Analog Circuits
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Module - 04
Lecture – 12

So, far we have discussed common source amplifier using an nMOS transistor in some detail including variety of schemes for biasing the transistor. Earlier in the course, I said that nMOS transistor is just an example, it is the most popular device being used today the MOS transistor, but you could use the same principles that I described to design amplifiers using other devices. What we will do in this lesson is to look at other devices that have been there in the past and probably will come up in the future, and showed that essentially you will be plotting the device characteristics and from there choosing the right operating point for amplifier. And hopefully any device that comes up in the future, you should be able to look at the characteristics and set the operating point correctly and use it as an amplifier or use it for any other function that you wish. Now, if you look back at history in the first half of twentieth century, these devices known as vacuum tubes came into being and they became quite popular, and they were the ones that were first used to amplify signals in a wide range of applications.

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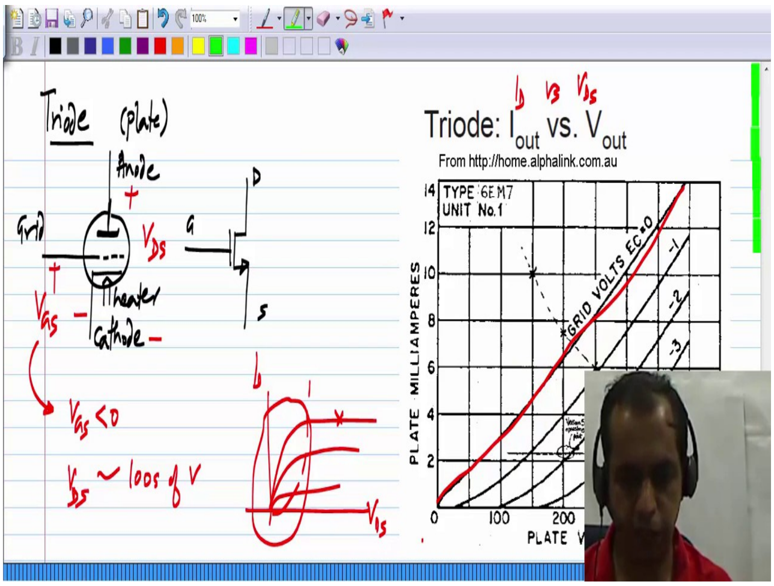

And first of those types of amplifier devices is what is known as triode; and the triode had a symbol something like this. These are the three terminals corresponding to the drain, gate, source of the MOS transistor. The drain corresponds to what is known as plate or anode, and the source corresponds to what is known as the cathode; and the gate corresponds to what is known as the grid. And in order for the vacuum tubes function properly, you also had to have a heater, the way these things work is by heating the cathode so that it emit electrons and they are captured by the anode, and the number of electrons being captured by the anode, is controlled by the voltage on the grid. So, you can see that there is a very close correspondence to the terminals of the MOS transistor.

This would be the V_{GS}, and the voltage between anode and cathode would be the V_{DS}. The only difference of course, is in the absolute value of the voltages that you would apply, it turns out that the V_{GS} grid to cathode voltage would always be less than zero. And what is equivalent to the drain source voltage, the anode to cathode voltage or plate to cathode voltage would be in the hundreds of volts. Now, just like the MOS transistor, the grid current was very small, and you can see here, what is shown here are the characteristic, what is shown here are the characteristic specifically they are I_D vs V_{DS}. I have labeled them I_{out} vs V_{out}, basically the output characteristics of the triode, and you can think of it as I_D vs V_{DS} characteristics for different values of grid voltage or different values of V_{GS}. You can see this zero volts minus one, minus two and so on.

So, just like in a MOS transistor, as V_{GS} increases, when I say increases here it is becoming less and less negative, the current will increase. Now, the one key difference between the MOS transistor and this, the characteristics are basically these curves given here, the key difference that you see is in a MOS transistor beyond a certain value of V_{DS}, the characteristics become flat, and that is where and that is the preferred region of operation for an amplifier. Whereas, in this case, you do not see a flat region at all, the current is going on increasing. And in fact, it looks more like the characteristics in this region of the MOS transistor. They look like the characteristics in this region of the MOS transistor in near the origin. The slope is not negligible, the slope is quite high. And in fact, this region is called the triode region, because the characteristic in this region resembles the characteristic of a triode. So, this is not an ideal amplifier, it does not have all the desired characteristics, but you could still make the amplifiers, and it was being used.

