is not in your control correct. So this type of biasing is called voltage biasing like whatever you did here is called voltage biasing why is it called voltage biasing? It is called voltage biasing because we were fixing, we were fixing V g s q right we were fixing V g s q we were fixing the overdrive right.

$$g_m = \mu_n C_{ox} \frac{W}{L} (V_{GSQ} - V_{TH})$$

If $V_{TH} \rightarrow V_{TH0}$ to $V_{TH0} + \Delta V_{TH}$

$$\Delta g_m = \frac{\partial g_m}{\partial V_{TH}} \times \Delta V_{TH} = -\mu_n C_{ox} \frac{W}{L} \Delta V_{TH}$$

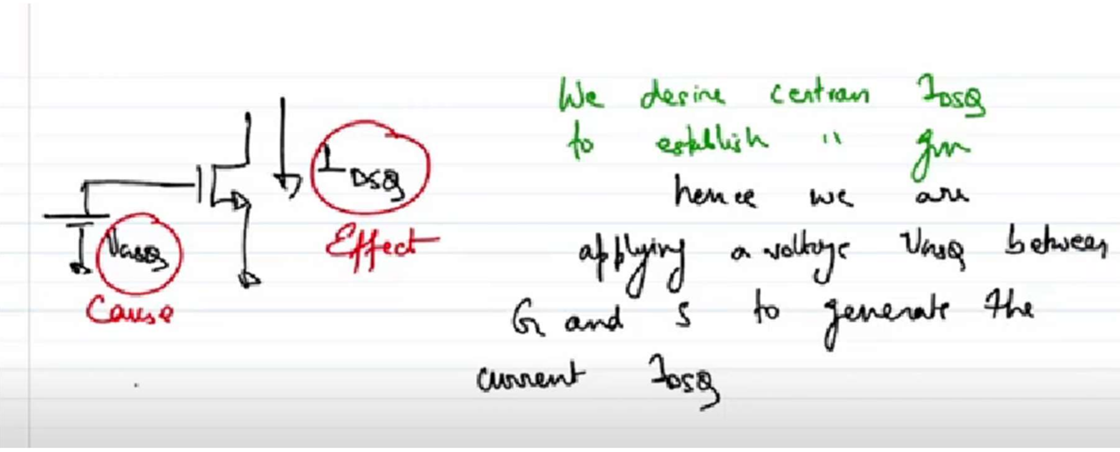
$$\Rightarrow \Delta g_m = -\frac{\Delta V_{TH}}{V_{GSQ} - V_{TH}} g_m$$

So this fixing the overdrive is often referred to as voltage biased transistors ok. So I mean as you clearly can see if you voltage bias a transistor there seems to be a seems to be an issue with the variability right. So but I mean let us look at it from another perspective. So why are we trying to fix the overdrive? Ultimately what decides the I mean why do we need to fix the overdrive right. So if I fix this overdrive using some V g s q what is the purpose? The purpose is I am trying to get some I d s q right.

So this is this is the cause and this is the effect right. So and another way of saying is that this is this is the desired we desire certain I d s q to establish certain g m to get certain amount of gain. This hence we are applying a voltage V g s q between gate and source to generate the current IdsQ right. We want IdsQ that is why we are tweaking V g s q right. If we did not want then we did not have to tweak it at all.

So now let me tell you that what if I give you a current source? How we make a current source is a different question right. But let us assume I give you a current source we have been using voltage sources right until now. But let us assume I give you a current source right. So let us say somehow I have given you a current source right and somehow I have ensured right. So let us say somehow we and so let us say assume somehow right.

Assume somehow we have ensured fixed current through M1 right. So I am saying that I have not shown you how but let us assume that the current IdsQ is fixed. When I say IdsQ fixed is, fixed what I mean is that IdsQ will not change even if temperature changes anything happens to the rest of the universe it does not matter IdsQ will not change right. So which means that IdsQ is fixed. In the note that this is different from the previous way of biasing a previous example that we took there V g s q was fixed or the overdrive was fixed.



In this case we are making IdsQ fixed right. So let us assume that we have made IdsQ fixed we haven't really I haven't really told you how we have fixed IdsQ right. So if we make this assumption let us see what are the side effects of this right. So if IdsQ is fixed what is the value of gm. So again you might say if I tell me that a by gm is mu n Cox W/L VgsQ minus threshold voltage I mean it is always true yes it is always true but this expression does not capture that your IdsQ is fixed correct.

