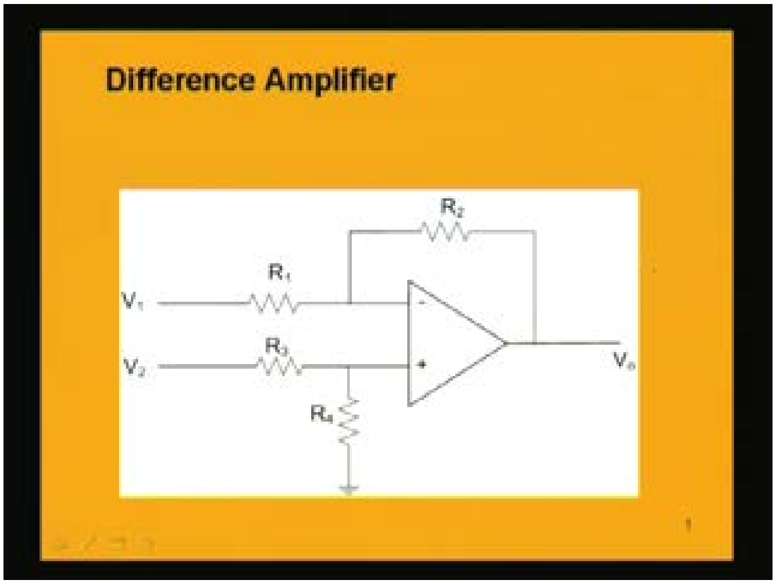
**Basic Electronics**
**Dr. Chitralekha Mahanta**
**Department of Electrical and Communication Engineering**
**Indian Institute of Technology, Guwahati**

**Module: 4 - Operational Amplifier**
**Lecture-3**
**Op-Amp Applications – Part 1**

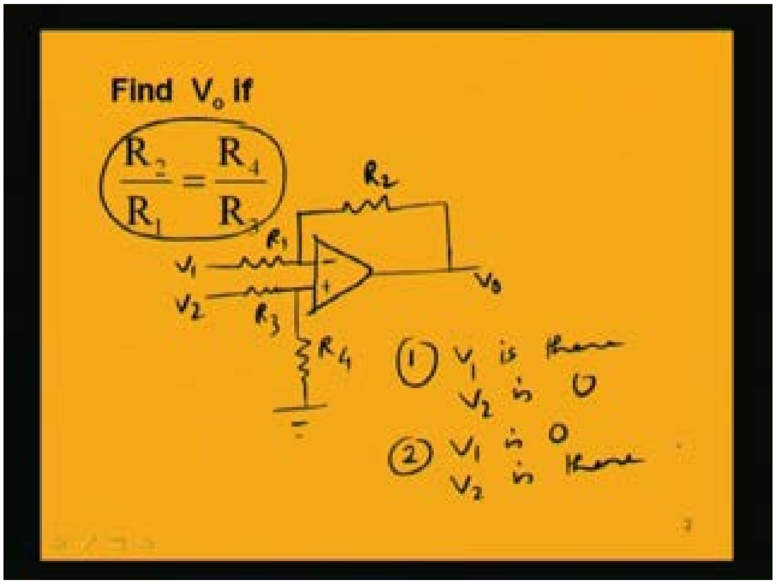
We are discussing about the op-amp or operational amplifier and we have been discussing about the application of op-amp in different circuits and we have seen applications of op-amp in practical amplifier circuits like inverter, non-inverter, integrator, differentiator and also we have discussed about the difference amplifier. The difference amplifier circuit is the circuit which gives the difference between the two input voltages with some scaling factor which is given by the connected resistances. Let us again visit that difference amplifier circuit.

(Refer Slide Time: 2:00)




In this diagram there is a circuit for difference amplifier and here we have to find out what is the output voltage $V_O$ naught for given input voltages of $V_1$ and $V_2$.

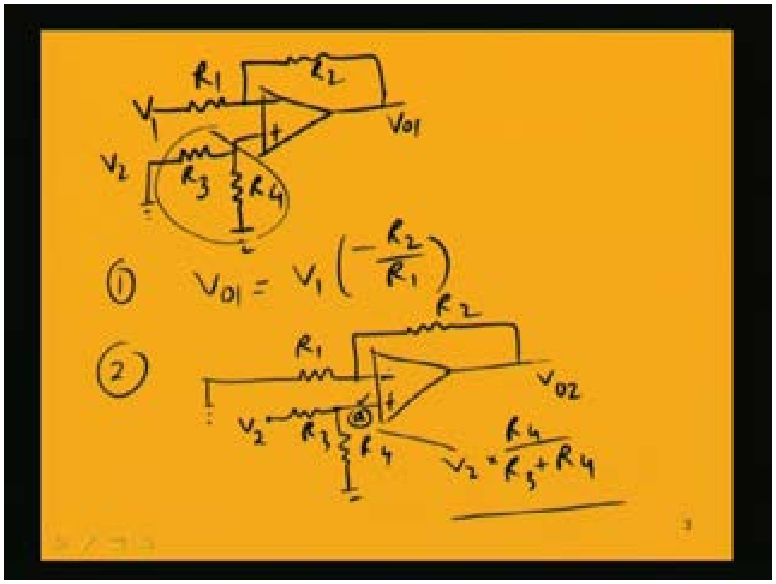
(Refer Slide Time: 2:21)




The ratio between the resistances is such that $R_2$ by $R_1$ is equal to $R_4$ by $R_3$. What will be the output voltage $V_0$ if this ratio is maintained? In order to solve such example we will apply the ideal op-amp consideration that we have been using till now, that the ideal op-amp has infinite input impedance, so there is no current entering into the op-amp. We have also seen that the gain being infinite for an ideal op-amp, the voltages at the two terminals of non-inverting and inverting, that is at these two terminals are non inverting and inverting terminals, are equal. Applying these principles we will try to solve the circuit. In order to solve, let us draw this circuit again. This is a difference amplifier having the resistances at the two terminals of inverting and non-inverting. The resistances are $R_1$, $R_3$ and we have another resistance to ground at the non-inverting terminal which is $R_4$ and the feedback resistance is $R_2$. So this is the circuit and at the input there are two voltages $V_1$ and $V_2$. We are interested in finding this voltage $V_0$ if the ratio $R_2$ by $R_1$ equal to $R_4$ by $R_3$; so this has to be satisfied.

If we look into the circuit, in order to find out the voltage $V_0$, view the two voltages; one is $V_1$ and the other is $V_2$. There are two input voltages. Applying the principal of linear circuit, this is a linear circuit; this op-amp is linear, we will find out this output voltage, applying the principle of superposition. We will find out $V_0$ first due to one voltage only, making the other zero and then sum up the responses due to individual voltages to give the combined output voltage. That is to be done; in these types of circuits that will simplify the solution. Here let us first keep voltage $V_1$ and make the voltage $V_2$ zero and find out what is $V_0$? First part of the circuit when $V_1$ is there and $V_2$ is zero and second part, we will do when $V_1$ is zero and $V_2$ is there.

(Refer Slide Time: 6:14)

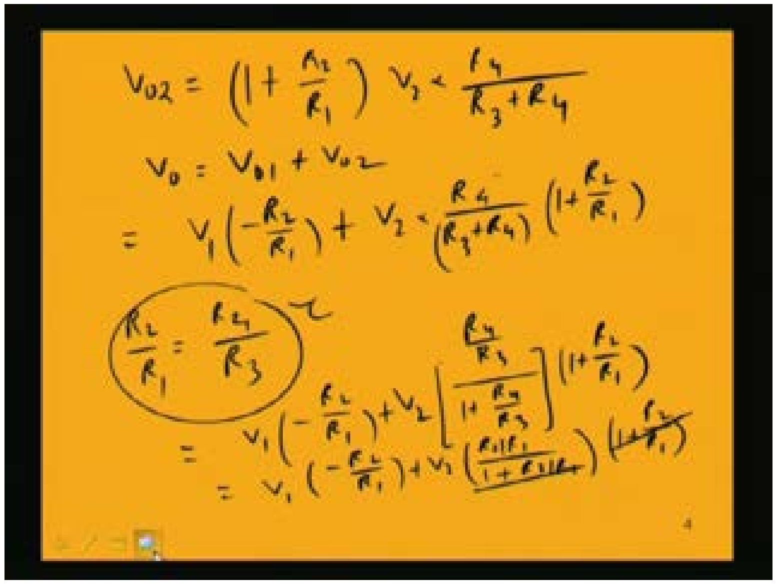



The first condition of making $V_2$ zero will give us the circuit as having $V_1$ here. This is the resistance $R_1$ and this is the inverting terminal and $V_2$ is zero. $V_2$ is zero means it is like grounded. $V_2$ here is grounded, but the resistances cannot be eliminated. The resistances which were connected to $V_2$ will still be there. This is the non-inverting terminal which is connected to these two resistances, which are connected to ground because $V_2$ has been made zero and the other is this $R_2$, as it is there. Let us name the response due to this $V_1$ alone as $V_{01}$. This is the first condition. Due to $V_1$ alone, the voltage if we want to find out, if we look into the upper part of the circuit it is an inverting type of circuit, inverting op-amp configuration that we have seen earlier. The voltage $V_{01}$ will be equal to $V_1$ minus $R_2$ by $R_1$. Here I am using the circuit, which was used earlier for inverting op-amp. Because if we look into the lower portion of the circuit, these two resistances $R_3$ and $R_4$ which are connected to the non-inverting terminal, they are not affecting in any way because the current entering into the op-amp is zero. So the current cannot flow through this $R_3$ and $R_4$. That is this part of the circuit which consists of $R_3$ and $R_4$ does not affect the overall op-amp circuit. That is why it is simple application of an inverting type of op-amp.

