Circuits for Analog System Design
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Module No. # 04
Lecture No. # 20

Input Resistance Calculations for Op amp

Good morning. Today we discuss other issues of the operational amplifier, namely, what is the impact of output resistance, how to find the output resistance for a given application, and how to find the input resistance of the operation amplifier. These two issues we will see in this class. If possible, we will also see something more about CMRR and some examples to go with the input resistance and output resistance.

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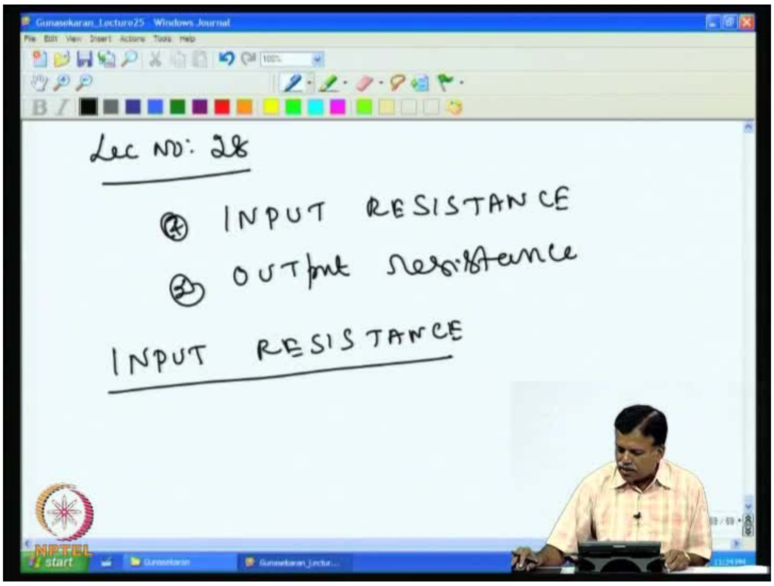

Today, our main focus should be input resistance of the op amp and what effect it has got on the design? Then the second one is the output resistance. These two issues we will discuss today.

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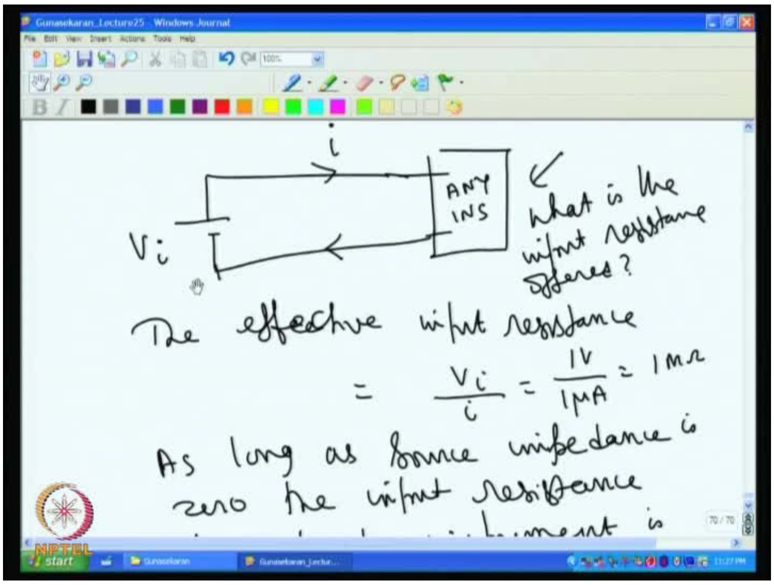

First, let us take the input resistance. The input resistance is an important parameter in any instrument. Why should one worry about the input resistance part? For example, if I have taken any general instrument, I will connect the voltage source to this instrument, the input now, if I connect like this, there will be a current flowing in this. Take any instrument whose we want to find out input resistance offered by this instrument. So, you want to find what the input resistance is offered.

In this case, if you want to find out, normally what is done is -- we have the input voltage V_i, then the effective input resistance would be V_i by i. For example, if I have 1 volt and then I have 1 micro ampere current, then we will have 1 mega ohm as an input resistance. That is input resistance offered by the instrument. Basically, we find the voltage and then the current that is flowing, and from there, we try to find what the input resistance is offered by the instrument.

The input resistance is of no consequence, as long as the source impedance is 0. The input resistance offered by the instrument is of no importance. This is because as long as there is no resistance on the input here, whatever may be the current that is flowing, the voltage that is appearing across this is same as V_i. So, the input resistance of the instrument whether it is low or high is of no consequence as long as source resistance is low.

