Basic Electronics
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Lecture – 50
Schmitt triggers

Welcome back to Basic Electronics. We will now start with a new topic namely op amp circuits based on positive feedback. First, we will take a qualitative look at positive and negative feedback and revisit our old (Refer Time: 00:34) inverting and non-inverting amplifiers in this context. We will then look at the Schmitt trigger circuit, which is based on positive feedback. Let us start.

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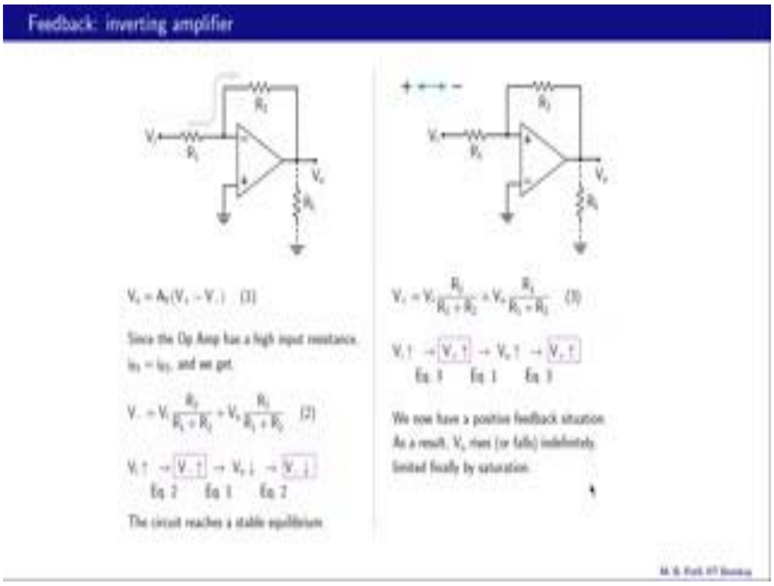

Let us now discuss feedback and our discussion will be qualitative in nature. And let us start with this inverting amplifier circuit, which we have seen before. And if you recall, we had mentioned earlier that these connections are very, very important. So, if you interchange the inverting and non-inverting terminals, the circuit would not work as an amplifier. And now let us see at least qualitatively, why it would not work as an amplifier.

Let us start with V o equal to A V times V plus minus V minus and this equation holds if the op amp is working in the linear region. Now, since the op amp has a high input resistance, this current is 0 and therefore, i R 1 is equal to i R 2, this current and this current are equal. And in this situation, we can obtain V minus using super position and this is what we get. And from this equation, we note that if V i increases or V o increases, then V minus will go up.

Now, let us perform a thought experiment, so to say in which V i is increasing, so this voltage is increasing. As a result what happens to V minus V i appears here and that is increasing, so therefore, the equation two V minus will also increase. Now, as V minus increases by equation 1 V o will decrease because this V minus appears with a negative sign here and therefore, V o decreases. If V o decreases this term decreases and therefore, V minus decreases, so that is what we have here. In other words, we have these opposing trends over here an increase in V minus causes a decrease in V minus. And this a negative feedback situation, which makes the circuit stable and therefore, we can proceed with the analysis that we carried out earlier.

Let us now consider this same circuit with the plus and minus terminals interchanged and see what happens. In this case, V plus is given by this equation here similar to this equation. And now let us imagine that V i have increased. What would happen as a result V plus would increase by equation 3; if V plus increases, V o will increase by equation 1; and if V o increases by equation 3 V plus will increase. And now we see that this trend is the same V plus increasing causes V plus too increase further and this situation is called a positive feedback situation and what happens is as a result V o rises or falls indefinitely limited finally, by saturation. So, V o will reach either plus V sat or minus V sat. And of course, the circuit cannot be used any more as an amplifier.