So in order to capture that effect of IdsQ right fixed IdsQ right. So what I will do is I will use the other expression of gm which has IdsQ inbuilt right. So what was the other expression this is that was 2 mu n Cox W/L IdsQ ok. And now let us see what happens if IdsQ got fixed. If IdsQ got fixed now tell me what is going to happen if special voltage of this transistor change right.

So if IdsQ is fixed and special voltage changes by delta V th what will happen to gm?

Clearly you see that change of g m will be 0 because g m does not depend on special voltage anymore right. So delta g m will be equal to 0 right. What will happen if mobility changes right if mu n changes by delta mu n what will be the effect? So again delta g m is dou g m dou mu n times delta mu n which is what my expression for g m is 2 mu n c ox w over l IdsQ under root which means this becomes 1 over 2 under root mu n times under root 2 c ox w over l IdsQ right which means if I incorporate that mu n terms what would I get? Times delta mu n right. So what would I get? So essentially I have to multiply with this multiply with mu n here and divide by under root mu n here. So what do I get? I get delta mu n by 2 mu n times gm right.

$$\Delta g_m = \frac{\partial g_m}{\partial \mu_n}\Delta\mu_n = \frac{1}{2\sqrt{\mu_n}} \times \sqrt{2 C_{ox}\frac{W}{L} I_{DSQ}}\;\Delta\mu_n$$

$$= \frac{\Delta\mu_n}{2\mu_n}\, g_m$$

So note that this is better than the previous case where we did voltage biasing in case of voltage biasing what was it? In the case of voltage biasing it was delta mu n by mu n times g m in this case it will be delta mu n by 2 mu n times gm right. So the variability of g m with respect to mobility will also be better, but more interesting thing is to see that variability of gm with respect to the threshold voltage has completely vanished right. So now if you are looking at it for the first time you might feel a bit bamboozled because what is happening I mean just because I have used a different equation does it mean I am supposed to get different result right. What happened if I had used this expression? If I had used this expression I mean the if I had used that expression the del gm was coming out to be something different. How come just because I shifted to this expression del gm with respect to threshold voltage became 0 right.

So the answer to that is you have to find out you have to appreciate what is happening in this network. When I say ok so let us take a deep dive into this. So when we say the current is fixed right. So let us say the current is fixed what am I implying? I am implying that probably there is a current source somewhere which is pushing current which is pushing current into the device right ok. So there is probably a current source which is pushing current in the device somehow fixing it right.

But so let me not put the current source right now ok. But we all know that the drain current is the effect it is not the cause right. We have to apply certain voltage at the gate between the gate and the source in order to get a drain current right. So again mind you drain current is the output is the effect cause is the gate to source voltage correct. So then the natural question is if drain current is the effect then how can I guarantee a constant drain current? We can guarantee what I am telling you is that we can guarantee a constant drain current if we already have a constant current source right.

Just like you have a constant voltage source let me assume that we have a constant current source and as it turns out you can build constant current sources it is not a part of this course but trust me and take it as a phase value that you can build constant current sources. So if you can build constant current sources what I can do is I can take a constant current source of value Idsq and connect it to the drain of the transistor I can always do that right ok. So what will happen a constant current source is an ideal source right. So if we have a constant current source and we connect it like this what is going to happen to this node and I leave the transistor as is. If I leave the transistor as is what is going to happen? So what is the voltage between Vgs is undefined it can be anything right.

It can be 0 it can be 1 volt it can be 9 volt I do not know right it is not in my control so it can be anything. If this is anything if this is anything what can you comment on what comment can you make on the voltage at the drain of the transistor? One might say that if I do not know anything about if the voltage at the between the gate and the source of the transistor itself is undefined how can you ask me to make a comment between the voltage between the drain and the source and that is a right assertion to make there is no way we can tell what will be the voltage at the drain. So now if we cannot tell what is the voltage at the gate and what is the voltage at the drain we cannot also tell what is the operating condition of the of the transistor correct. Now if we cannot tell the operating condition of the transistor or in other words you cannot establish the operating condition of the transistor then obviously we cannot even use it for our amplification purposes right. So what is the first thing we need to do? We need to establish the voltages at the gate and the drain properly so that we will be able to establish we will be able to establish the operating condition of the transistor ok.

So let us see. So let us say I, let us say let us do a thought experiment. So I give you a transistor and I give you a constant current source of value I0 right. So let us say I tell you that I0 is 1 milli amp. Let us say I tell you I0 is 1 milli amp. Here is your transistor with certain mu n, Cox and threshold voltage.

Go and bias it with a constant current source so that IDSQ will be equal to 1 milli amp also so that the transistor is in saturation right. So what will you do? And I also tell you that you have voltage sources available. Obviously you need voltage sources in order to bias a transistor. So let us assume you have voltage sources available. What will you do? I will tell you what I will do.