Second part is when you have $V_1$ zero and $V_2$ is alone there. If we consider that $V_1$ is zero, this is $R_1$, this is the inverting terminal and this is the feedback resistance $R_2$. In the non-inverting terminal we have $R_3$ and $R_4$ like this and $R_3$ other terminal is connected to $V_2$. In this part of the circuit, what is the response at the output? Let us name it as $V_{02}$, which is due to $V_2$ alone. In order to solve this circuit, let us focus on this part that is the non-inverting terminal. The voltage which is applied at this point, let us name it as say a, that is the non-inverting terminal is $V_2$ into $R_4$ by $R_3$ plus $R_4$ because this voltage $V_2$ is having voltage division one part across the resistance $R_3$ and the other voltages across this resistance $R_4$. So, the voltage which is available at the positive terminal that is the non-inverting terminal which is denoted by this node a, that is nothing but $V_2$ into $R_4$ by $R_3$ plus $R_4$. If this voltage is applied at this terminal a and we are to find out the output response $V_{02}$, this is nothing but a non-inverting type of op-amp.

We have a voltage at the non-inverting terminal and this voltage we have found out $V_2$ into $R_4$ by $R_3$ plus $R_4$ and we have connected these resistances at the inverting terminal which is due to $R_1$ and $R_2$. That is nothing but a non-inverting op-amp and the voltage at the output $V_{02}$ if we want to find out that is equal to 1 plus $R_2$ by $R_1$ into the voltage which is given at the non-inverting terminal.

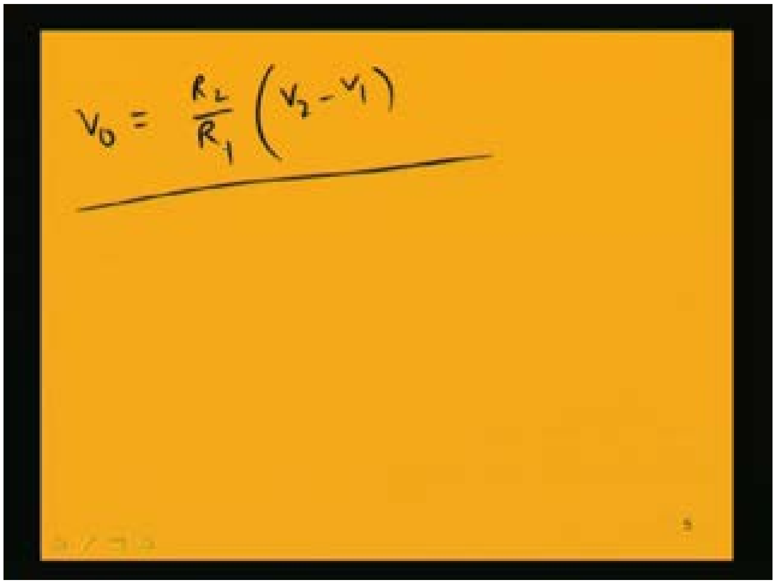
(Refer Slide Time: 11:03)




If we want to find out $V_{02}$ that is equal to 1 plus $R_2$ by $R_1$ into the voltage at the non-inverting terminal, which we have found out and that is equal to $V_2$ into $R_4$ by $R_3$ plus $R_4$. Now the total response $V_0$ we have to find out and that is equal to $V_{01}$ plus $V_{02}$. We just add up these two voltages; individual responses we add up to find the final response. $V_{01}$ we have found out to be equal to $V_1$ into minus $R_2$ by $R_1$ plus this portion of $V_{02}$ we have to add up and that is equal to $V_2$ into $R_4$ by $R_3$ plus $R_4$ into 1 plus $R_2$ by $R_1$. This is finally the voltage available but we will also use the condition given here and the condition which we are having is that $R_2$ by $R_1$ is equal to $R_4$ by $R_3$.

Manipulating this response a little and using this relation, we will further simplify this voltage expression $V_0$ and you can look in this expression. If we divide this numerator and denominator by $R_3$, then we will get in the numerator $R_4$ by $R_3$ and in the denominator we will get 1 plus $R_4$ by $R_3$. As this ratio is equal, we can now utilize it. One more step we will write, which is equal to $V_2$ into, we will write it $R_4$ by $R_3$ by 1 plus $R_4$ by $R_3$ into 1 plus $R_2$ by $R_1$; so this we get. Now this $R_4$ by $R_3$ we can replace by $R_2$ by $R_1$. Then the term in the denominator and this term will cancel out and then we will get further simplified expression which can be written as minus $R_2$ by $R_1$ plus $V_2$; in the numerator we will write $R_2$ by $R_1$ using this relation. In the denominator again 1 plus $R_2$ by $R_1$ and you can see here in this expression we are cancelling out these two terms.

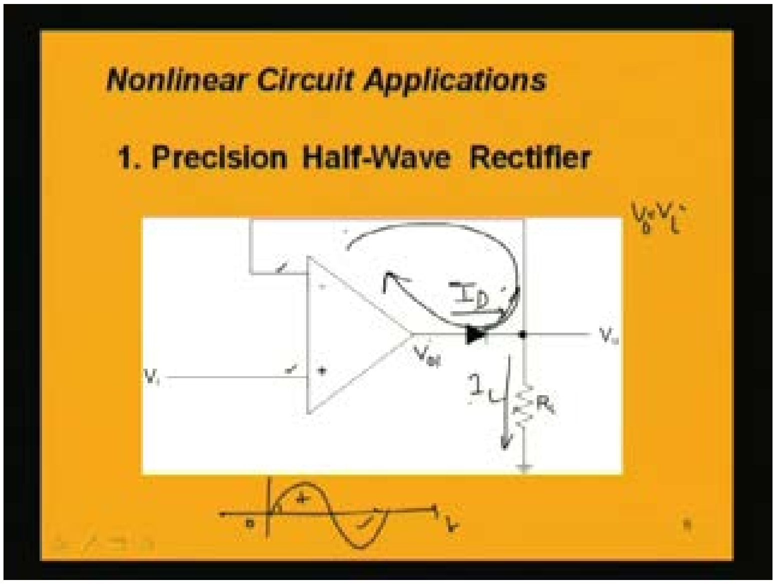
(Refer Slide Time: 14:07)




Finally what will we get? We take common this $R_2$ by $R_1$, because in this expression we see $R_2$ by $R_1$ finally will be left here in the second part of the expression; $R_2$ by $R_1$ we can take common and what we will get is $R_2$ by $R_1$ into $V_2$ minus $V_1$. This is the final expression for the output voltage $V_0$. If we maintain this resistance ratio that $R_3$ by $R_4$ equal to $R_1$ by $R_2$ or $R_4$ by $R_3$ equal to $R_2$ by $R_1$, then we get a simple difference amplifier which is giving the output voltage as a difference between the two voltages at the input and it is multiplied by a scaling term and that scaling term is coming from the resistances $R_1$ and $R_2$. This is one example of application of op-amp which is very important and we will see later that these are difference amplifiers. Basically these are used in many instrumentation circuits where we want to amplify a very small voltage. Because in instrumentation what happens is that generally the voltage which has to be measured, may be in the order of millivolt or even lesser and we want to amplify it to be used somewhere. We have to basically amplify this small magnitude of voltage and in that case we will use the basic principle of the difference amplifier because here this $V_2$ minus

$V_1$ is that available differential voltage at the input and that is amplified by this resistance network.