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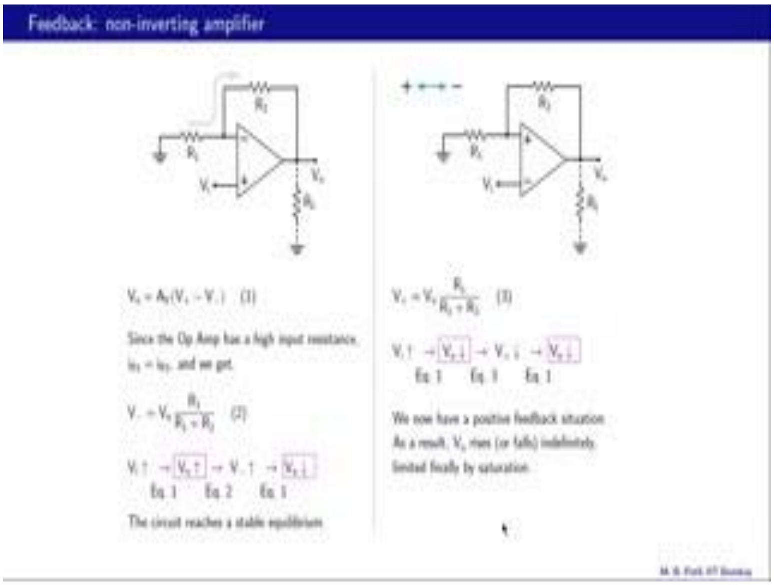

Let us now look at the feedback in a non-inverting amplifier. Here is the circuit. Once again, we have V o is equal to a V times V plus minus V minus and this V plus is the same as the V I here. Since the op amp has a high input resistance this current is zero and i R 1 is equal to i R 2. And in this case, V minus can be obtained simply by voltage division, so that is V o times R 1 by R 1 plus R 2 that is our equation 2.

Now, let us imagine that V i has increased V i is as same as V plus. If V plus increases V o will increase by equation 1; if V o increases V minus increases by equation 2; if V minus increases because of this negative sign, V o will decrease. And we see that this is a negative feedback situation because these trends are opposite. So, the circuit is stable and we can proceed with our analysis.

Let us now see what happens if we interchange the non-inverting and inverting terminals given by this circuit here. In this case, V plus is given by voltage division that gives us this equation 3. And let us now imagine that V i have increased. What is V i in this case V i is same as the V minus. And if V minus increases because of this negative sign V o will decrease like that; if V o decreases V plus will decrease by equation 3; and if V plus decreases V o will decrease by equation 1. So, clearly we have a positive feedback situation, because these trends are the same; a decrease in V o will cause a further decrease in V o, and as a result V o will rise or fall indefinitely limited finally, by saturation. And this circuit of course cannot be used as an amplifier.

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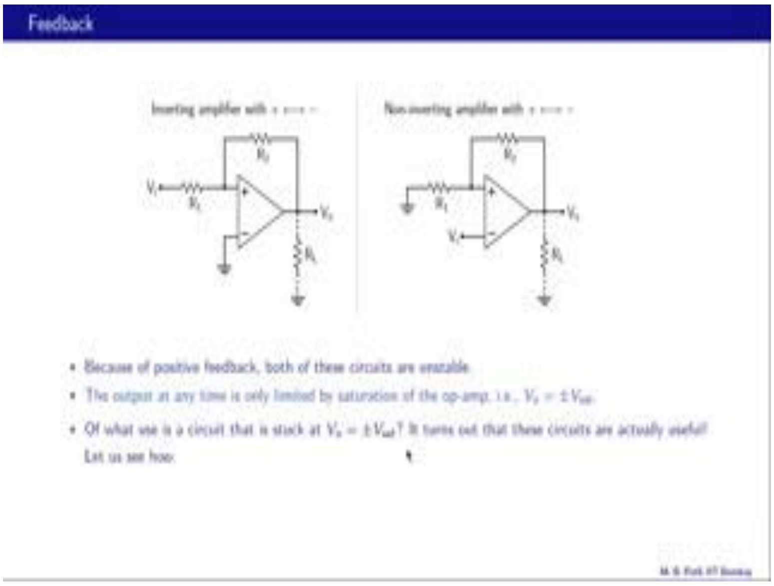

Let us summarize. Here is the inverting amplifier with the plus and minus input terminals interchanged. And here is the non-inverting amplifier also with the plus and minus input terminals interchanged. And as we have seen both of these circuits are unstable because of positive feedback. And the output at any time then is only limited by saturation of the op amp. So, V o here or V o here will be plus minus V sat. Now, the question is of what use is a circuit that is stuck at V o equal to plus V sat or V o equal to minus V sat. It turns out that these circuits are actually useful and let us see how.

