Semiconductor Devices and Circuits
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Lecture – 48
Amplifiers using MOSFET

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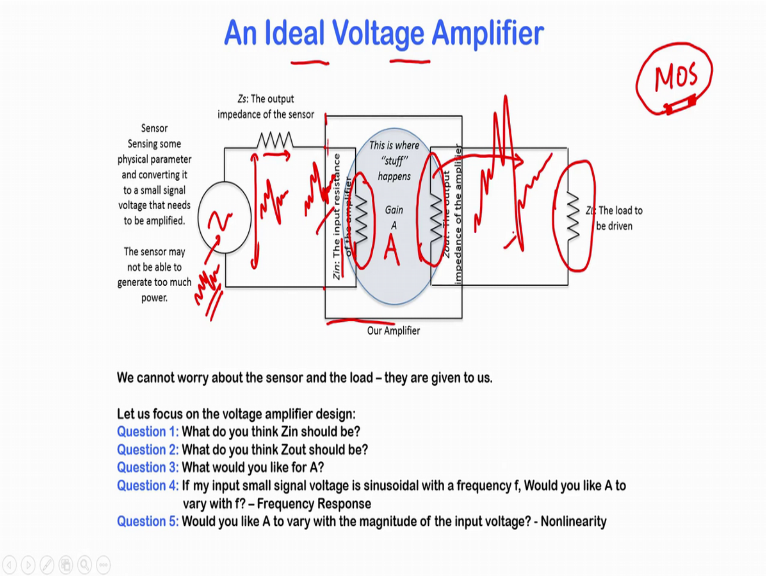

So, now let us look at voltage amplifiers ok. So, we the lectures over the next few slides, we will have a very strong flavor oriented towards circuit design and we will cover some very fundamental aspects of how to analyze, and how to build some basic circuits. But, nevertheless the point is not the point of the scores is not so much in perfecting the methods of analysis of circuits, but rather trying to understand at least qualitatively as to what happens and then connect those properties of the circuit with that device physics of the device being used.

And in this case, we have completely focused on only using MOSFETs. So, it is essentially going to be connecting the device properties of the MOSFETs with the behavior of the circuit.

So, let us so in our discussion of an voltage amplifier, we should start off by looking at what an ideal voltage amplifier is and firstly, what is an voltage amplifier and what is it used for. So, let us say you have a sensor ok. Now for example, this could be a microphone that is picking you know acoustic waves, and it is converting it all to voltage. So, you have a voltage across this microphone that is varying in correspondence to the voice that the microphone is picking up.

And you have an output resistance of the microphone, which is not really important at this moment. And this voltage waveform from the microphone, it is too weak ok, it cannot it cannot travel too far without being completely corrupted by ambient noise. And therefore, it needs to be immediately amplified. And in order to do that we use something called as a voltage amplifier.

Now, the voltage amplifier has got is, this circuit that you see inside this box ok, and it is basically got an input impedance. So, you have this voltage appearing across an input node of the amplifier. And then the input from the input impedance the input impedance is the place, where the amplifier actually picks your signal ok, it picks the signal there. And then the amplifier does its magic, and it provides a massive gain A. And then the output voltage is sent to a through the output node of the amplifier. So, this is where the amplifier sends it off to the load element or the external environment. So, here you should have a amplified voltage signal of whatever came inside, so that is the purpose.

So, what are the properties of an ideal voltage amplifier? So, we will in the previous section, we looked at an ideal switch, and we saw how far how far behind we were in terms of achieving an ideal switch because of the limitations of the device. So, let us do the same thing for a voltage amplifier. So, what are the properties of an ideal voltage amplifier? So, I post these as a series of questions ok. So, what do you think the input impedance of the amplifier should be ok. Do you think it should be low or should it be high? So, let us ask ourselves that.

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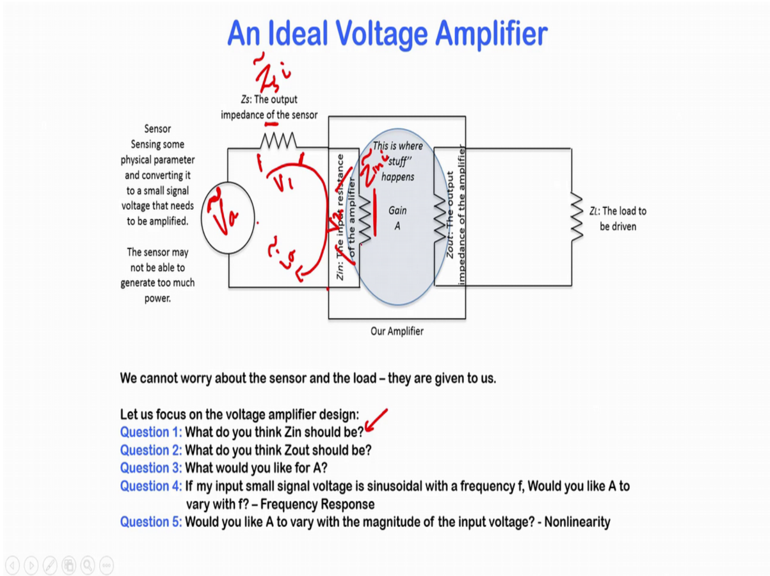

So, think of your sensor as a little voltage source ok. So, think of it does it, it is an alternating voltage source. And it is a got some output impedance right no sensors perfect, it is got some output impedance. So, essentially this is the circuit the sensor sees. And we are trying to take the amplifier needs to get a large portion of this voltage source, preferably it would like all the voltage source to all of this voltage to drop across the amplifier input, because, this voltage is going to set up a current in this path.

And this is going to lead to resistance drops, so you will have a drop of Z s i and Z in i across these two resistors. And therefore, there is a going to be some voltage drop here, and some voltage drop here. You do not want all the voltage to be dropping across the resistor, which is the output impedance of the sensor. You, in fact want as much of the voltage being dropped across the input of the amplifier. You want the amplifier to sense a strong enough input voltage, so that it can work very efficiently.

So, in order to do that we want to make Z in as high as possible right, theoretically we would like it to be infinite. If it is infinite, there is no current in this path and every voltage all in the complete voltage drop drops across the amplifier. But, on the other hand if it is very small, then a large amount of voltage will drop across this output impedance the sensor and the amplifier will get a very small amount of voltage.