(Refer Slide Time: 16:03)



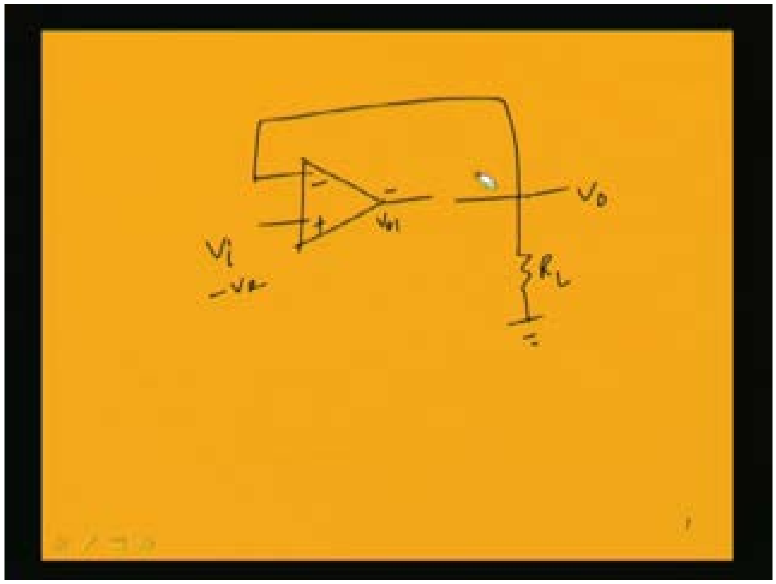

Let us consider a circuit where, in the output we want to have a half wave rectified output. But this output is exactly same in magnitude with the input voltage in that half of the input cycle when it is rectified. That is why the name is precision rectifier. In the normal rectifiers which we have seen earlier, in our diode study we were discussing about half wave rectifier circuit and in that type of circuits what we saw is that using a single diode we get rectified output at the output side for one half of the input signal and for the other half we get zero voltage. But what is important is that, in that half wave rectification for a very small voltage the diode was not conducting because diode conducts when the voltage applied is greater than the cut in voltage which is 0.7 volt for silicon and 0.3 volt for germanium.

For that portion of the input voltage when it is very small and less than the cut in voltage, there was zero current in the diode and so at the output also we got zero voltage. So there is a lag between the start of the current and the application of the voltage. But in this precision rectifier, which we are going to discuss that problem will be overcome. That is we will get exactly the input voltage at the output for the portion of the cycle when the rectification is occurring or for that portion of the cycle when the diode is conducting. Let us see a circuit where we are using an op-amp along with a diode. This diode is connected at the output side. This is the feedback part which is formed by this diode. If we consider positive half cycle of the signal, suppose we are giving AC signal which is sinusoidal. In the positive half cycle of the signal when this $V_i$ is positive, at the output which we are naming as $V_{01}$ that will be also positive which means that the phase of the input voltage is not changed at this output $V_{01}$ because it is the non-inverting terminal. As we are applying positive half cycle and here also we are getting a voltage which is positive, this diode will conduct. Let us take this diode current. When it is conducting the current is $I_D$. The diode current will flow through this $R_L$ resistance. Let us name this resistance as $R_L$ and this current through this resistance is $I_L$, so the current part is like this.

Now what will be $V_0$? We are considering say this feedback loop. This feedback loop is now complete and it is nothing but like a voltage follower circuit; we have earlier discussed voltage follower. This diode is conducting. So this voltage $V_0$ is equal to $V_i$. The voltage here and voltage here are same. So this voltage is $V_i$; so $V_0$ equal to $V_i$. When in the positive half cycle we are having this feedback loop is complete and $V_0$ is equal to $V_i$ and when $V_i$ is very small, even less than this cut in voltage still $V_0$ is equal to $V_i$. So we are getting at the output same voltage as $V_i$. $V_0$ and $V_i$ are equal, so there is no portion of this output voltage where we will get zero voltage. In the positive half cycle of the signal when this diode is conducting, then also we get $V_0$ equal to $V_i$ but when this $V_i$ is very small voltage, still as this is a voltage follower circuit we are getting $V_0$ equal to $V_i$.

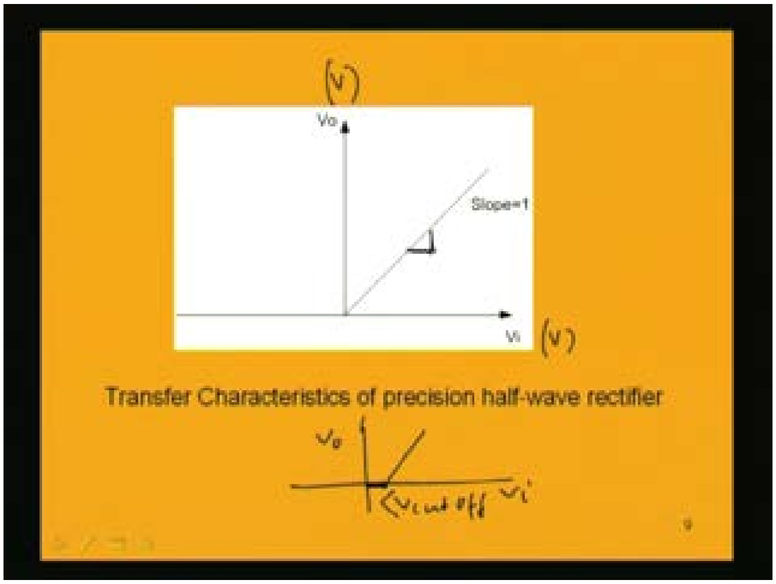
But what will happen in negative half cycle of this input signal? For example in this negative half, we are applying a negative voltage at $V_i$. So $V_{01}$ also will be negative. Because it is a non-inverting terminal, the polarity of the applied voltage does not change; same polarity. So $V_{01}$ will be also negative. When $V_{01}$ is negative, then this diode does not conduct. When this diode does not conduct, this feedback loop is now not complete because there is a break here.

(Refer Slide Time: 21:37)



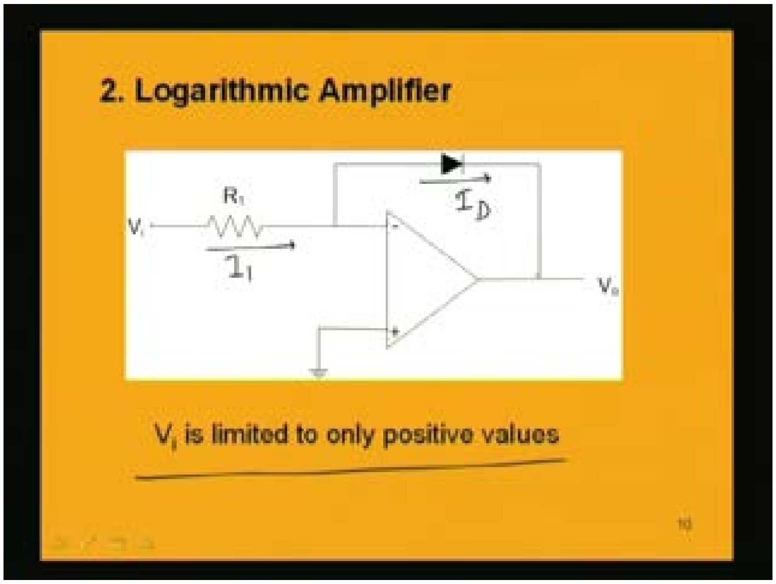
What we will get? Actually if we have $V_i$ negative, then we are having this diode and this is the feedback part and this is the resistance which we are considering. We are interested in finding out $V_0$. As this voltage input is negative, this $V_{01}$ is also negative. This diode doesn't conduct, so there is a gap in this feedback part. This feedback part is not complete. That means it is not continuous, there is a break. As there is a break, $V_0$ will be now equal to zero. There will be no flow of current through $R_L$. $V_0$ will be equal to zero; that means we are having in the negative half cycle, zero voltage and in the positive half cycle equal to input voltage. We are having now a perfect half wave rectifier which is called precision rectifier, the reason being that we are having exactly the input voltage at the output for the positive half cycle.