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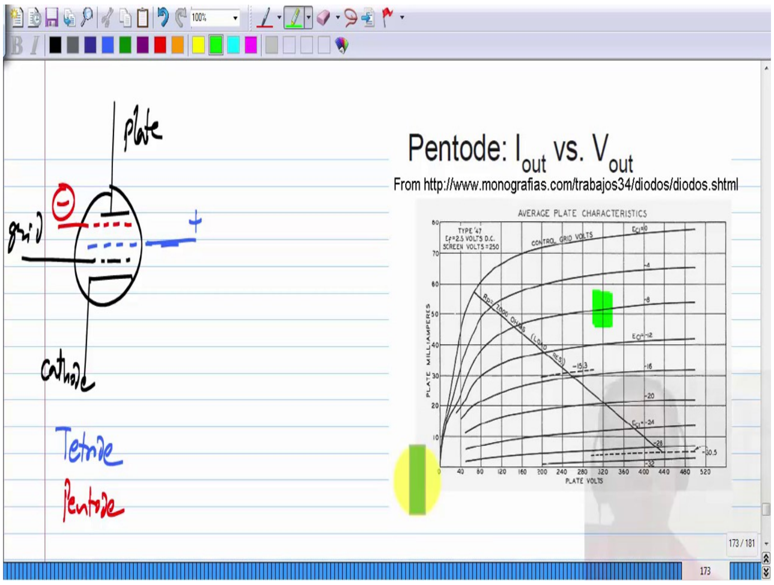

Now, later people got ideas about how to make the device better, what they did was, so we have the three terminals of the triode, plate, grid and cathode. And for a variety of technical reasons, which I would not discuss here; they found that they could add another terminal and make it better, and this terminal had to be biased such that the voltage is positive the same as the drain or even higher. And that device is known as a tetrode meaning it has four electrodes and somebody else found that it will be even better, if you add a fifth one here, and this is biased with a negative voltage, it is connected to ground in most circuits, and such a device is known as the pentode.

And here I show the I_{out} vs V_{out}, basically I_D vs V_{DS} characteristics of a pentode; as with the triode, the grid or the gate voltage is negative. I hope you can see here, the gate voltage here is zero, and here it is minus four, minus six and so on. So, as the gate voltage becomes more positive, the current increases. And also you can see that this part of the characteristics, it resembles the MOSFET, there is a flat region which means that a pentode is much better amplifier device than a triode. Remember before we did anything, we try to look at what the characteristics of an amplifier should be and we found that y_{22} should be very small, close to zero. And you can clearly see that y_{22} of a pentode approximates that whereas, that for a triode did not do it at all.

So, what is the difference between MOS transistor and a pentode, typically today when you talk about MOS transistors, there is of course, a huge variety, but for most amplifier devices, the x axis V_{DS} will be a few volt at most whereas, here you can see that it is going all the way to five hundred volts. But the principles are exactly the same, you choose some operating point here, and bias your amplifier there so that you get a pretty high gain. Of course, you have to be little more careful with building this circuits, because instead of five volts, you have five hundred volts and you cannot be sticking a figure everywhere in the circuit, and getting an electric shock and so on. But the pentode is rather close to a MOS transistor and this was a very popular amplifier device.

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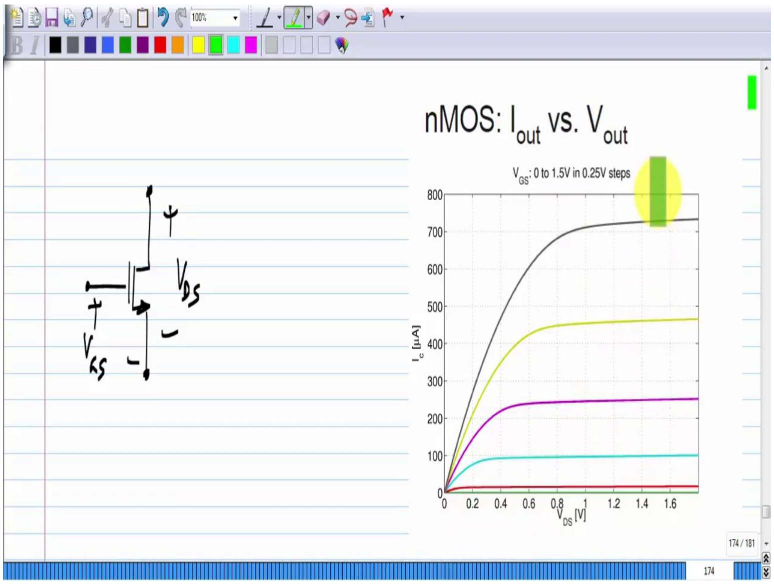