I know that the gate source voltage is the is the cos and the output drain current is the effect. If I have to stick the drain current into the if I have to stick this I0 into the drain, what should I do? I will first go and see as plug in some arbitrary voltage, some arbitrary battery between gate and source right and let me call this some arbitrary battery Vbat okay. So let me call this Vbat. So if I connect this arbitrary battery Vbat and let us say I put some arbitrary voltage 2 volt and I did my calculation. So let us say after calculation I figured that if M1 this is after my calculation I figured that if M1 is in saturation right a current of 1 milliamp will require 2 volt Vgsq correct.

So let us say I did all my calculations and I have figured it out. So I stick a battery in right. So then I have a Vtsq of 2 volt I have a current of 1 milliamp then do you think this will be fine? Of course this will be fine right. But now let us assume that the threshold voltage changed right. So let us say the threshold voltage was Vth was 1 volt and Vth changed from 1 volt to 0.

9 volt let us say. So Vth change from 1 volt to let us say change by delta Vth is minus 0.1 volt right. The threshold voltage dropped. If the threshold voltage drops what will happen to Idsq? Idsq will increase.

This will increase by delta Idsq correct. But note that I have a current source from the top. Since I have a current source from the top the current in the top will not change correct. So this Idsq under this initial condition was 1 milliamp. But now I am drawing more current than 1 milliamp right. So what will happen to the node voltage Vd? I am drawing so the node voltage Vd is now seeing there is a current source from the top which is the current source on the top which is pushing 1 milliamp current and a current source in and the and a current source on the bottom which is pulling out 1 milliamp plus some extra current ok.

So if you are if you are pulling more current out of a node than you are pushing in what is going to happen to that node voltage? That node voltage is going to drop right. So this voltage this drain voltage is going to drop. So Vd will so consequence of this is Vd will decrease. And how long will Vd decrease? Will it go will it keep on decreasing and go to minus infinity or 0? No it will not because it will decrease till the transistor goes out of saturation right. If the Vd decreases, a decrease or decreases and it will eventually go into linear region when what is the problem here? The problem here is the problem here is the current in the MOSFET in saturation is not dependent on the drain to source voltage right.

It is like an ideal current source right. It is not dependent on the drain to source voltage. Since it is not dependent on the drain to source voltage right, you no solution exists if you have a difference of current right. You are pushing in 1 milliamp, you are pulling out more than 1 milliamp and the threshold and the Vd will keep on dropping. But moment that transistor enters linear region, it is now dependent on the current of the transistor in linear region is dependent on the drain to source voltage. Since that current is dependent on the drain to source voltage, a solution will exist and the solution will be such that the transistor is actually in linear region right.

So Vd will drop till M1 reaches or enters or not till I mean it will drop and M1 will enter linear region of operation. So naturally you are all your good properties of a transistor are gone simply because the threshold voltage changed by change by certain amount ok. So what is the solution? So this I cannot do. So what is the solution? So let us let us brainstorm a bit more. So let us say I still want to use this current source and I still want to connect it at the drain right.

And let us say I have a variable voltage source and I have stuck it here. So what is the problem? The problem is if this voltage source is fixed, if this voltage source is fixed and this is 1 milliamp and because of change in threshold voltage this current became 1 milliamp plus delta plus delta I right. The transistor Vgs or the transistor overdrive changed right. So if I had the ability to change the overdrive also right, if I had the ability to change the Vgs also then it is possible that I could have changed the capacity of the transistor to try to sink in different values of current right.

Let me explain it again. So what I am essentially saying is that what is the goal? The goal is to match the current from the top to the current from the bottom right. The goal is to match this 1 milliamp current with the current that the transistor is sucking out. So how do I, what is the key variable or the key variable to focus on? Let us say I tell you that I will only try to focus on this voltage Vd on the drain voltage Vd and I will try to conclude if the transistor is biased properly or not. Is it possible? It is possible right from the example that we just saw if we only observe Vd right, I take it to the lab and I only observe Vd what will I see? What will I observe? If the transistor is biased such that it is trying to pull out more current than 1 milliamp Vd is going to drop right.

So if Ids let me call this Ids of the transistor. If Ids is greater than 1 milliamp right or rather if Ids yeah if Ids is greater than 1 milliamp or rather if expected Ids I should say not Ids because if expected Ids is greater than 1 milliamp then Vd will decrease and transistor will go into linear region. Similarly if expected Ids is less than 1 milliamp Vd will increase right Vd will increase and something bad might happen to the current source let us not get into that right. So let us say we take the first case where the Vd is decreasing. So I am in the lab and I am observing this phenomena that Vd is decreasing. So what is the only conclusion that I can draw? The only conclusion the immediate conclusion that I can draw is the transistor is stronger than it is supposed to be.