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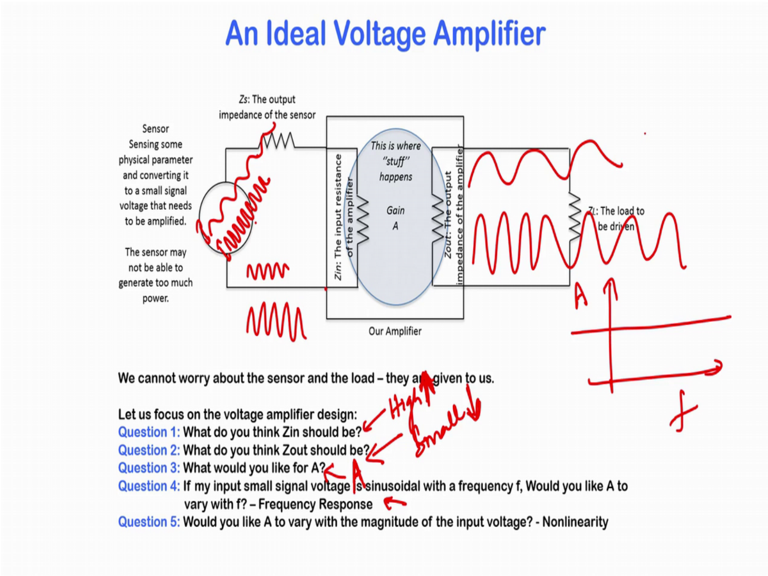

So, therefore we want the answer to these questions, we want it to be very very high ok, so that is the input impedance that we are design. What should be the output impedance of the amplifier, which is the impedance here. So, the amplifier now received this voltage, and it amplified it. And now it is going to act like a voltage source, it is going to play the role the sensor played, but it is going to play that role on the output side ok.

So, now the job of the amplifier must be to take this amplified voltage, and make sure that the load gets to see all of this ok. And therefore, using the same argument as before, we want Z out or the output impedance of the amplifier to be very very small. We do not want it to be large; we want we do not have control on Z l, because that is chosen by an external circuit. But, we would like we would like that Z naught be so small that no matter what Z l has chosen, it really does not matter, because the amplifier can easily submit all the voltage to the lower.

So, we want to keep Z out as small as possible, and we want to keep Z in as high as possible. What about the gain shall we have a gain less than one, if we have a gain less than one, there is no point in having an amplifier unless it is used to modulate say Z out or Z in ok, which is in some sense exactly what certain kinds of amplifiers do, but we would like good gain at the end of it. We would like good gain that is the point of a voltage amplifier ok; it is not a voltage attenuator.

So, what about the speed of the amplifiers? So, do forgive all if you find there lot of circuit jargon here it is, because I have taken these slides from a circuit course that I teach, but you can ignore that. Essentially, the next question is what about the speed of the circuit, would you like it to be fast or slow what is there how should the circuit respond as the frequency of the voltage changes.

So, let us say you have a sinusoidal input of that frequency, and you have another sinusoidal input of this frequency, I get a higher frequency. Would you like the gain to be it frequency dependent, I would you like it to be frequency independent, the answer is we would like it to be frequency independent of course, because irrespective to the frequency we want to get a good amount of gain ok.

So, if we want the amplify, if you were to plot if you what plot the amplifier gain versus frequency, we would like it to be constant. And should the amplifiers gain vary with the input voltage magnitude ok. So, what a what happens, if I have a frequency fixed, but the input voltage varies it just doubles in size, would you like the gain to vary ok. And the answer is no, because that will induce non-linearity ok. So, there are several aspects that we will not talk about in these lectures, but there are some aspects that we will cover, but nevertheless these are the properties of an amplifier.

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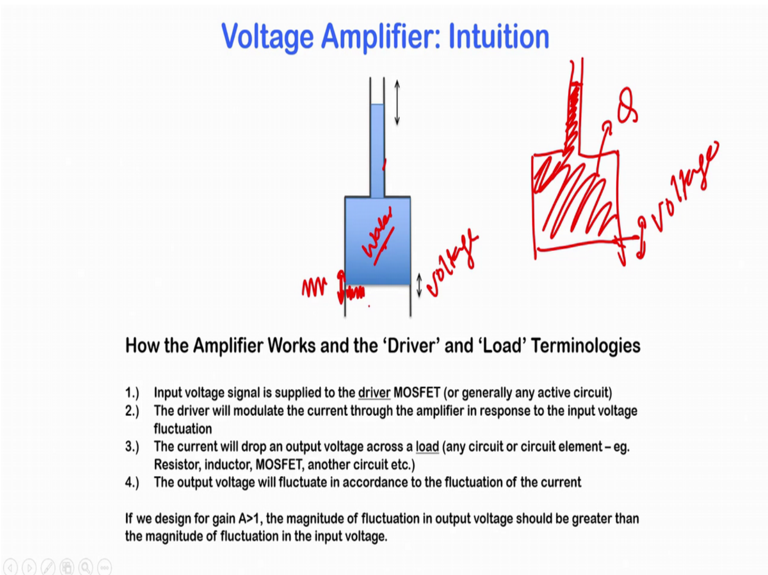

So, in general you will see that all the MOSFET amplifiers, all the voltage amplifiers have a tendency to work in a manner shown here ok. So, it is just an analogy, because we have always use this analogy of water in a bucket to understand Fermi levels to bands band and to Boltzmann's coefficient etcetera. I will continued with the same analogy here.

So, imagine to you know two pipes ok. So, one is a large pipe and other one is a much narrower pipe. And both these pipes have got a certain amount of water, there is a water it is a continuous volume of water that fills these pipes ok, this is all water. And the amount of water is charged. So, the amount of water is essentially charged, and the fluctuation in this level of water is the voltage, so this is the voltage. So, we design an amplifier such that one pipe is very wide and the other pipe is very narrow. And we will design it such that the input sensor submits the fluctuation here, which allows the water to move up and down a little ok.