(Refer Slide Time: 22:52)




This is the plot between $V_0$ and $V_i$ and this plot as we know, it is called transfer characteristics. If we plot this $V_0$ versus $V_i$, this $V_0$ and $V_i$ being the same unit, both are voltage, $V_1$ is also voltage $V_0$ is also having unit voltage. As in the positive half cycle, when $V_i$ is positive, $V_0$ is equal to $V_i$. It is a straight line passing through the origin and the slope is 1. Slope is 1 because at any point if we find a slope this is equal to this. That means n theta is equal to 1. So theta is 45 degree angle. This is the characteristic of the $V_0$, output voltage versus input voltage $V_i$. In the negative also it is totally zero. This is the transfer characteristic of the precision half-wave rectifier but in the normal half wave rectifier we did not get this type of characteristics because for a considerable portion of $V_i$, we are getting actually zero voltage, only then $V_0$ and $V_i$ were equal. But for this portion when the voltage $V_i$ is less than cut off, cut off voltage means silicon has 0.7 volt; for that portion $V_0$ was zero. Now we are achieving this precision in the half-wave rectifier with this precision rectifier circuit.

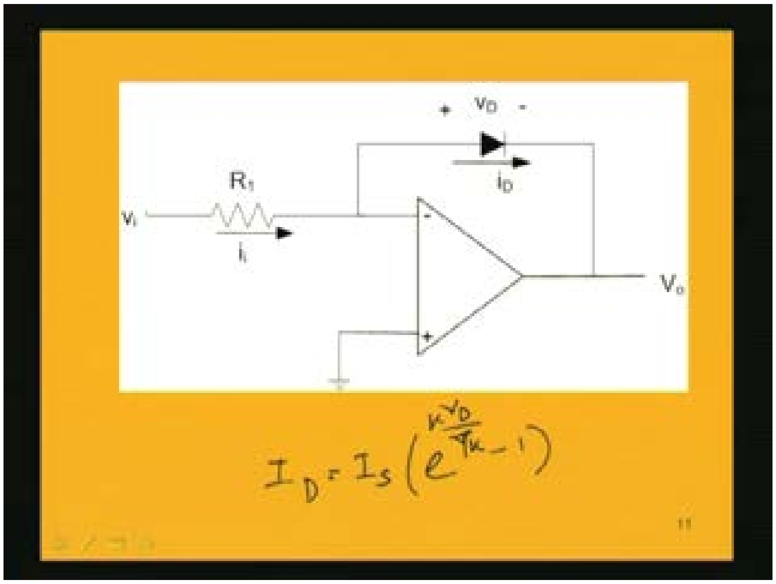
(Refer Slide Time: 24:42)




Another example of application of an op-amp with non-linear components is logarithmic amplifier. As the name suggests it has something to do with the logarithm. Here what we will get finally that we are going to derive. If we find out the output voltage $V_0$, that will have a logarithmic function of the input voltage. That is why it is called logarithmic amplifier. In this circuit we are having this op-amp as well as a PN diode, which is connected in this feedback part. Resistance in the input is $R_1$ and $V_i$ is the input voltage. One thing to notice is that we will have to apply only positive values to the input voltage. That means we will only apply positive $V_i$. Because this diode has to conduct, we cannot apply negative voltage so, $V_i$ is actually limited to only positive values. If $V_i$ is limited only to positive values that means we will consider only positive $V_i$.

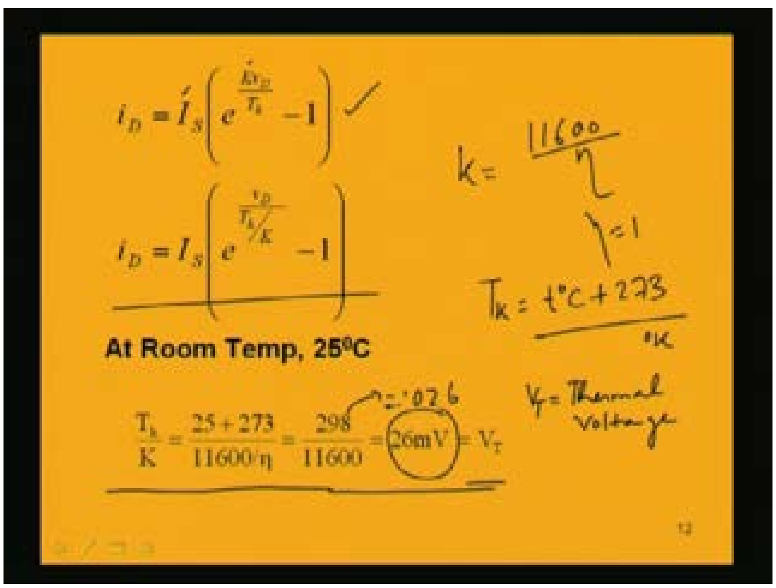
So what will happen when we have a positive voltage at $V_i$? This circuit is having this diode. As this diode is forward biased by this positive $V_i$, it will conduct. The current part if we consider, this is the current say $I_1$. This current is same as the current through this diode $I_D$. Because there cannot be any current into the op-amp, the current $I_1$ must be equal to current $I_D$. What will be the output voltage $V_0$? If we look into this output voltage $V_0$, the voltage here is zero because this voltage is equal to same as this voltage.

(Refer Slide Time: 27:01)




In this circuit if I consider the voltage across this diode as $V_D$, $V_D$ is the potential across this diode.

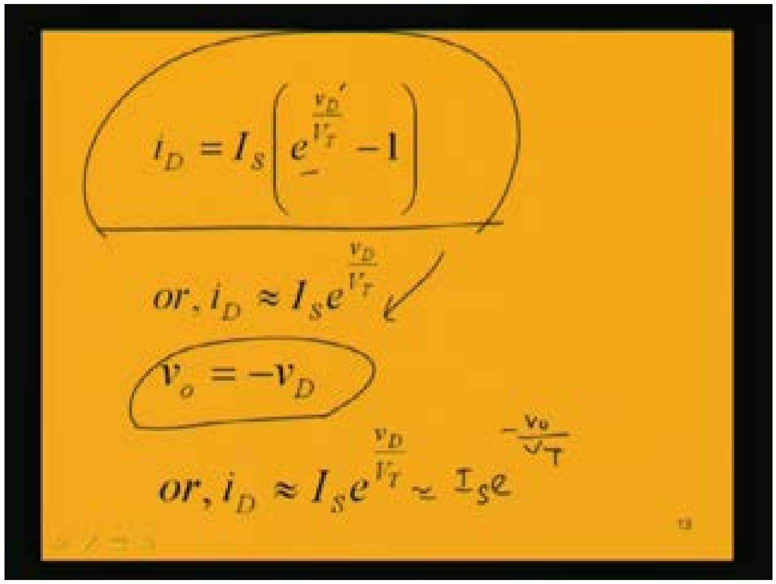
(Refer Slide Time: 27:16)




In order to find out this $V_0$, let us first find out what is the diode current? The diode current is nothing but the diode current in a PN diode or PN junction and we have already discussed about a PN junction extensively and we know the expression for the diode current and if I consider diode current as $i_D$, $i_D$ equal to reverse saturation current $I_S$ into exponential to the power $v_D$ into K by $T_k$ minus 1. This expression we already know. The terms which are used here is that $I_S$ is the reverse saturation current, $v_D$ is the voltage across the diode. K is a constant which is given by 11600 by eta. The value of eta is 1 for the higher portion of the diode current for both silicon and germanium and we will use that eta value 1. $T_k$ equal to the temperature in Kelvin, absolute temperature; whatever the temperature in centigrade plus 273, that will be in degree Kelvin. We will consider the room temperature to be say 25 degree centigrade. Generally 25 to 27 centigrade is considered to be the nominal room temperature in centigrade. If we convert it to absolute temperature scale Kelvin, then it is equal to 25 plus 273, which gives 298. So 298 Kelvin is $T_k$ and the value of K is 11600.