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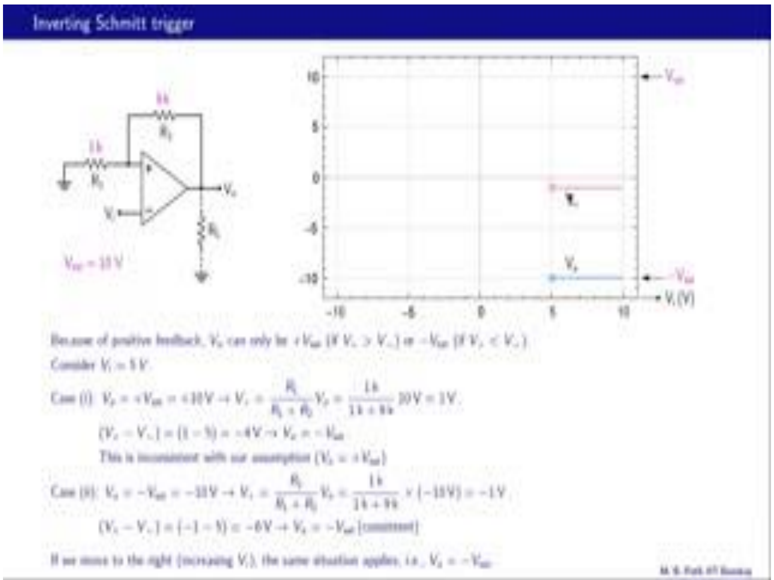

Let us look at the circuit, which is our non-inverting amplifier with the plus minus inputs interchanged. R 2 is 9 k, R 1 is 1 k and we were assumed V sat to be 10 volts. Now, as we have seen because of positive feedback V o can only be either plus V sat or minus V sat; it will be plus V sat if V plus is greater than V minus; otherwise it will be minus V sat.

Now, let us take an example. So, V i is equal to 5 volts. So, we have 5 volts here, and figure out whether the output would be plus V sat or minus V sat. Let us take case one first in which V o is plus V sat. So, we have 5 volts here, we have 10 volts here; if this is 10 volts then by voltage division this V plus would be 1 k divided by 10 k times 10 volts or 1 volt. And the situation now is V plus is 1 volt V minus is 5 volts. So, V plus is smaller than V i or V minus, and therefore V o should actually be minus V sat. So, clearly there is a inconsistent situation here, and therefore this cannot happen. So, what happens in this case is V o is equal to minus V sat, and let us check quickly whether that is consistent or not.

So, we have 5 volts here, minus 10 volts here. And by voltage division V plus would be minus 10 times 1 by 10 or minus 1 volt. So, V plus is minus 1 V minus is 5, and therefore, V o would be minus V sat and everything is consistent. Let us show that data point on this plot here. What are we plotting, we are plotting V plus as well as V o as a function of V i. And right now we have only one data point that is V i equal to 5; for V i equal to 5, we have V plus equal to minus 1 volt; and V o equal to minus 10 volts that is the same as minus V sat. And if we move to the right that is increasing V i, the same situation applies and V o remains equal to minus V sat as shown here. So, in this entire range, V o remains equal to minus V sat and V plus remains equal to minus 1 volt.