Now, here I show the simulated I_D vs V_{DS} characteristics of a real MOS transistor that I have used in many designs. And you can see that it sort of follows what we have been using, it would not be exactly the square law, so like everything else there will be approximate models, which help us carry out any calculation at all. And there will be more detailed models which will show you all kinds of deviations from the approximate model. The approximate model is square law, this would not be exactly the square law, but you can see qualitatively the resemblance, the triode region, the saturation region and the increase in current with V_{GS}. It is not labelled here, but you can see that V_{GS} has been varied from zero to one point five volts in some small steps.

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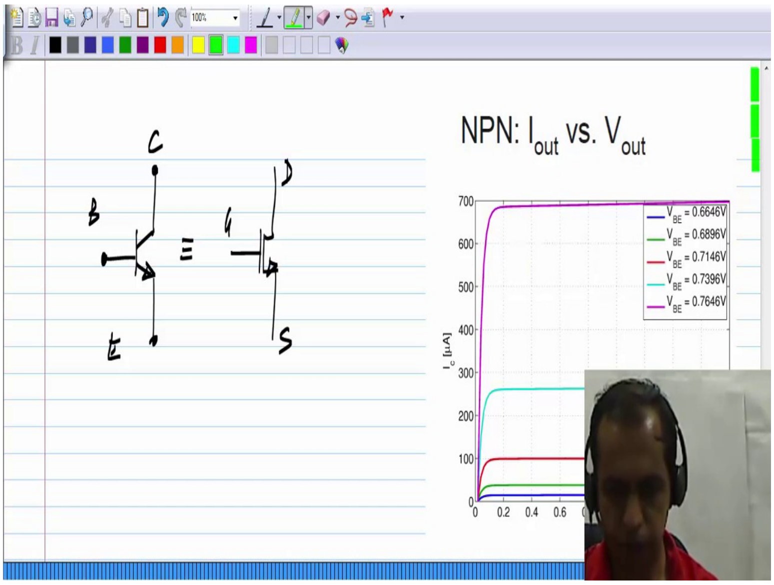

Now, here we have another device, which is known as an NPN transistor, which we will discuss later in this course. This was the type of semiconductor transistor that came after the vacuum tubes, it displaced the vacuum tubes, and it was itself kind of displaced by the MOS transistor for many applications. These are still being used, but the MOS is more popular. So, this has three terminals collector, base and emitter, which corresponds to respectively the drain, gate and the source. And you can see the characteristics are similar, there is the part of characteristic where this I out versus V out is very flat meaning the amplifier must be biased in this region. You can also see that the region corresponding to the triode is very small. In a MOS transistor, the triode region is quite useful, it turns out that in a bipolar junction transistor such as this it is not useful at all.

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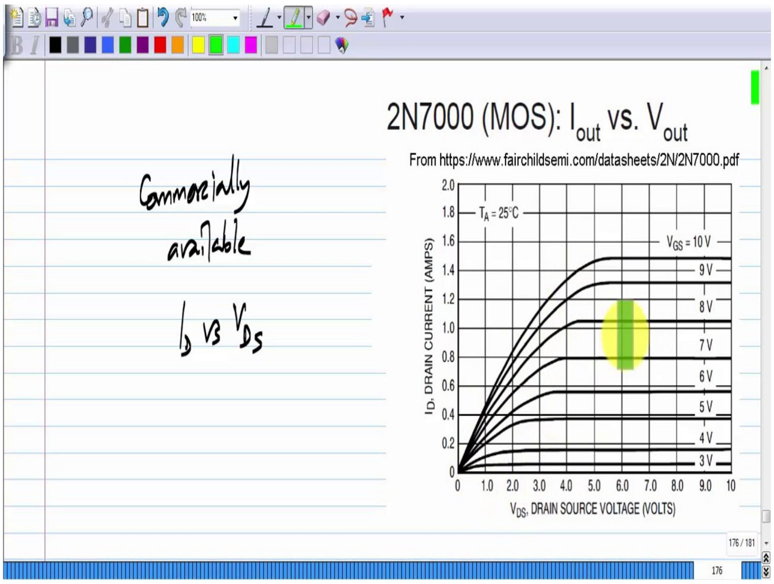

And this shows a commercially available MOS transistor, and its characteristics. This is I_D vs V_{DS}. And you can see it is sort of follows characteristics that we have described. And it does not quite square law, because for equal increments in gate voltage the increments in drain current are not increasing sharply, but it does follow it qualitatively.