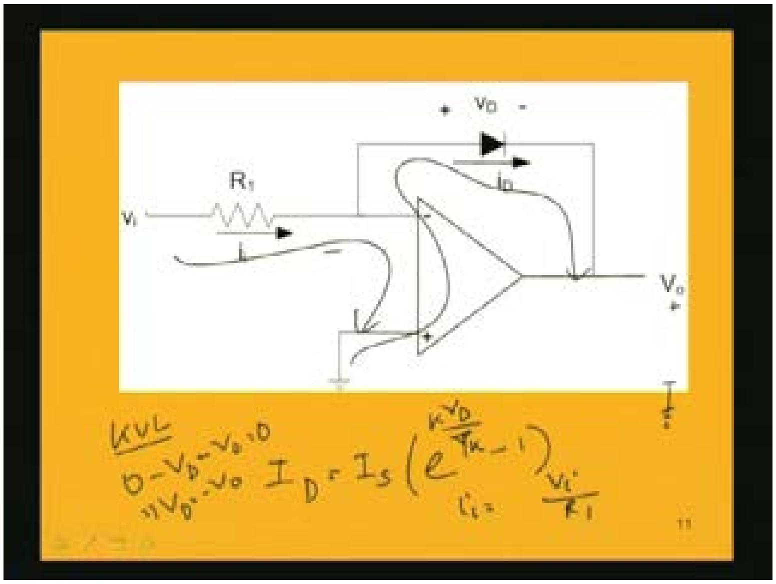
If we rewrite this expression a little, we get $i_D$ equal to $I_S$ into e to the power $v_D$ by $T_k$ by K. This K by $T_k$, I am writing in the denominator; so, it becomes $T_k$ by K and $T_k$ by K we have computed to be equal to 298 by 11600 and that is giving a value of 0.026 volt or 26 millivolt. Actually this is 0.026. This expression has a value of 0.026 and the unit is volt and that can be written in millivolt as 26 millivolt. This is a very important parameter known as thermal voltage $V_T$. So $V_T$, which is equal to $T_k$ by K is having the value of 26 millivolt at room temperature. This is called the thermal voltage. $V_T$ is known as thermal voltage and at nominal room temperature, it is 26 millivolt; this value you should remember.

(Refer Slide Time: 30:37)




Our expression for the diode current will be now simplified using that $V_T$, which will be now written as $i_D$ equal to $I_S$ into e to the power $v_D$ by $V_T$ minus 1. Here we have to only know what is $v_D$ that is the voltage across the diode because others, $V_T$ which is thermal voltage that we know at room temperature and $I_S$ is the reverse saturation current. Unless and until temperature changes, then $I_S$ does not change. If we consider a constant temperature, $I_S$ value will not change. If we look into this expression when the diodes starts to conduct, then the diode current is having a high value. The component 1, inside bracket can be very easily neglected because this value e to the power $v_D$ by $V_T$ is considerably greater in comparison with 1. We can write this expression, when the diode conducts, to be almost equal to $I_S$ into e to the power $v_D$ by $V_T$.

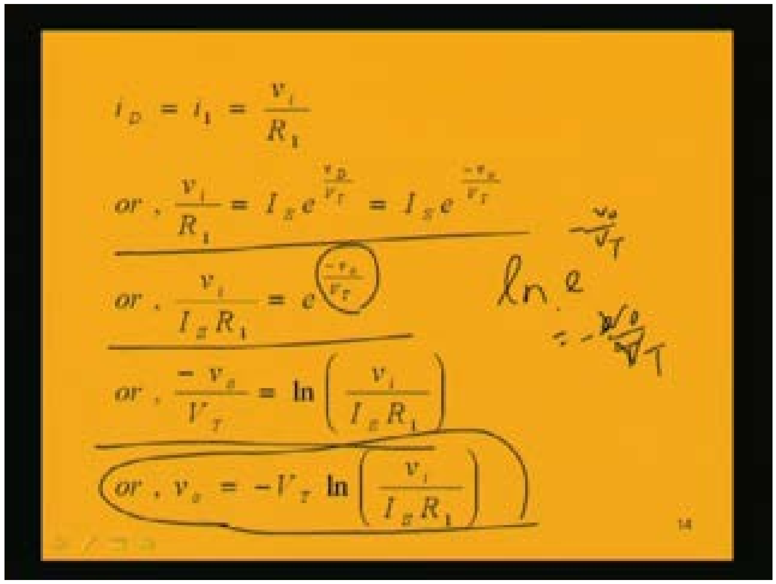
(Refer Slide Time: 31:45)




Again if we look into this output voltage, to find out the output voltage then we go by this loop and write down the KVL, Kirchoff's voltage law. Starting from ground, zero minus this drop we are naming as $v_D$ minus $V_0$ equal to zero. Because $V_0$ is with respect to ground; that point even though it is not drawn you must always remember it is with respect to ground. This Kirchoff's voltage law in this loop gives zero minus $v_D$ minus $V_0$ equal to zero; means $v_D$ equal to minus $V_0$. We will use this $v_D$ equal to minus $V_0$ or $V_0$ equal to minus $v_D$ and replace it here in this expression by this. We are getting now $i_D$ equal to almost $I_S$ into e to the power $v_D$ by $V_T$. That expression we can write down as equal to $I_S$ into e to the power minus $V_0$ by $V_T$; we can write it this way, replacing this $v_D$ by minus $V_0$ from this expression.

Again you look into the circuit and what is $i_D$ current? Again let us look from another point of view, from the input side. If I look from the input side what is this current? We are naming it $i_i$. $i_i$ is equal to $V_i$ by $R_1$ because the loop which will be effective in finding out this current is this one, if we consider so $V_i$ this point is ground. $V_i$ by $R_1$ is equal to $i_i$; so $i_i$ is equal to $V_i$ by $R_1$. Again this current is the same current as the diode current $i_D$.

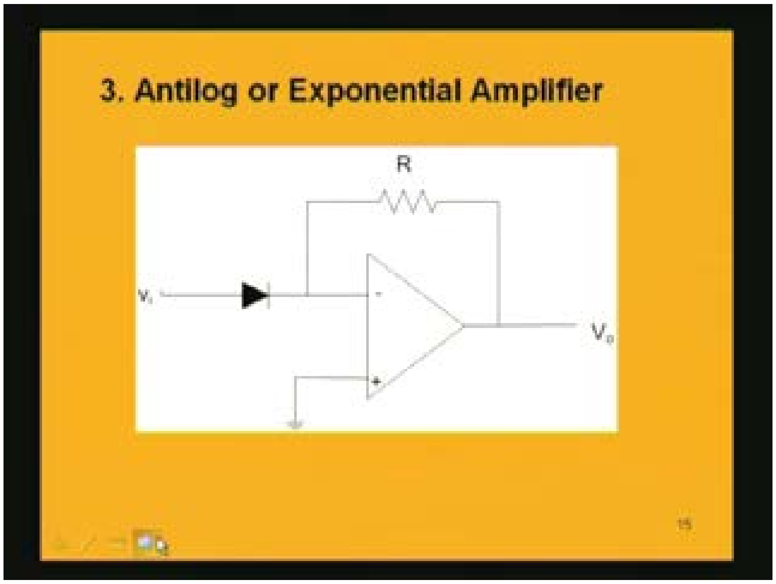
(Refer Slide Time: 33:42)




Whatever diode current expression we have got, we can equalize it to $V_i$ by $R_1$. That is $V_i$ by $R_1$ is equal to $I_S$ into e to the power minus $V_0$ by $V_T$. From this we can also write as $V_i$ by $I_S$ into $R_1$ equal to e to the power minus $V_0$ by $V_T$; just I am dividing both sides by $I_S$. Again manipulating a little further what we will get? If we want to free this term, we have to use natural logarithm; logarithm to the base e. Taking logarithm to the base e both the sides, what will I get? Left side will be logarithm. Natural logarithm is written as simply ln $V_i$ by $I_S$ $R_1$ equal to right side will be only simply minus $V_0$ by $V_T$ because ln e to the power minus $V_0$ by $V_T$ simply is minus $V_0$ by $V_T$. Because this is to the base e only, this whole thing will become minus $V_0$ by $V_T$ equal to this term.