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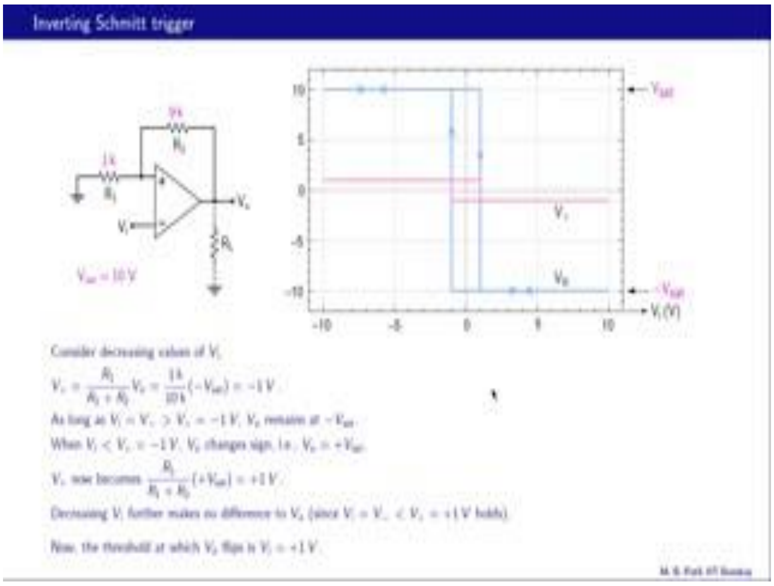

So, we have got this part of the V o versus V i relationship. And now let us consider decreasing V i so that means we are going in that direction. And V plus as we have seen is V o times R 1 by R 1 plus R 2; and since V o is minus V sat V plus is minus 1 volt and that is what we have shown here as well. Now, as long as V i which is same as V minus remains greater than V plus V o will remain at minus V sat, and what is V plus V plus is minus 1 volt. So, up to this point, things will not change. If V i is decreased further that means it goes below V plus which is minus 1 then V o will change sign, V o will become plus V sat and that is shown over here. And if V o changes V plus also changes, it will now become R 1 by R 1 plus R 2 times plus V sat or plus 1 volt. So, V plus has also changed from minus 1 volt to plus 1 volt here.

And if we go on decreasing V i further, what happens this V plus is equal to 1 volt and we are decreasing this V i further. So, nothing is going to really change, because V plus will remain larger than V i and that is what we get if we go on decreasing V i. Now, the threshold that which V o flips is plus 1 volt. So, now imagine that we are increasing V i in that direction and V plus is sitting at 1 volt when V i crosses that 1 volt the output is going to change again like that. So, that is our V o versus V i relationship and we see this strange plot here which is called hysteresis.

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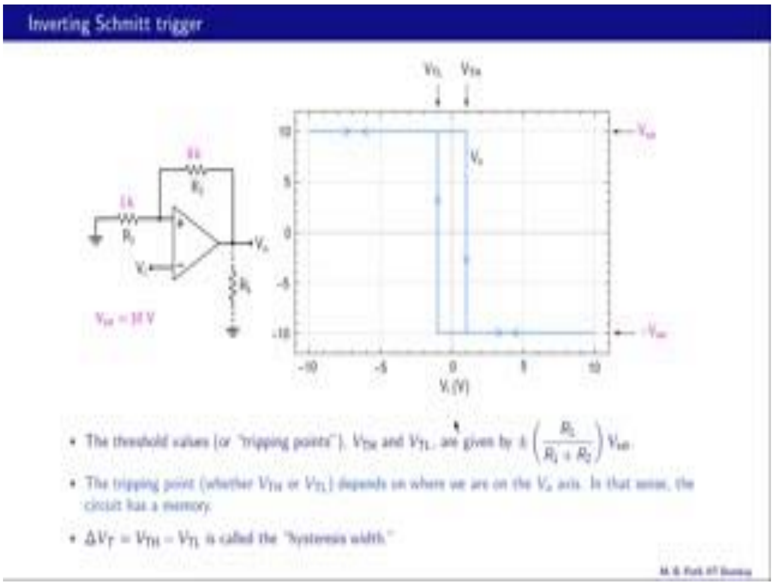

Here is the V o versus V i relationship again and this circuit is called the inverting Schmitt trigger. And let us summarize the salient features now. First, there are this threshold values - lower threshold and higher threshold. The lower threshold is called V TL and the higher threshold is called V TH. And these threshold values are also called tripping points denoted by V TH and V TL. And as we have seen in the last slide, they are given by plus minus R 1 by R 1 plus R 2 times V sat. Now, which tripping point applies really depends on where we are on the V o axis and that is a big difference between this circuit and other circuits, we have seen earlier.