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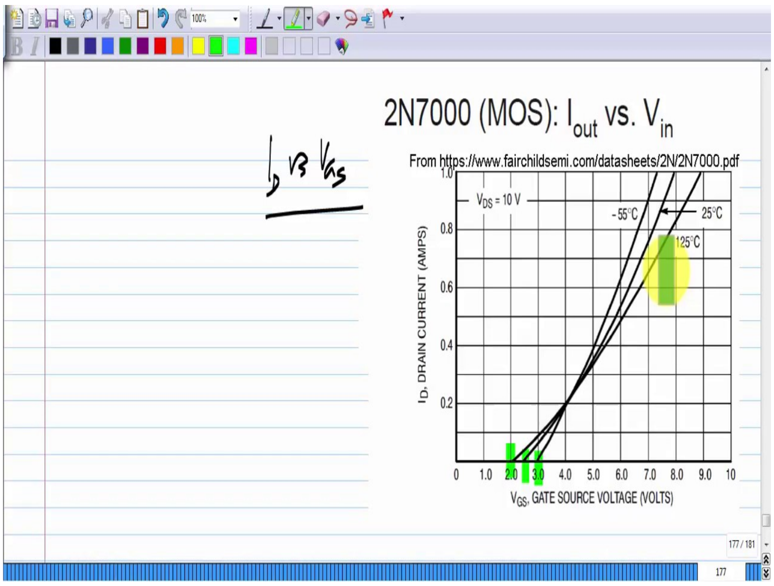

And this shows I_{out} versus V_{in} meaning I_D versus V_{GS} for the same type of transistor. And you can see that it follows this square law characteristics, and what is also shown here are characteristics at different temperature. Earlier I had mentioned that the characteristics of all these change with temperature, and you can see that here, you can see that both the threshold voltage and the current factor are changing with temperature.

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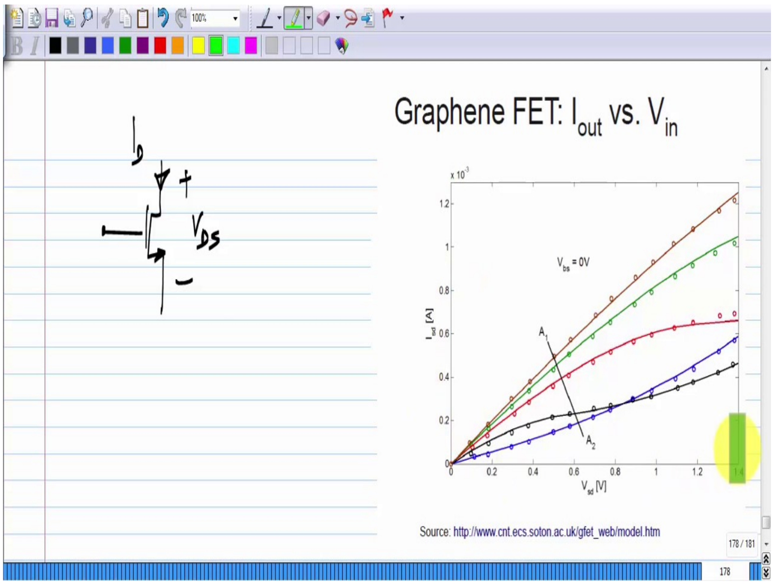

Now, let us go to some futuristic devices that people have been working on. These are still in the lab stage, you cannot buy an integrated circuit which use these transistor, but people have been trying to use all kinds of other materials to make transistor in the hope that some of them will be even better than the transistor that we already have. So, this is some transistor I will continue to use the MOS symbol for it. And again what I have shown are the I_D vs V_{DS} characteristics, you may heard of this material called graphene, it appears in the news for all kinds of reason. And here people have tried to make transistor using graphene and you can see that there are some parts of the characteristics where it becomes flat like the red curve here, and this brown ones are not quite becoming flat, so obviously the aim of the people designing devices is to get this flat regions, so that you can make good amplifiers.