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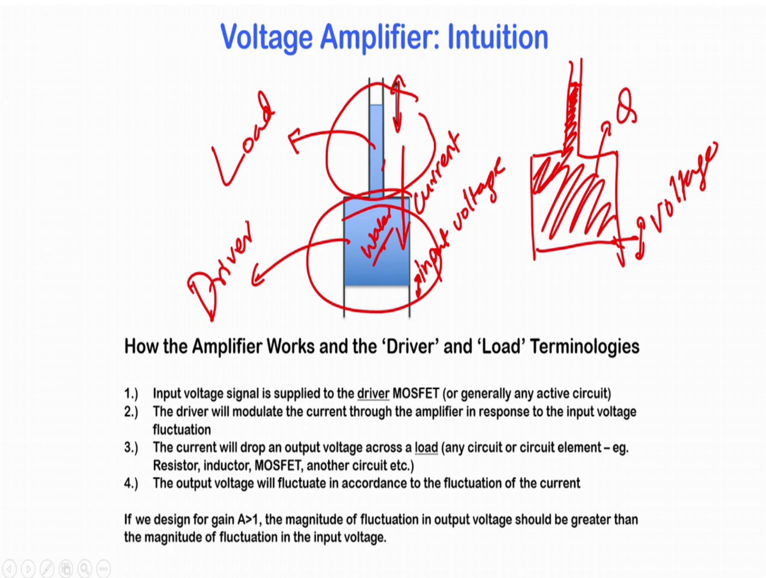

The input voltage is very very so this is the input voltage. The input voltage is very small, but since the flux has to be the same or the current through these two pipes. The flux of water has to be the same. A small fluctuation here, simply because the geometry of this design becomes a very large fluctuation there ok, so that is exactly how a voltage amplifier works that is the best intuition ok.

And this so these are basically going to be construct with the two devices, it could be a resistor or a transistor acting as a thin capillary, which is called as the load. And a MOSFET acting as a large capillary, which is called as the driver. So, when we say driver, it is the device that is going to receive the input signal and which is going to modulate the current or the flux through the circuit.

And the load is the one that is going to receive this change in flux, and it is going to drop a voltage across it, which is the amplified version of the input voltage received by the driver. So, this is the voltage amplifier. So, this is the very good intuition to the what the voltage amplifier is going to do, and you are going to see this happen in all the different circuits ok.

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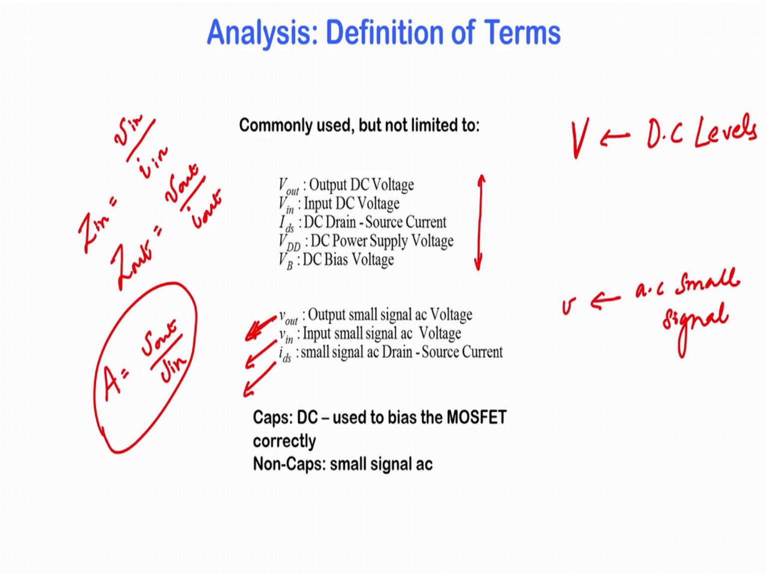

Now, before we begin so now, what we are going to do now is going to draw some topologies of circuits. And we are going to perform an analysis because, without that analysis you are not going to be able to feel the operation of the amplifier. And you are not going to be able to relate the operation of the amplifier to the device properties that are required.

So, therefore do bear with me. So, what we have defined here is the different symbols that you will see. So, everything in capital is refers to DC voltages, these are not fluctuating, these are constant values, these are DC levels. And everything in small alphabets refer to ac or small signal responses.

And why do we use all these small signal, because we want to linearize the MOSFET we want to linearize the device ok, so that is going to be the output voltage of the MOSFET that is going to be the input signal received; that is the output signal that is the current through the MOSFET and these are all small signal terms. And what is the gain of the voltage amplifier, it is a small signal output voltage divided by the small signal input voltage ok.

So, we will always be trying to calculate the gain. And what is the input impedance of the amplifier. So, we are always talking about small signal parameters, it is the input voltage the small signal input voltage fluctuation divided by the small signal input current into the circuit. And what is the output impedance of the circuit, it is the output voltage divided by the total current that is coming out at the output or in fact we will look at certain techniques to look at all this ok.

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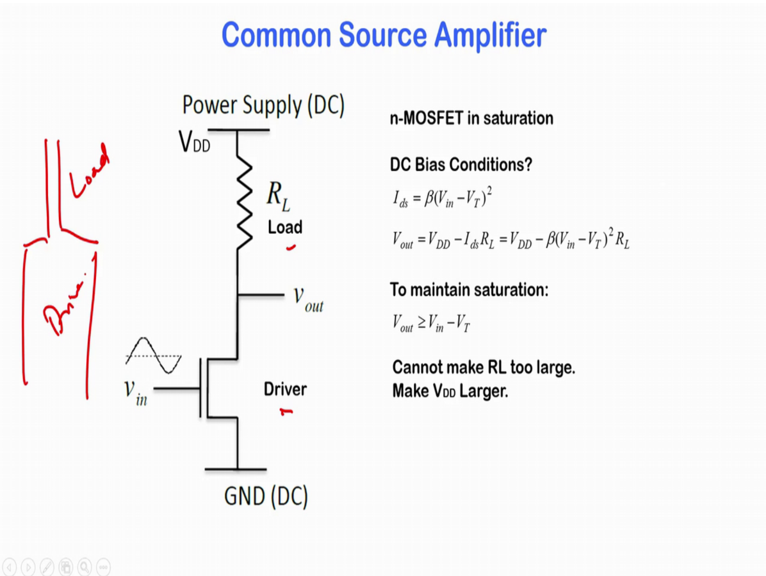

So, the very first circuit we will study is a series combination of a resistor and a MOSFET. And if you remember your capillaries the two capillaries with water, we said that was the load and this is the driver. So, here we have the driver, and we have a load.