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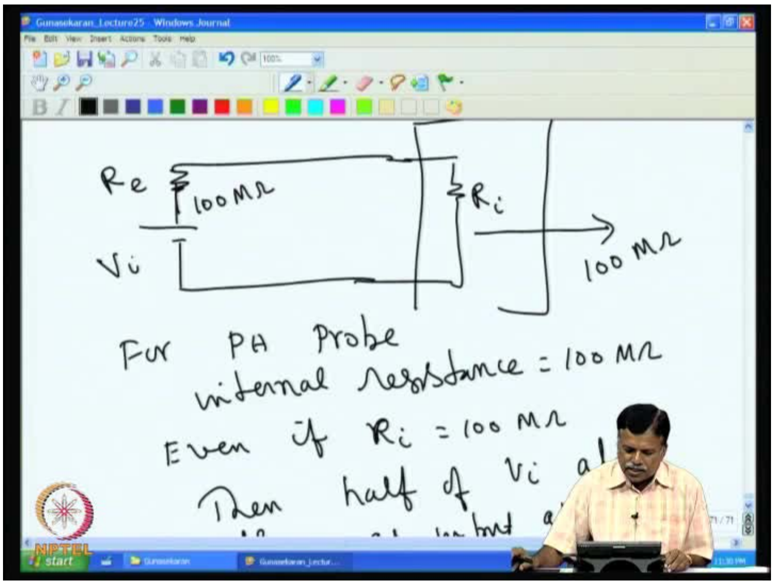

Now the problem comes only when the source resistance is high. For example, if I have a source, which already has an internal resistance, then if I have a instrument that is connected to this, then there will be the input resistance R_i and this internal resistance R_e. In this arrangement, R_e is internal resistance of the source, and because of R_i there will be a current in the circuit, which will drop a voltage across this. If this resistance is lower, the input resistance offered by the instrument is lower, and more current actually flows through this.

When more current flow through this, then more voltage drop will occur across this. That means, we will get only less voltage across this. Eventually, the input resistance offered by the instrument matters very much when R_e is more, because otherwise, it will be lot of voltage loss. For example, if I take PH meter, then 100 mega ohm is the internal resistance of the PH probe. Even if, R_i is 100 mega ohm, then only half the voltage will appear as input at the instrument. So in this example, we have found that because of this 100 mega ohm and this 100 mega ohm, half of the voltage is lost here and only half is appearing here.

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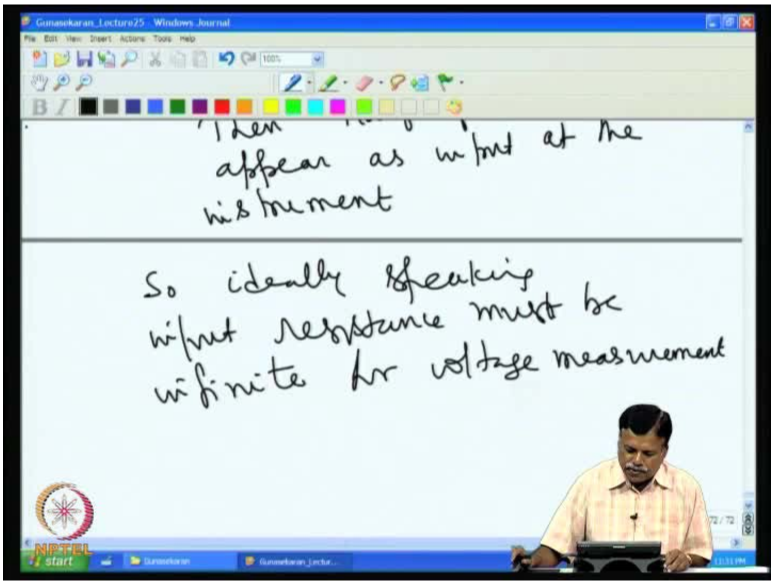

Of course, in this case, the input resistance is always found by the applied voltage across this divided by current flowing through that. If input resistance must be higher, if my source impedance is higher, then only it is half. Then, you can get the entire voltage of the source appearing at the instrument. That is why we like to have instrument with as high impedance as possible, if you are measuring the voltage.

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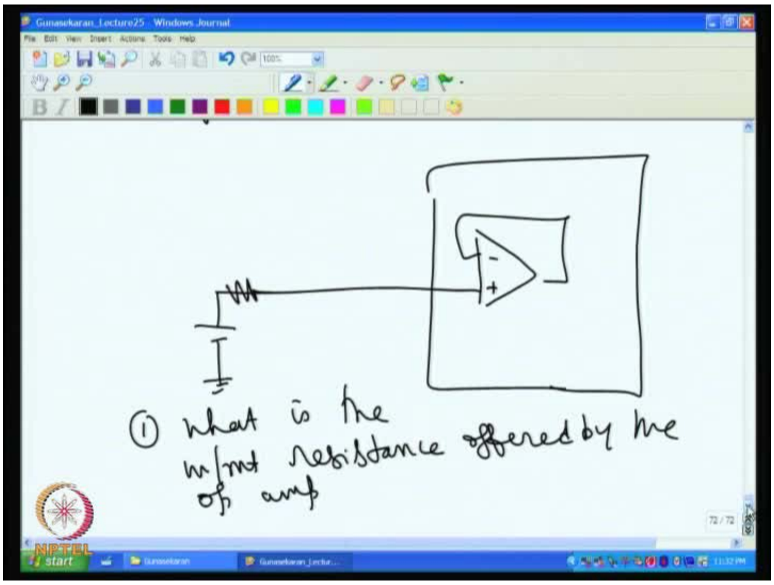

Ideally speaking input resistance must be infinite for voltage measurement. That means, if I take an operational amplifier and operational amplifier sees the input voltage in any instrument, we have to worry about the input resistance offered by the instrument. Because if you take any voltage measuring instrument, then we have, at the input, the operational amplifier appearing. We are connecting the operational amplifier to the source, which has its own internal resistance.