But even if you do not have this flat region, you can use it as an amplifier, it will be a poorer amplifier, you will get lower gain, but just like the triode you could possibly use that. And you can see that the current and voltages are similar to what would you get in a MOS transistor.

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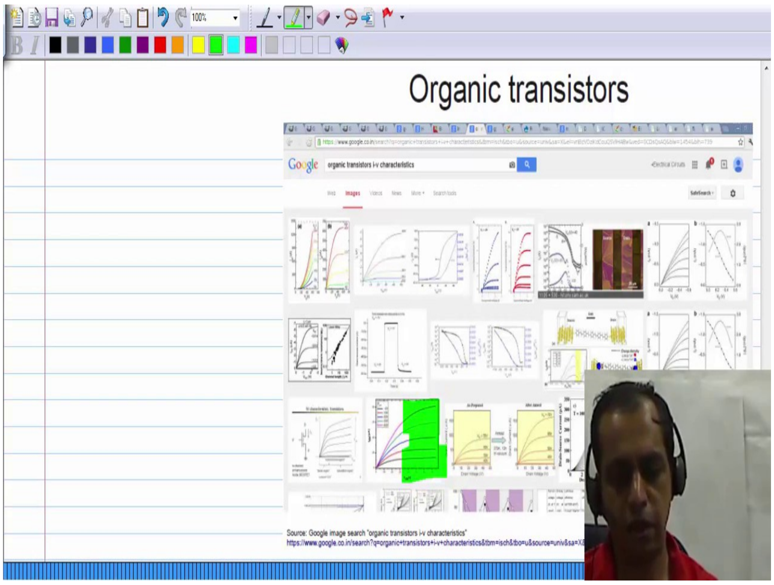

And this is the picture which I pick from the web, and you may go to Google and search for organic transistors, do not worry about all the details, there are some many many curves here, but you can see that it has characteristics like these. You can see it starts from zero and goes up and then kind of becomes flat and here it goes up in a strange way, but it becomes flat again. So, essentially any transistor you make must have this type of characteristics that is what people are aiming for. And if you want to use it as an amplifier, obviously, you must bias it in the flat region like here.

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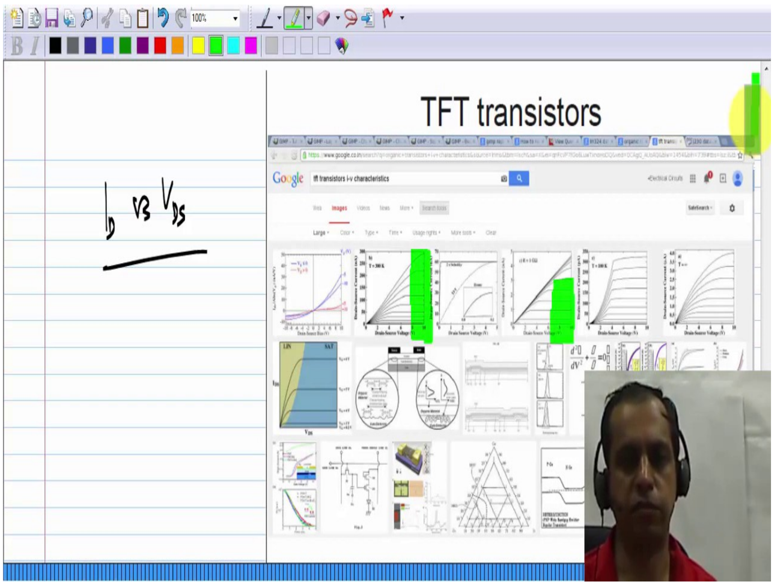

And here is another variety of transistor known as TFT transistor. Again this is obtained from a web search. You can see, it has these regions where there is substantial variation of I with V_{DS}, and these regions where the curves become flat. By the way everywhere, what I am showing are the I_D vs V_{DS} characteristics, and you can realize that these are crucial ones. If you have flat region in that, you can make very good amplifier. You need to look at both parts of the characteristics I_D vs V_{GS}, and I_D vs V_{DS}. And I_D vs V_{GS} must have a very high slope, and I_D versus V_{DS} must be very as flat as possible.