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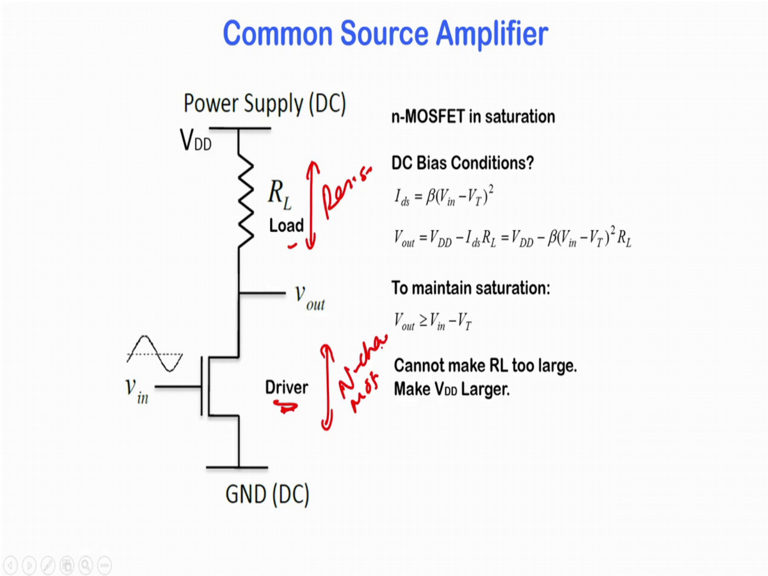

So, we have a load element, which is the resistor and we have a driver element, which is a N-channel MOSFET ok. So, this is the way the circuit is connected.

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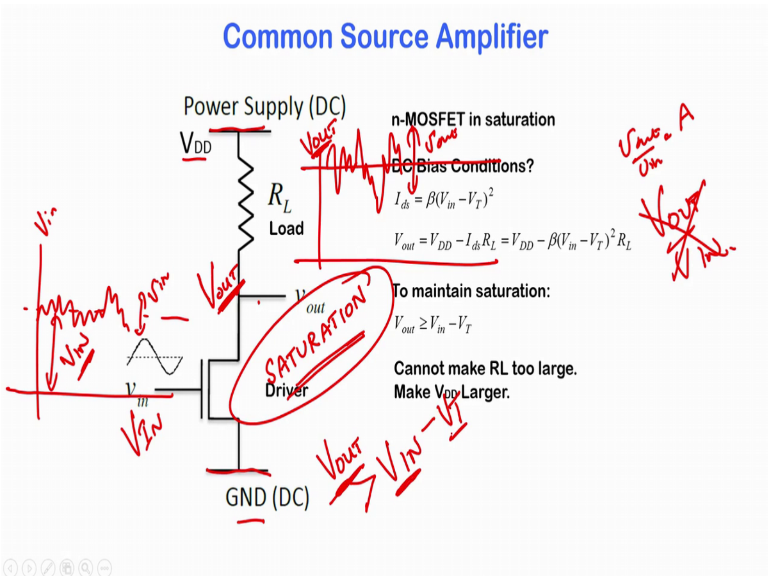

So, you see a power supply here. And the power supply is in capital V D D that is ground. And the power supply is designed, so that there is a DC voltage V out, which is not shown here. There is a DC voltage V out, which is kept here such the and there is a DC voltage V in, which is not shown here. And everything is done, so that the MOSFET is in saturation.

So, we were building voltage amplifiers, we will always try to keep the MOSFET in saturation, and I will tell you why ok. The MOSFET is going to be in saturation mode operation, which means that the DC value of the input signal. So, the input signal has got a certain DC value, and it is got a small fluctuation around and this is the AC signal.

And similarly, output you will find that there is a DC value to the output. And then the amplified input is going to fluctuate around, so that is your v out small v out. And it is the small v out by small v in which is going to be the amplifier gain. We are not interested in capital V out by capital V in ok, but the capital V out and capital V IN are chosen by some external circuits is already designed in such a manner that the MOSFET is in saturation. And this is going to be the case everywhere, we are never going to show these DC values, they will only show the small signal values, and the MOSFET is in saturation everywhere.

So, V out the MOSFET has to be in saturation, your capital V out must be greater than small V IN minus V T, because this is V D S that is V G S and that is V T. So, we are only illustrating this fluctuation. We have ignored we have ignored all this; we are only interested in these small signal fluctuations of the MOSFET ok. So, we can draw two circuits, we can draw two different circuits. So, we can say that there is AC and DC all happening together it would be too confusing to analyze both of them together.

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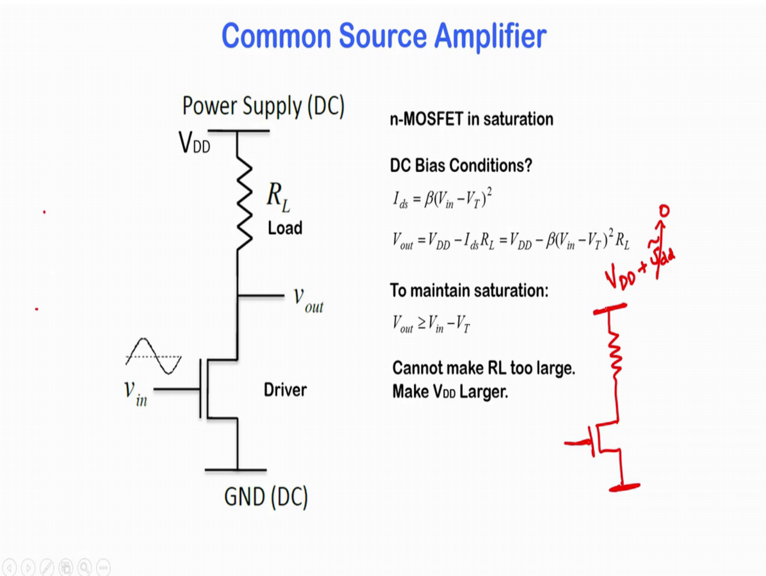

So, what we will say is from this point on whenever we do AC analysis, we will ground all DC points. So, what we are saying is there is V D D plus small signal v d d is there a small signal power no, this has to be 0 we would like the power to be constant ok. So, so before I do this, let me just reiterate the point I made.