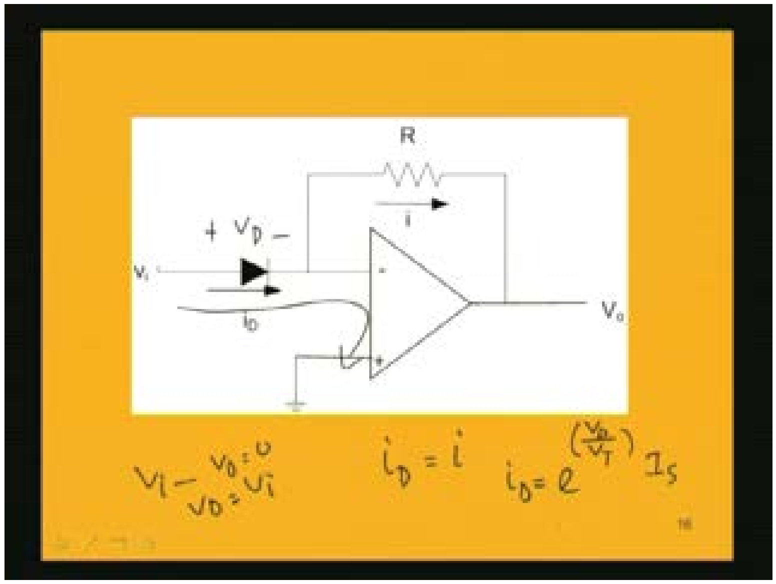
So what is $V_0$? minus $V_T$ into ln of this inside term. In the final expression if we just focus we see that output voltage is the function of the $V_i$ but this function is a logarithmic function to the base e. So we get natural logarithm of this $V_i$, which is the output voltage. There are other terms which are scaling down terms like we have to multiply it by $V_T$, which is the thermal voltage and also $V_i$ divided by $I_S$ into $R_1$. But as these terms are constant, we are not going to actually vary this $R_1$ and $V_T$ because if temperature does not vary, the thermal voltage $V_T$ will be also constant; it does not vary and $I_S$ that is the reverse saturation current also does not vary. When we have already connected in a circuit, we are not going to change the $R_1$ value. So finally it is having the variable $V_i$ only. So output voltage will be a function of $V_i$ and that too a logarithmic function. That is why this amplifier circuit is known as logarithmic amplifier; we are amplifying but we will get a logarithmic expression.

(Refer Slide Time: 36:26)



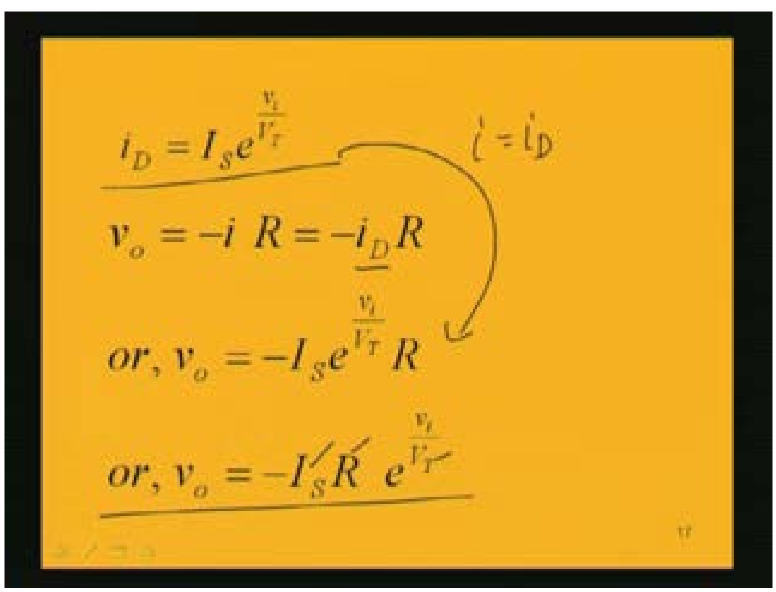

Similarly another circuit which is reverse of the logarithmic amplifier is antilog or exponential amplifier. Here also we are using the same diode as well as the resistance but the connection is different from the earlier connections. What we are having here is a circuit. When you have a diode here in the input side and the feedback is having resistance R, what will be $V_0$ in this circuit? To analyze this circuit, let us name the current through the diode as $i_D$ and the current through the resistance which is the same current but we are naming it as i. $i_D$ and i are in fact same; equal. We now find our $i_D$; we have already discussed about this diode current using the expression $I_S$ into e to the power $v_D$ by $V_T$ minus 1. Again we will simplify it to be written as $I_S$ into e to the power $v_D$ by $V_T$ , because it is higher than 1 we will just neglect 1. But then what is this voltage across this diode?

(Refer Slide Time: 37:49)



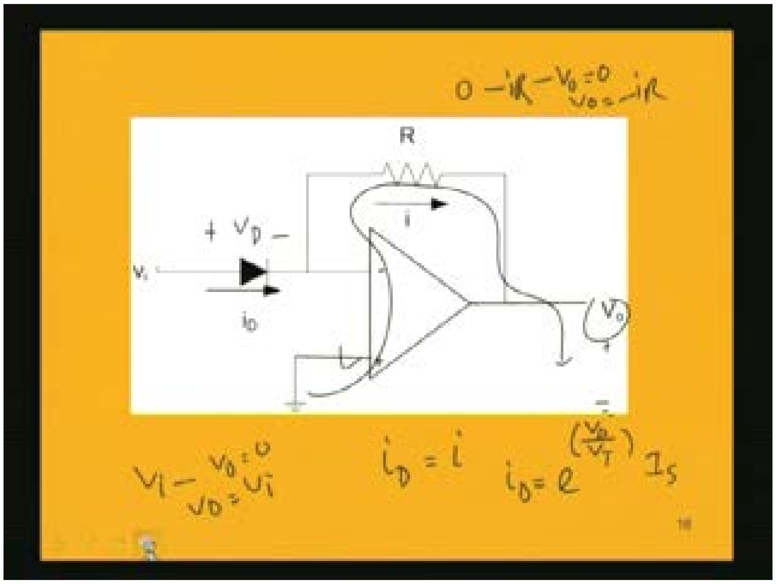

If we consider this circuit using KVL, Kirchoff’s voltage law if we name it as say this is $v_D$, $V_i$ minus $v_D$ equal to zero. That means $v_D$ equal to $V_i$. So the voltage drop across this diode, which we are denoting by $v_D$, is nothing but input voltage. This expression for the current $i_D$ can be written down as e to the power $v_D$ by $V_T$. That was the expression for the $I_S$ into that $I_S$ is there.

(Refer Slide Time: 38:39)



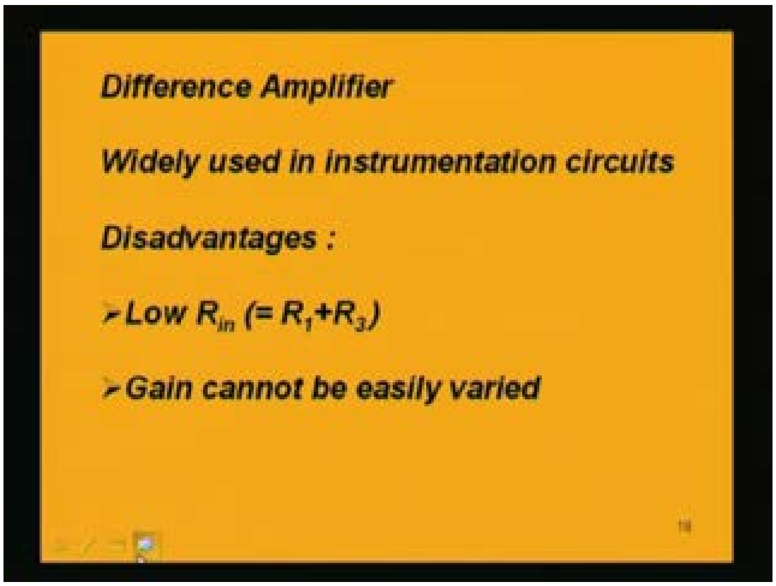
What we get? $I_S$ into e to the power $v_D$ by $V_T$. $V_D$ is nothing but $V_i$, input voltage. So we are replacing $v_D$ by $V_i$ and then what is again $V_0$? Going from the ground to $V_0$, by this loop if we come this is ground plus minus; so what this loop is giving us? zero minus iR minus $V_0$ equal to zero.