When I say stronger what I mean the transistor is expecting with the Vgs that the transistor has is it has been tuned in such a way that that transistor is expecting more current right. But again Vgs is a controlling variable for me. So what should I do? I should go and tune the Vgs right. I should go and tune the Vgs right. So if I take this example if I take this example what is the this is this is observation right.

So this if so if Vd is decreasing so observation is your Vgs Q is higher than required right. It is only because Vgs Q is higher thnt require the current that the transistor is expecting to pull out is higher and because the current source is limiting the current your Vds as a consequence of it is strong right. So what is the action? So the action required so implies required action is to decrease Vgs Q correct. If I am in the lab what will go I will tune the Vgs Q knob till I see Vd is not decreasing anymore right. So what is again quickly what is the algorithm? The algorithm is if Vd decreases then decrease Vgs Q right.

Alternatively if Vd increases then increase Vgs Q right. So this is what I will do in the lab. So can you think of an architecture which does this automatically? Again what I am wanting to do if Vd increases I want to increase Vgs Q in this case only Vg because source is grounded. If Vd decreases I want to decrease Vgs Q. So what is the simplest that thing that you can think of? I can simply connect the gate and the drain right. So some of you might be familiar with this circuit this is often called diode connected configuration but we will get to that later on but the first thing to notice here is that if I do this what is going to happen? Firstly the thing is that we need to notice is, is the transistor in saturation? That is the first thing to notice right.

Is the transistor in saturation? If threshold voltage changes for example right or even without threshold voltage change. So is the transistor in saturation what should I see? So the only thing that I should see is for saturation Vd should be greater than equal to Vg minus threshold voltage. In our case Vd is exactly equal to Vg hence it is in saturation. So in this case for M1 Vd is equal to Vg hence saturation condition is ensured.

Now let us assume that the threshold voltage changed right. If threshold voltage change is a transistor in saturation of course transistor is in saturation because the gate and the drain are connected Vd is always equal to Vg. So the transistor is in saturation but what happens to the what happens to the gm? Or let me ask you if threshold voltage changes right let us say this is 1 milli amp right. The threshold voltage was 1 volt and Vgsq let us say under this condition I matched my I did the calculation and I found 1 milli amp equal to certain half UMC ox W over L and let us assume we know some value of W/L then what is the value of Vgsq that we will get? We will get Vgsq let me call this I naught instead of 1 milli amp let us keep it general. So Vgsq will be threshold voltage plus under root 2 I naught by mu n Cox W over L right.

For sat. $V_D \geq V_G - V_{TH}$

For M1 $V_D = V_G$ Hence sat.

$$I_0 = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}\left(V_{GSQ} - V_{TH}\right)$$

$$\Rightarrow \boxed{V_{GSQ} = V_{TH} + \sqrt{\frac{2 I_0}{\mu_n C_{ox}\frac{W}{L}}}}$$

I basically did the algebra. So if threshold voltage decreases right so this is Vgsq right so this is the Vgsq. So if threshold voltage decreases let me use the same color right for quiescent let us use black. So if threshold voltage decreases by let us say 0.1 volt what is going to happen to Vgsq? Note that current is constant so Vgsq will adjust right will adjust itself so as to keep the overdrive Vgsq minus threshold voltage same right.

So Vgsq will also change by minus 0.1 volt right. So if you stare at this equation you will see that if threshold voltage changes the Vgsq will also decrease by an equivalent amount because I have because we have biased it with a constant current source right. So in this case we have somehow figured out a way of making the current the independent variable the current we have made the constant current source the independent variable and I am asking the constant current source to develop an equivalent amount of Vgs right. I am asking the transistor to develop the equivalent amount of Vgs that is required to sink in that current of 1 million and because I am doing that whatever happens to mu n whatever happens to threshold voltage right your transistor will always the transistor will always be able to sink in that 1 million current and because it is always able to sink in 1 mili current and if we go back to our equations of transistor currents in saturation if the current is constant then naturally Vgs minus threshold voltage is also constant and since we Vgs minus threshold voltage is constant which means if threshold voltage changes Vgs will have to change right. So naturally the transistor Vgs auto adjusts itself right. So transistor Vgs auto corrects under the condition of a constant current source biasing ok so that is the beauty of using constant current source biasing instead of constant voltage source biasing ok. So we will talk about this in more detail in the next lecture. Thank you.