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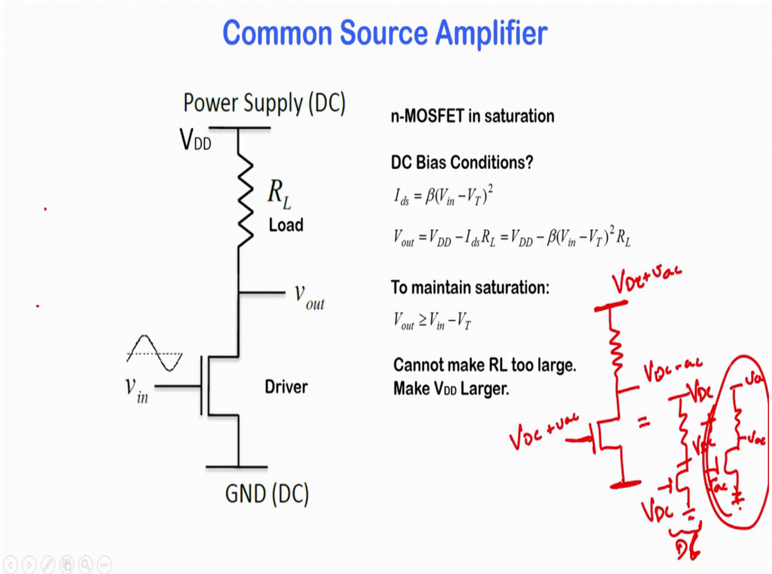

So, if there is a DC plus ac, AC is all shown in small signal ok, so everywhere you have some DC nodes and ac nodes. We are going to say that this circuit is a combination of two circuits. One of them is purely DC; we will only look at DC. So, we will only consider capital DC everyone. And the other one is only ac, we will only consider capital the small ac signals everywhere ok. So, we are only interested in analyzing this ac circuit, because we are only interested in small signal analysis. And when needed, we will do the large signal analysis ok.

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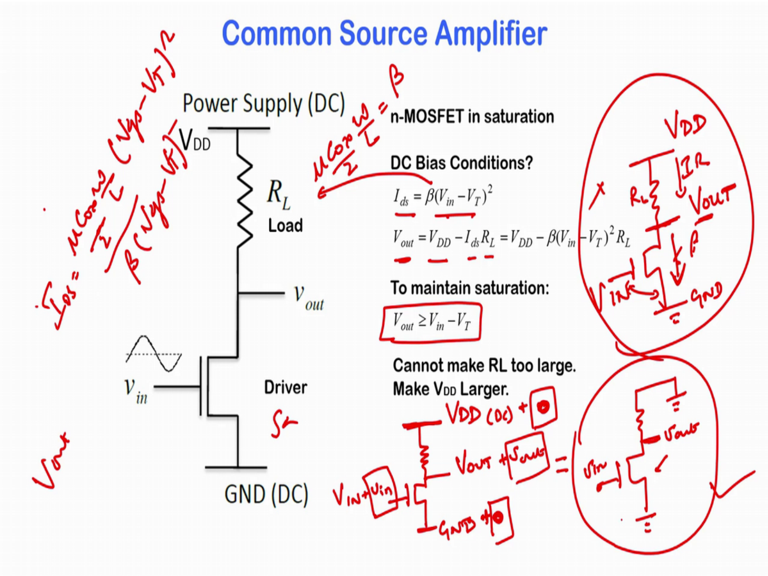

So, now I probably should have made a separate slide here. So, do I apologize, if it is not clear, but you can only send me a mail. So, now let us try to build our two different circuits. We have capital V IN plus small v in going here. We have capital V OUT plus small v out going here. We have ground, and there is no small there is no small signal here, ground is DC ground, it is AC ground its ground ok.

And the power supply is constant ok, it is a DC voltage. And there is no small signal fluctuations here. So, there are no small signal fluctuations in power supply and ground, definitely these are not desired, you want the power supply and ground to be as steady as possible. So, what is the AC circuit for this? If you draw only the AC circuit, so we will only consider these portions ok. And if you draw the AC circuit, we find that this is ground. The power supply can be thought of as AC ground, although it has got at large DC voltage.

The output node will only have v out, and the input node will only have small signal v in. And what is the DC circuit; the DC circuit will have your ground. Now, you cannot ignore the power supply. There is a large DC voltage, there is some AC I mean DC voltage at the output, and there is a DC voltage at the input ok. So, this understanding is key ok, you need to understand what we are doing here, before we proceed.

And we have now biased this circuit in such a manner that it since saturation, you want to keep this transistor in saturation. So, what do you mean by saturation, let us go to the

DC circuit. We want the current in the transistor to be beta ok. So, beta is nothing but my mu C ox W over L by 2, so that is called as beta.

So, we want the current through this transistor is in saturation, so its beat it is mu C ox W over L by 2, so that is the current in saturation is mu C ox W over L by 2 into V g s minus V T the whole square, so which we are writing as beta into V g s minus V T the whole square.

And we want that to be beta into V IN minus V T the whole square, so that is your V g s. And what is V out capital V out is V D D minus the IR drop here. So, V D D minus I d s into R L is my V out. And to keep this in saturation, we want V out to be greater than V in minus V T, so that is the DC condition required to keep this driver in saturation mode, and that is the DC circuit ok.

And when we do AC analysis, we will not worry about this circuit, we will only use this circuit, where all the DC nodes like power supply and ground have all been grounded, and we only look at small v out and small v in ok. So, I hope this is clear. I have probably raced through this part a little quickly, but I have nevertheless try to make it as clear as possible. Ok, so let us move ahead.