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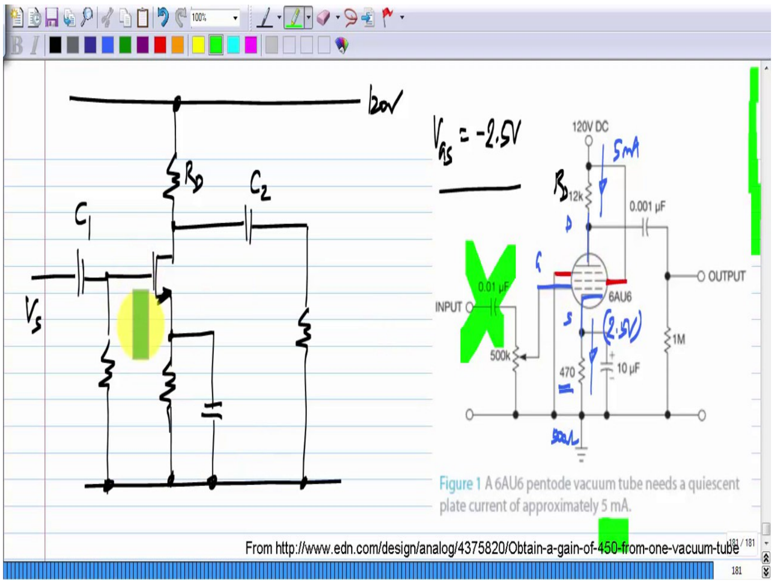

And just for fun, I am showing you in an example of a vacuum tube amplifier, it uses a pentode. So, now I do not want to confuse you too much, so just ignore this and that electrode. Like I mentioned earlier, this one is simply connected to the supply voltage, and this one is connected to ground. If you exclude those two, the remaining three terminals corresponds to the drain, gate and source of a MOS transistor. And this is taken from some circuit form EDN, and it says that the quiescent current is five milliamps. So, essentially it means that at the operating point, five milliamps is flowing here into the drain or into the plate, and it is coming out of the source or the cathode. So, this I will approximate it to five hundred ohms and say that the source is at two point five volts, if five milliamps is going through five hundred ohms.

And hopefully you will be able to recognize this structure, this is one of the circuit that we discussed. This is the circuit where you of course, have the drain bias resistor, which corresponds to this. And you would like to bias with a current source at the source terminal, but because current sources are harder to implement you substitute a resistor instead, that is exactly what this is. So, this is essentially what we have here is the common source amplifier with a resistance in the source which is standing in for current source at the source of the transistor. So, this source feedback bias and that is exactly what is used here. And you can see that there is a big capacitor from the source terminal to the ground, or the cathode to ground.

So, if you remember this is exactly what we did for our common source amplifier as well. The reason I am going through this amplifier is it is not likely that you will see this particular amplifier now, this is quite obsolete except some audio enthusiast still use them. But if you do encounter circuit like this or may be from a futuristic device, you should not confused or if you are given a futuristic device, you should be able to use the same principles to design the amplifier. And you can also see the output side, this is quite familiar we have ac coupling to take the output, this is C_2, and this case it is some one nano farad device. And also when we bias it like this, we would in case of MOSFET bias the gate using a voltage divider.

Here, you can see this is a relevant this capacitor relevant only for signals, so in the quiescent condition, the gate of the vacuum tube or grid of the vacuum tube is connected to zero. Now, remember it is connected to zero, but the source or the cathode is at two point five volts. So, this is operating with a quiescent V_{GS} of -2.5 volts and that is correct. In case of a MOS transistor, the type that I described, you needed a positive gate source voltage, whereas, in case of a vacuum tube, in this case, you need a negative gate source voltage so, it is simply connected to ground. You do not say voltage divider connected to the grid terminal. You see just the resistor connected to ground.

And you couple the signal using the capacitor C_1. Now, there is another additional detail here, this resistor made variable, this is I guess for an audio application and this variable resistor acts a volume control as well or a gain control as well. And of course, this supply voltage is much higher than what we used to, it is one twenty volts. So, essentially this is nothing, but a common source amplifier with source feedback bias, and the current source at the source terminal replaced by a resistor. So, the only difference between this and the MOS amplifier are the operating point. We need a negative V_{GS} and V_{DS} in the many tens of volts for a vacuum tubes, whereas, in our circuits, we have a couple of volts V_{GS} and few more volts of V_{DS}.

So, this is the lesson of the more general type just you expose to more things. And you can in fact, go to internet and look for amplifier using other devices, even if we have not discussed that particular device in the class you should still be able to understand the amplifier topologies as long as the correspond to the common source amplifiers. So, as we go along we also discuss other types of amplifiers.