For example, if we are here then the tripping point that is relevant is this one - V TH, and that is also the reason we have used these arrows here. If you are here and we keep reducing V i now then the tripping point that is relevant is this one - V TL. So, in that sense, the circuit has a memory, because its behavior depends on the past. What is the past that is whether V o has high earlier or whether V o was lower? And this quantity delta V t which is the difference between the V TH and V TL is called the hysteresis width, this width here.

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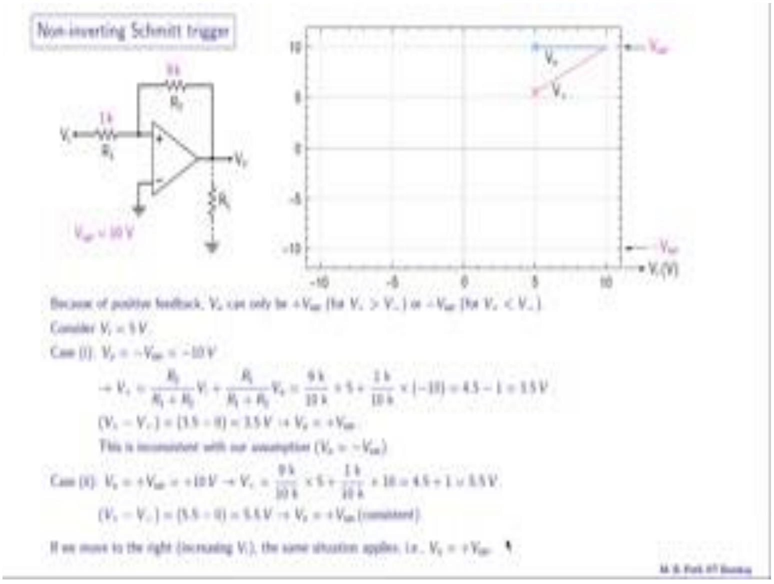

Let us now look at the non-inverting Schmitt trigger which is obtained from an inverting amplifier by interchanging the inverting and non-inverting op amp inputs like that. And as we said earlier because of positive feedback V o can only be either plus V sat or minus V sat, plus V sat if V plus V is larger than V minus and minus V sat otherwise. So, let us take an example say V i equal to 5 volts, and see whether V o is expected to be plus V sat or minus V sat in this case. Suppose V o is minus V sat, so this V o is minus 10 volts, what is V plus then this current is 0, and V plus can be obtained by super position.

So, we have V i here and V o here, consider these two as independent voltage sources, and then we get this expression here. So, R 2 by R 1 plus R 2 times V i plus R 1 by R 1 plus R 2 times V o, R 2 is 9 k R 1 plus R 2 is 10 k. So, 9 k by 10 k times V i which is 5 volts plus R 1 1 k R 1 plus R 2 10 k times V o, V o we have assumed to be minus 10 volts, minus 10, so that turns out to 3.5 volts. So, V plus minus V minus is 3.5 minus 0, so obviously, V plus is greater than V minus, and therefore V o must be plus V sat. And clearly there is some inconsistency here because we started assuming V o equal to minus V sat and we ended up with V o equal to plus V sat. So, clearly this is not going to happen.

So, what does happen is V o becomes equal to plus V sat that is plus 10 volts and let us now check whether that is consistent. So, let us first find V plus from this same expression here 9 k by 10 k again times V i which is 5 volts plus 1 k by 10 k times V o which is 10 volts, so that turns out to be 5.5 volts. So, V plus is 5.5, V minus is 0. So, therefore, V o is plus V sat and that is consistent with our original assumption. So, that is the data point not over here V o is 10 for V i equal to 5 volts, and at that input voltage V plus is 5.5.

Now, if move to the right that is in the direction of increasing V i. What do we expect to happen, it turns that V o remains equal to plus V sat of course, V plus is not constant anymore because V plus varies as V i varies. So, the relationship between V plus and V i is a straight line and the slope is positive and that is what we get. And now what we want to do is as we decrease V i, we want to see what happens.