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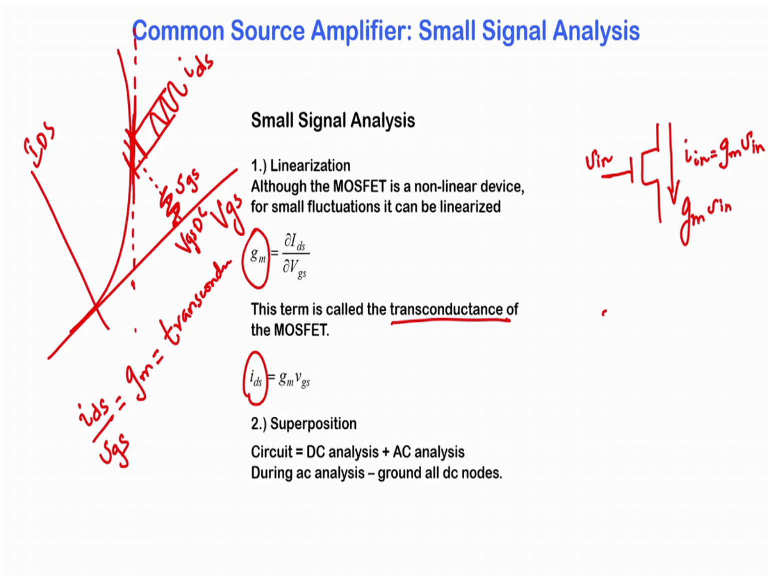

Now, when we do small signal analysis, we would like to define certain terms ok. So, we are now interested in the small signal behavior of the MOSFET. And what do you mean by a small signal behavior to reiterate, you have the transfer and output characteristics. So, let us say that is the transfer characteristics of the MOSFET. So, the entire curve if you take as such is an the MOSFET is definitely a non-linear device ok, but in a small region ok.

So, if I fixed my DC voltage, and I am only looking at my AC signal there is going to be my small V g s. In this region, I can define the slope to be constant, it is an infinite. If it is infinitesimally small section, and I can define my V g s a fluctuating within this segment. And therefore, the slope here is constant. And that slope determines the amount of fluctuation of the AC drain to source voltage ok.

So, in other sense by keeping the slope here constant, we have linearized the behavior of the MOSFET, we are saying that the MOSFET is like this, if I were to bias my DC voltage at that point. So, here it is useful to define this term, which is your small signal fluctuation of i d s by small signal fluctuation of v g s is something called as the transconductance of the device of the MOSFET; it is called g m or the transconductance of the MOSFET. So, if somebody gave us the input node fluctuation at the gate of a MOSFET, and asked us to identify the current the small signal current in the MOSFET. The answer is simply g m times the input node fluctuation ok, so that is the useful term.

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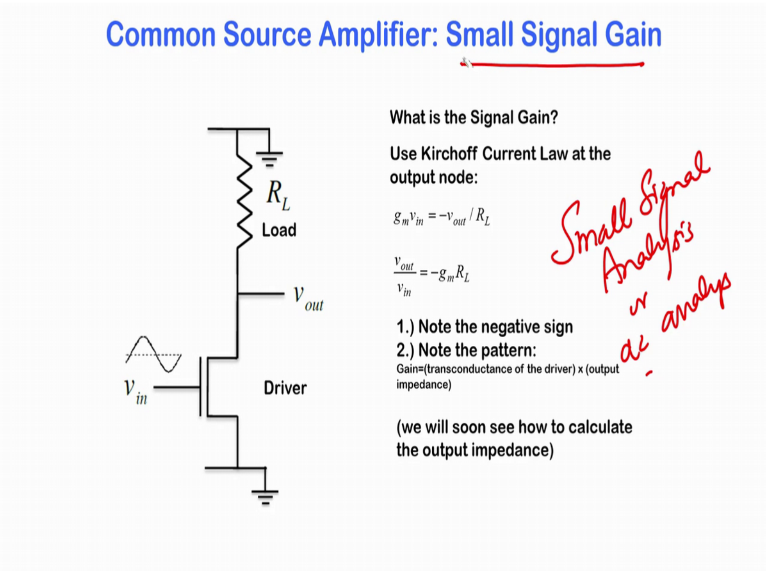

So, now we are all set to go ahead, and do the ac or small signal analysis small signal analysis or ac analysis of the circuit.

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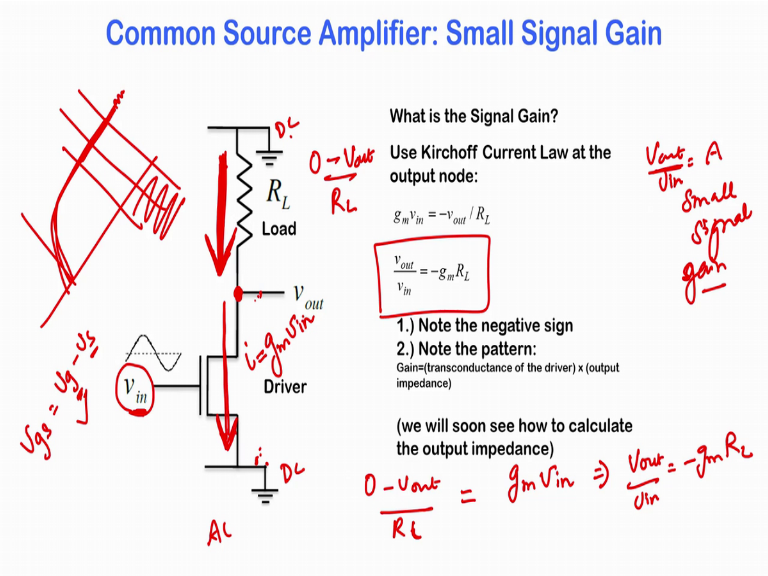

So, let us say that you have this resistor, and now we have drawn only the AC circuit. So, you can see that we have grounded the DC nodes, and we have only got the AC node. So, we have small v out and small v in, we have a small v in going in, and we want to know what is the gain of the circuit. What is v out by v in, which is the gain, we are talking about small v out by small v in which is the small signal gain of the circuit. So, we said that this is an amplifier, so what is the gain of this amplifier.

So, all you have to do is solve Kirchoff's law current law at this point, just solve Kirchoff's current law at this point, which means what which means all the current going in here is equal to the current coming out here ok. So, what is the current from here to here through this resistor, it is 0 minus v out that is the voltage drop across the resistor divided by R L that is the current in this direction. And that current, so you should keep the direction very it is very important to keep the direction right ok.