(Refer Slide Time: 39:20)



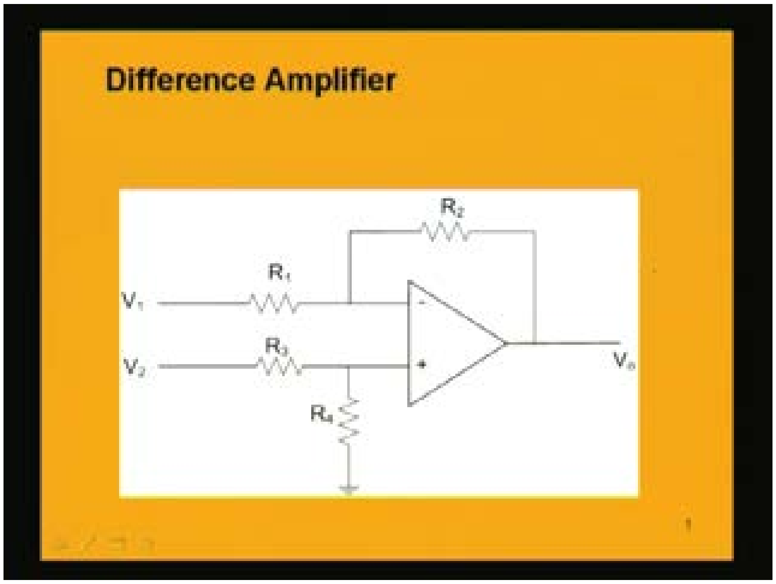

So $V_0$ equal to minus iR. $V_0$ equal to minus iR and what is i? i is again nothing but $i_D$; the same current is flowing through both the diode as well as the resistance R because there cannot be any current entering into the op-amp. This current and this current are same. So what we get from this expression is $V_0$ equal to minus $i_D$, we will write from here. Replacing here this $i_D$ by this expression that is equal to minus $I_S$ into e to the power $V_i$ by $V_T$ into R. That means we are getting a voltage which is $V_0$ that is equal to minus $I_S$ into R into e to the power $V_i$ by $V_T$. If we look into this expression closely, we see that we are getting a output voltage $V_0$ which is exponential function of the voltage $V_i$, which is at the input. We are having an exponential of the input voltage or it is an antilog of the input voltage because as we have earlier seen these terms $I_S$, R and $V_T$ are constants. So it is a function of only the input voltage and that function is nothing but an exponential function. From these two examples we have seen that we are able to do logarithmic as well as exponential operations. These arithmetic operations are possible by connecting an op-amp with a non-linear component like diode. We have seen only simple examples but practical limitations are there because of which we have to improve upon the circuit. But then those complex circuits we are not discussing because we are only trying to get the idea of these operations like arithmetic operation how it is done with the help of an op-amp. We will not go into detail complex circuits but the main principle or idea which is used is this one.

(Refer Slide Time: 41:40)



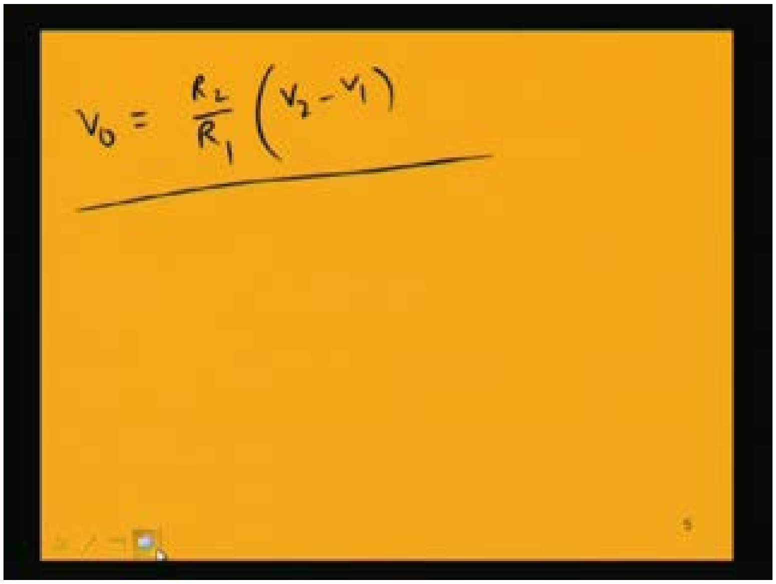

The difference amplifier which we have seen is widely used in instrumentation circuits. Instrumentation circuits as I have said earlier, has to amplify a very small voltage in the order of millivolt. But while using this difference amplifier in instrumentation circuit there are some practical disadvantages.

(Refer Slide Time: 42:27)



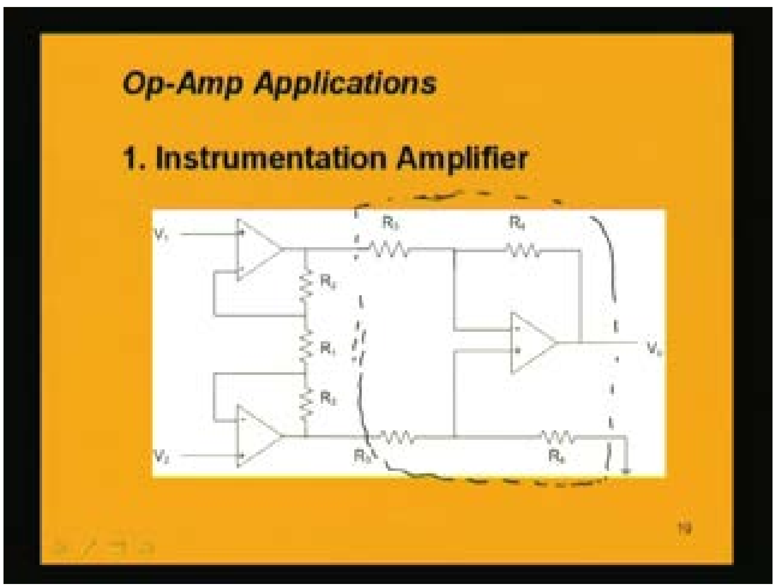

One disadvantage is that the input resistance is very low because if we look into the difference amplifier, again we see that the input resistance which is only defined or which is given by the resistances $R_1$ and $R_3$, these has a limited value. That is, it is finite and it is a low value. So input resistance is low and that is a practical disadvantage of a practical voltage amplifier.

(Refer Slide Time: 43:01)



Another disadvantage is that we have seen that we have got the output voltage $V_0$ which is $R_2$ by $R_1$ into $V_2$ minus $V_1$. The gain is very important in an instrumentation amplifier because it is dealing with a very small millivolt order and that has to be amplified. So we need a very high gain basically and here it is difficult to change the gain because of the fact that the ratio, $R_2$ by $R_1$ is the determining factor for the gain of the op-amp circuit. But to change the gain, we have to change $R_2$ and $R_1$ and that is not very easy actually. So the gain change is difficult in this type of difference amplifier; that is gain cannot be easily varied. We have to take help of another improved instrumentation amplifier which is based on difference amplifier but we have to modify the circuit a little to overcome these difficulties. That circuit we are going to discuss now. This is an instrumentation amplifier circuit which is a very vital application of op-amp. Op-amp applications we are going to discuss and first we will discuss instrumentation amplifier.

(Refer Slide Time: 44:36)

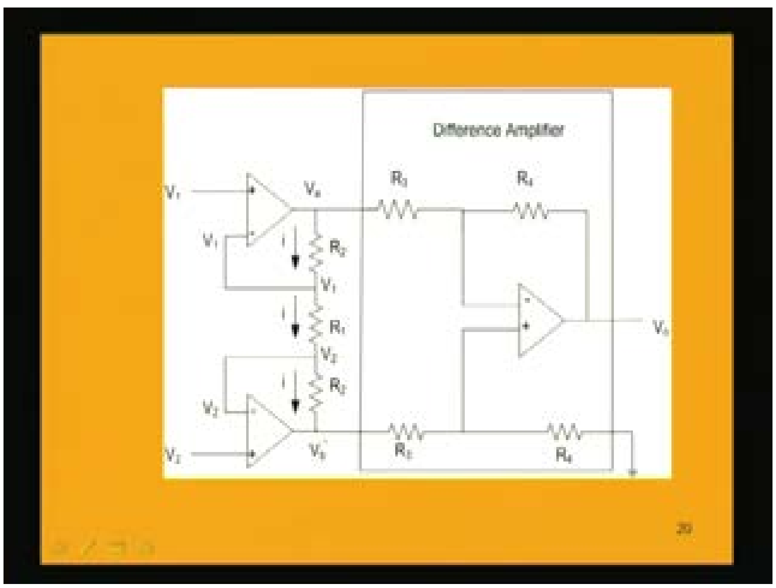



The circuit of an instrumentation amplifier is shown here. Here we can very easily recognize this portion. If we just focus on this part, it is nothing but the difference amplifier which we have earlier discussed. It is a normal difference amplifier having these values of resistances. The ratio we have to keep constant; that is we have seen earlier, $R_2$ by $R_1$ is equal to $R_4$ by $R_3$ in order to get an output voltage which is equal to

$R_2$ by $R_1$ into $V_2$ minus $V_1$. Here in this amplifier, the resistance is $R_2$ only; $R_3$ and $R_4$ and $R_3$ is this resistance and equal to the resistance here. Instead of four different resistances $R_1$, $R_2$, $R_3$ and $R_4$ we are maintaining the ratio by making the resistances $R_1$ and $R_2$ equal to $R_3$ and $R_4$. That means we are using only two resistances $R_3$ and $R_4$ in this difference amplifier and prior to it we have another circuit having two op-amps and resistances and these resistances are $R_2$ $R_1$ $R_2$. The connection is like this. The resistances are connected in this way along with two op-amps.