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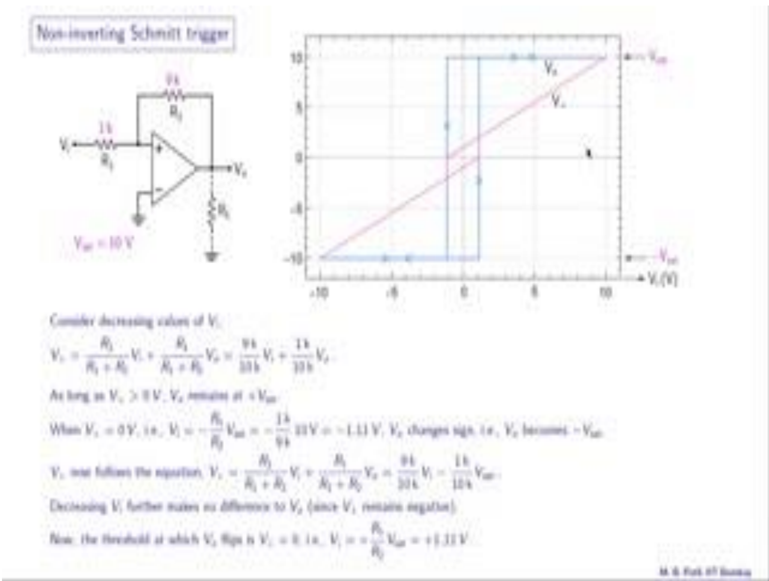

Now, let us see what we expect as V i is decreased, V plus is going to decrease, because as we saw in the last slide V plus is proportional to V i. And at some point, V plus would become negative and at that point V o will flip from plus V sat to minus V sat, and let us see when that happens. So, consider decreasing values of V i, V plus the same expression as we saw earlier R 2 by R 1 plus R 2 times V i plus R 1 by R 1 plus R 2 times V o. So, that is 9 by 10 times V i plus 1 by 10 times V o.

Now, as long as V plus is positive V o will remain equal to plus V sat like that and that happens up to this point. So, V plus is positive just positive at this point. And if we decrease V i further in that direction, then V plus is going to cross 0, and then V o is going to flip from plus V sat to minus V sat. And when does that happen, when does V plus becomes 0; for V plus to become 0; this expression has to become 0 and that gives us V i equal to minus R 1 by R 2 times V sat which is minus 1 by 9 times 10 or minus 1.11 volts.

So, when V i is minus 1.11 volt then V o changes sign that is it goes from plus V sat to minus V sat. So, this is how V o has changed from plus V sat to minus V sat. What about V plus, V plus is given by this equation, the same equation as this one except, now V o has become minus V sat. At this point, V i is minus 1.11 volt a we saw earlier. So, this term is already negative and this term is also negative now, because V o is minus V sat. So, the net result is at this point V plus is a negative number, we can calculate that.

So, now what happens as we continue to decrease V i further in that direction V plus is proportional to V i. So, as V i is decreased V plus will also decrease and at this point V plus is already negative. So, what will happen V plus will keep going down, it will become more and more negative as V i is decreased. If V plus continues to be negative that is less than V minus, V o will then continue to be minus V sat and we would expect V o to stay at minus V sat.

And let us now look at the equation that V plus will follow in this region. V plus is given by this expression same as this one except now V o has become minus V sat. So, we have V plus equal to 9 by 10 times V i minus 1 by 10 times V sat. So, V plus versus V i is still a straight line with a positive slope, but now the x intercept has changed. So, we will now have this line here and its x intercept will be somewhere here like that.

Now, let us consider V i increasing. So, we go in that direction now. And V plus will also increase and at some point V plus will cross 0 and that is where V o will flip from minus V sat to plus V sat. And what is V i at that time. So, what is the threshold that is given by V plus equal to 0. So, we have 0 equal to 9 by 10 times V i minus 1 by 10 times 10. So, V i turns out to be R 1 by R 2 times V sat or plus 1.11 volts like that. And now if we keep increasing V i, V o will not change and we have completed the V o versus V i picture.