Otherwise, you will end up with a sign mistake, and that current must be equal to this current. Now, this MOSFET is in saturation, so if it is an ideal MOSFET in ideal saturation, there is no channel length modulation would a fluctuation in v out or in the drain to source voltage would a fluctuation here, cause any current variation the answer is no. So, therefore this v out does not contribute to any current in the MOSFET.

But, on the other hand you have a gate voltage fluctuation v in ok. What is important to see, whether there is a gate to source voltage fluctuation is there a fluctuation in either v g or v s. Now, v s is not fluctuating, because it is a DC, but the gate is definitely fluctuating ok. And the fluctuation is basically v in. And therefore, yes there will be a current through the MOSFET, and the current as we looked at will be given as g m times v in, where g m is the transconductance ok.

Therefore, we just write Kirchhoff's law. We say that 0 minus v out by R L is the current through the resistor, and that is equal to g m times v in which is the current through the MOSFET. And therefore, what is v out by v in v out by v in is minus g m times R L, so that is the gain of the circuit that is the gain of the circuit.

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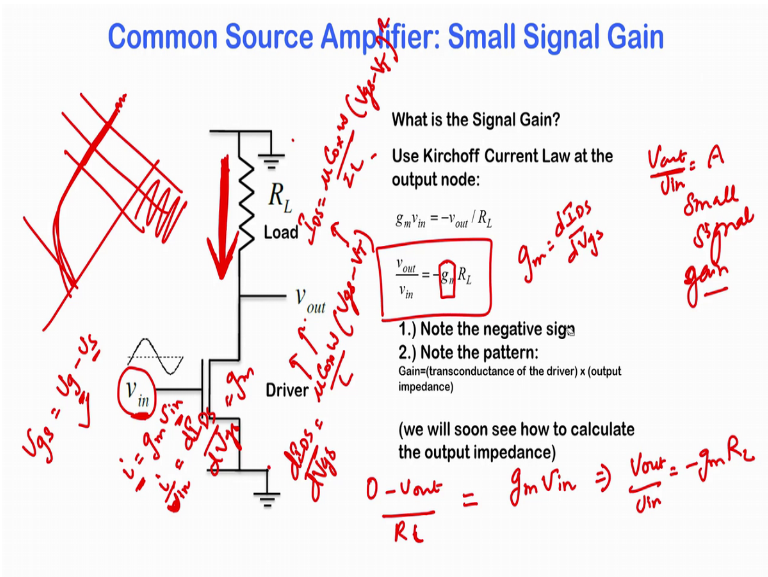

So, now what let us connect all this the device physics, this is quite easy. R L is simply an external resistor; the only thing that you need to worry about is g m. So, what is g m? G m is d I D S by d v d V g s when the MOSFET is in saturation ok, it is a small signal it is its telling you what is how much the current varies, when the voltage vary. So, I the small signal v current through the MOSFET divided by the small signal gate to source voltage, which is basically a d I D S by d V g s in the MOSFET.

So, in saturation mode your I D S is beta or which is your mu C ox W over 2 L into V g s minus V T the whole square. So, what is d I D S by d V g s? D I D S by d V g s is mu C ox W over L into V g s minus V T, so that is the transconductance g m. So, we already know what mu depends on, we know what C ox depends on, and we know what V T depends on ok. It is got a very it is quite coincidental that this g m value of a MOSFET in saturation is the same as the inverse of the r on value for a MOSFET in linear mode ok.

So, you can it is basically the inverse of the is 1 by the r on of the MOSFET, but when the MOSFET is in linear bias and deep linear bias ok. So, the second thing that is that is the that is so we are already we already understand the device physics, so there is nothing new to connect here. So, the other thing to note is this negative sign ok, why is the negative sign occurring ok. So, it is showing that its showing that when v in goes up, v out is actually coming down ok, its phase shifted. And why is that actually quite easy to understand.

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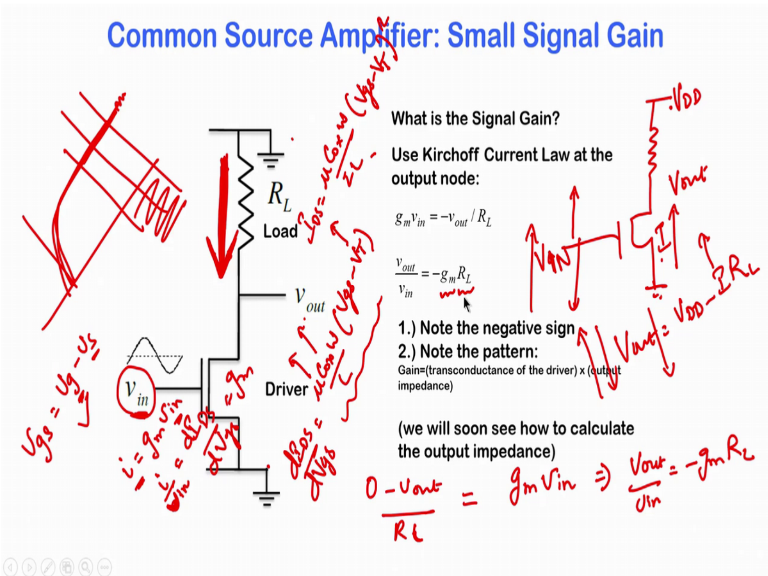

Ok, so if you were to look at the DC circuit and AC circuit together, let us put the DC and AC together. Essentially this voltage goes up, the current in the MOSFET increases. And if the current in the MOSFET so this is the gate voltage of them, say V IN goes up, the current in the MOSFET increases. If the current in the MOSFET increases, the voltage drop across the resistor increases ok, so that is V out.

And what is V out? V out is V D D minus the current into R L. So, if the current increases V out comes down. Therefore, if V IN increases V out comes down; and if V IN decreases, V out goes up. And therefore, there is a negative sign here showing the phase shift.