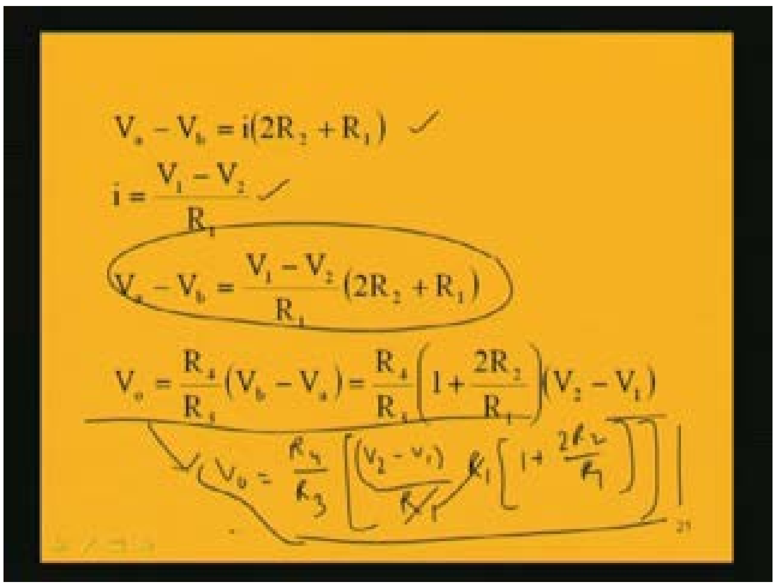
These op-amps are getting the input voltage $V_1$ and $V_2$. For this circuit, we are going to find out what will be the output voltage $V_0$? If we look into this circuit using ideal op-amp considerations, we will first look into the current that flows and the voltages.

(Refer Slide Time: 46:47)




For that let us name the voltages and currents as shown in this figure. Here let us name the voltage at this node as $V_a$ and at this node as $V_b$. Other voltages at these two nodes are $V_1$ and $V_2$. If I consider the currents which are flowing in this circuit, the current in the top resistance $R_2$ which is flowing is $i_1$. Then as current cannot enter into this op-amp, the current which is flowing in $R_1$ will also be $i_1$. Similarly the current which will flow in $R_2$ is also $i_1$. That means same current from top to bottom will be flowing because of the fact that there cannot be any current into the op-amp. If we look into the voltages, if these voltages $V_1$ we are naming, this is the same voltage here which is $V_1$ that is equal to this voltage $V_1$. That means in this circuit if this voltage is $V_1$, then this voltage is also $V_1$ and that is why if this is $V_1$, this is $V_1$, this is also $V_1$ and we are getting $V_1$ at these three points. Similarly this voltage is $V_2$. Using ideal op-amp consideration, this non-inverting voltage is equal to the inverting terminal voltage. This $V_2$ equal to $V_2$ and this is nothing but this point, so this is also $V_2$.

(Refer Slide Time: 48:31)

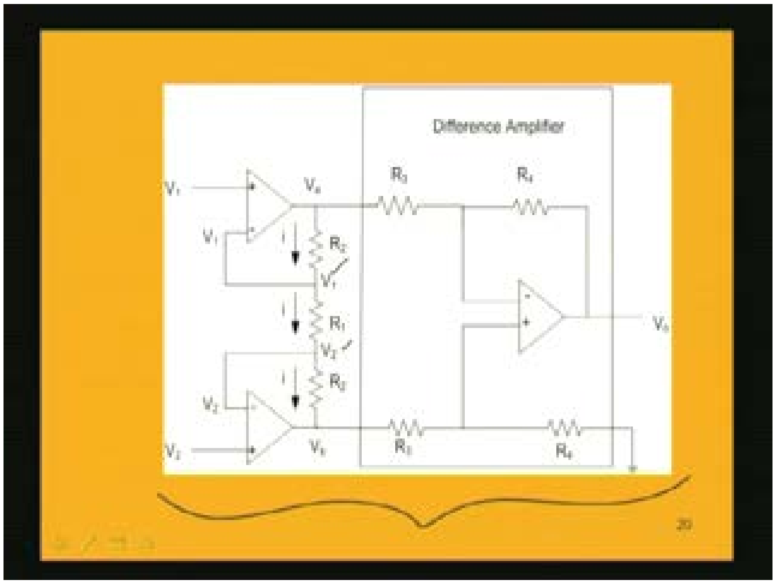



What is the current i? We can find this current i equal to $V_1$ minus $V_2$ by $R_1$. If we consider these two voltages, at the two ends the potential difference is $V_1$ and minus $V_2$ divided by $R_1$ is this current i. So that is written here and what is the voltage between $V_a$ and $V_b$. That is $V_a$ minus $V_b$ same current i is flowing; i into the whole resistance combination will give you the potential between these two points $V_a$ and $V_b$. $V_a$ minus $V_b$ equal to i into $R_2$ plus $R_1$ plus $R_2$ that means i into twice $R_2$ plus $R_1$ is equal to $V_a$ minus $V_b$. These are the key equations and from these two equations we can find out $V_a$ minus $V_b$. By replacing this i by this second equation we have now $V_a$ minus $V_b$ equal to i being replaced by $V_1$ minus $V_2$ by $R_1$ into twice $R_2$ plus $R_1$.

If we look into the difference amplifier portion, this is the difference amplifier portion and the voltages at these two points are $V_a$ and $V_b$. This is the non-inverting terminal, this is the inverting terminal and just using the result which we have earlier derived, we will straight forward write down the voltage output for this difference amplifier. This portion you look individually and find out what is $V_0$? $V_0$ is nothing but equal to $V_b$ minus $V_a$ into $R_4$ by $R_3$. Because earlier we have got that $V_b$ minus $V_a$ into $R_2$ by $R_1$, where $R_2$ and $R_1$ were the resistances in the feedback as well as the input part. Using that result we will now write, $V_b$ minus $V_a$ into $R_4$ by $R_3$ is equal to $V_0$. Now replacing $V_b$ minus $V_a$ by this previous expression, we will write that is equal to $R_4$ by $R_3$ into $V_b$ minus $V_a$, if we take the negative of this, it will be $V_2$ minus $V_1$ into twice $R_2$ plus $R_1$. We can write down by taking $R_1$ common and cancelling with $R_1$. I am writing one more step to simplify $V_0$ equal to $R_4$ by $R_3$ into $V_b$ minus $V_a$ is nothing but from this expression if I write $V_b$ minus $V_a$ give a minus sign in from it will be $V_2$ minus $V_1$ by $R_1$ into, again taking $R_1$ common, it will be 1 plus twice $R_2$ by $R_1$. Then this and this cancel. So what we will get is this expression that is $V_0$ equal to $R_4$ by $R_3$ into 1 plus twice $R_2$ by $R_1$ into $V_2$ minus $V_1$. The whole amplifier action is to give an output voltage $V_0$ equal to this expression.

If we see this instrumentation amplifier as a whole, it is having the difference amplifier using the basic principle of difference amplifier but there are other portions in front that take care of the disadvantages and over come. Because now what we see here is that we are having an instrumentation amplifier whose input impedance if we look, the input impedance will be now infinite because we are having the whole block as the amplifier.

(Refer Slide Time: 53:04)




If we consider this side as the input then, we are getting very high input impedance. Also it is now easy to change the gain. Because if we look into this expression the gain can be changed if we change this $R_1$ keeping the $R_2$ part constant. That means you can connect a differential resistance; we can connect a rheostat type of resistance where we can change the rheostat value to change the value of $R_1$. This has more flexibility in order to change the gain than the earlier difference amplifier, which we were using earlier. This instrumentation amplifier circuit is a better circuit than only difference amplifier and it is used enormously in instrumentation circuits.

In this discussion today, we saw the application of op-amp along with non-linear circuit components to build some very important arithmetic operation amplifiers like logarithmic amplifier, then exponential type of amplifier and also we have seen an example of a precision half wave rectifier, how it is being made. Also we have seen about a practically important circuit of instrumentation amplifier which works under basic principle of a difference amplifier. But it is better and modified and it overcomes the drawbacks of the regular or normal difference amplifiers and these different examples that we have discussed gives us the idea that op-amp can be used extensively in various circuits for use in different applications.