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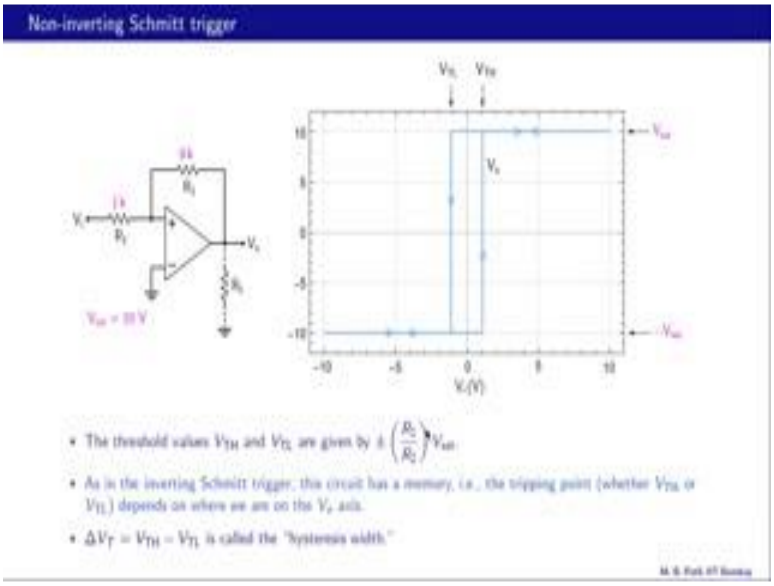

Let us summarize the situation for the non-inverting Schmitt trigger. Here are the threshold values V TH and V TL; V TH is given by plus R 1 by R 2 times V sat, and V TL is given by minus R 1 by R 2 times V sat. And as in the inverting Schmitt trigger this circuit also has memory. Why do we say that? Because the tripping point or the threshold point depends on where we are in this V o versus V i plane. If we are here and if we are increasing V i then the tripping point is V TH. If we are here and if we are decreasing V i then the tripping point is V TL and that is indicated by the arrows here. Once again delta V T equal to V TH minus V TL is called a hysteresis width.

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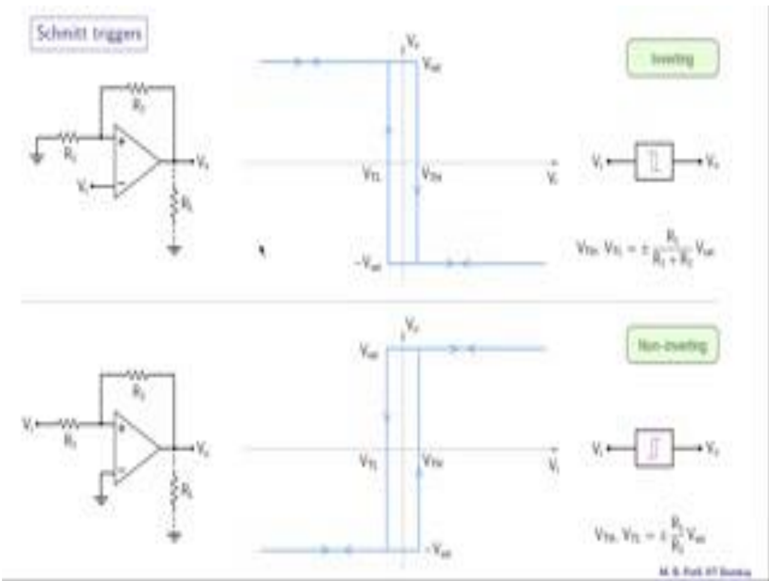

Here is a summary of a both types of Schmitt triggers which we have seen inverting and non-inverting. The inverting Schmitt trigger is denoted by this symbol here; and the non-inverting Schmitt trigger by this symbol; essentially this symbol comes from the V o versus V i relationship. The V TH, V TL expressions are also included here. And it is a good idea to turn off your monitor at this point. Draw the circuits, go through the derivation in your mind and come up with the V o versus V i relationship for each of these Schmitt triggers. And also remember to derive the expressions for V TH and V TL rather than remembering these.

To summarize we have started looking at a different class of circuits in this lecture. In contrast to the circuits, we have seen earlier the circuits we have seen today, the Schmitt trigger circuits are based on positive feedback. In the next class we will look at some applications on the Schmitt trigger, until then goodbye.