And finally, look at this pattern ok. So, you start observing this pattern, you have g m into R L. Since, this an amplifiers like a lever, you have a driving strength into the load output impedance. So, you will always find no matter how complicated your voltage circuit voltage amplifier circuit. You always find that there is an effective transconductance of the driving stage multiplied by the effective output impedance of the circuit will be the gain of your circuit ok, but it is all right. If you do not observe the pattern for several cases, it will just it is just a matter of practice ok. So, this is how you calculate the gain.

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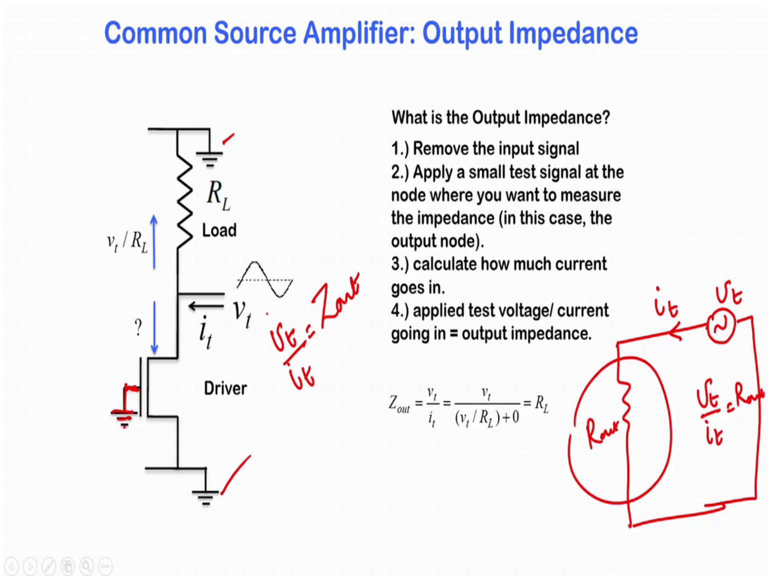

Now, let us calculate I will show you the technique to calculate the output impedance of the circuit of the circuit. So, we want to know, so this is the circuit we analyzed right. So, you want to know what happens, what is the impedance. So, suppose there is another stage here ok, the circuit is going to drive some other stage.

Now, when this stage looks inside the circuit, we want to know what is the impedance it sees or in other words what is the output impedance of the circuit. So, if you go back to our definition of the voltage amplifier here ok. So, we have understood what the gain is ok, but we still did not understand the input impedance and the output impedance ok. And we are now looking at the output impedance, which is if this circuit here, were to look back into this amplifier what resistance would it see here, what it is the value of that resistance ok, we ideally want that value to be small. So, it is good to understand, what constitutes that value. So, you want the gain to be large and we already saw that the gain is dependent on g m into R L.

So, now let us see what constitutes the output impedance of the circuit. So, in order to calculate the output impedance, what we do is we just get rid of all are input signals, you know let us just take the circuit alone separately ok. Let us say there is no input being applied. So, if there is no input being small signal input being applied, the input node is also grounded. And this is power line is grounded the gate ground is ground, because we are doing AC analysis.

And we will apply an artificial test voltage here ok. So, what we will do is we will apply a test voltage, it is an artifact. We just doing an experiment a thought experiment. And we will measure we will try to calculate the current that will go inside this inside the circuit ok. We will apply an artificial test voltage, and we will try to calculate the current that will go inside the circuit. And this small signal test voltage divided by the small signal current will basically be our output impedance of the circuit.

Because, if I were to put this entire circuit in this black box, and say it has got some output impedance. What we are doing is we cannot see inside this black box, but we are saying that we are going to drive, we are going to apply a test voltage here, we are going to send a test say current here. And this ratio is basically going to be my R out ok.

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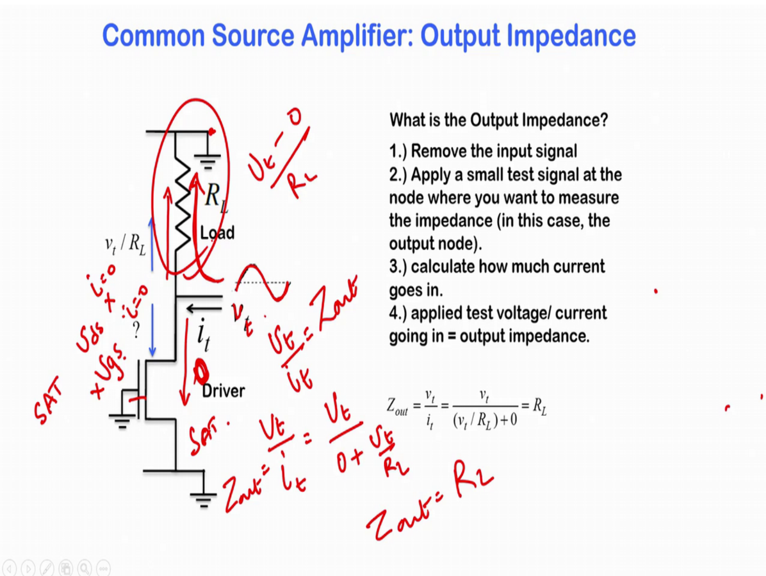

So, let us see what the currents are now if you were to do this ok, what are the cons, we will we just solve Kirchoff's law here, so where will the currents go. So, this i t will go it sees two parts, it can go down this way, and it can go down that way ok.

Now, what is the current through the MOSFET, the MOSFET is in saturation. And any fluctuation that the drain to source node is not going to create any current. So, ask yourself if the MOSFET is in saturation, the fluctuation in v d s really does not matter, there is going to be no current ok. If it is an ideal MOSFET, because we are not considering channel length modulation if you consider channel length modulation, yes there will be a current. And is there a gate voltage fluctuation a gate; gate or source voltage fluctuation gate minus source right. So, gate or source voltage fluctuation will create a current, but since there is no gate voltage fluctuation the current is again 0.

So, therefore the current through this path due to this test signal that you apply is 0, there is no current through this path. All the current only goes through this path. And what is the current in this path, it is the V t that you have applied, so it is going to be V t minus 0 minus this node, which is 0 divided by R L. So, therefore my output impedance is equal to V t by i t. And what is i t? The i t is 0 through the MOSFET plus V t by R L, which means that my output impedance is simply R L. So, the output impedance determined by the load, it is just a method to show you how to calculate the output impedance.