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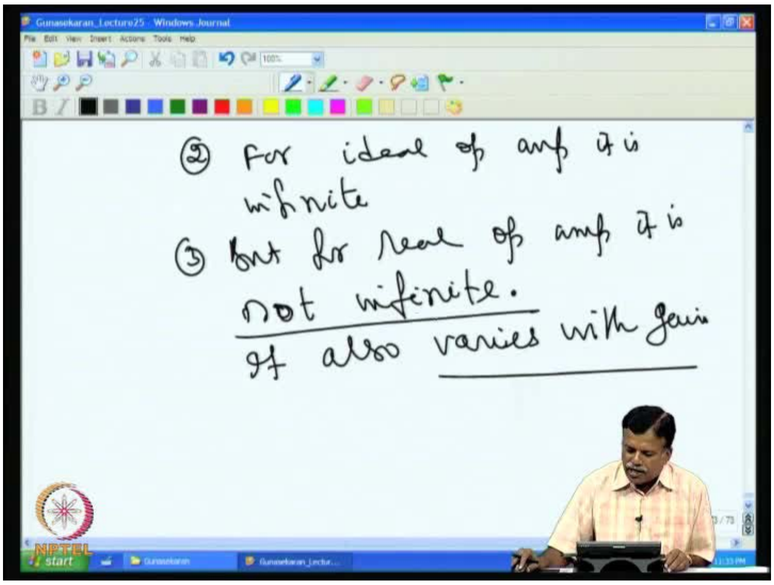

Now, the question is -- what is the input resistance offered by the operational amplifier? What is the input resistance by the op amp? Second question, is it always constant? Theoretically, for ideal op amp, input resistance is infinity, but it is not infinity for the ideal op amp. So, second one is for ideal op amp, it is infinite; but for real op amp, it is not infinite. Not only that, it varies with gain. These are two important points we have to realize for the real op amp -- it is not infinite and it varies with gain. This is overlooked by most of the designers in real life. This has very big effect in error calculation actually.

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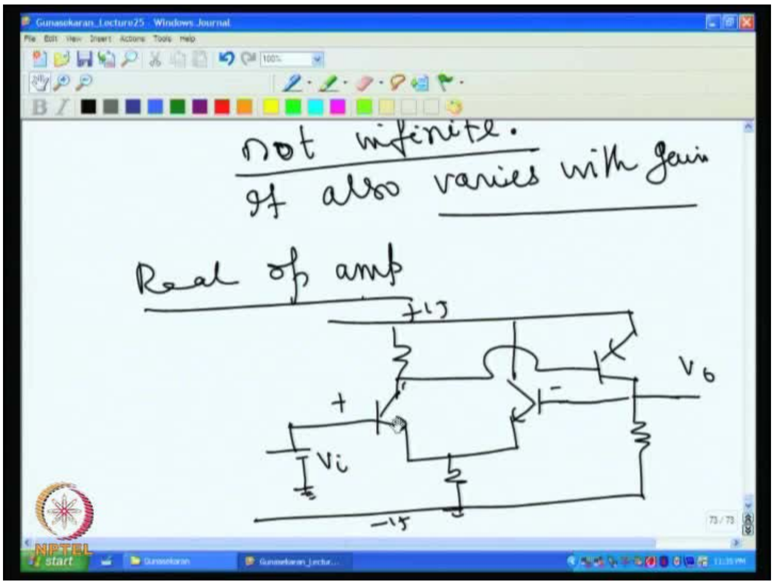

We will see how the input impedance looks like. If we look at the real op amp, what really happens is that we have an input real op amp, if you take a real op amp, the input stage consists of the difference amplifier. We can go back to our original circuit – our operational amplifier design and see how that it is looks like. Then for example, if you have plus 15 and minus 15, and this is plus input, this is a minus input, and then this is the output that we have. For example, for voltage follower, we are connecting this, now we are giving the input here with respect to ground.

Now if you see the two things, that is, as you increase this V_i you will find that the current in this is increasing, and then you find that this current slightly decreasing. Because most of the op amp maintain this current almost constant, which makes that if I increase the voltage, this current will be increasing and this current will be slightly decreasing. Also, we have to realize, even if V_i is 0, there is always some current flowing through this. There is current in this. That means, this is slightly different from the classical example we had shown with a passive circuit for input resistance.

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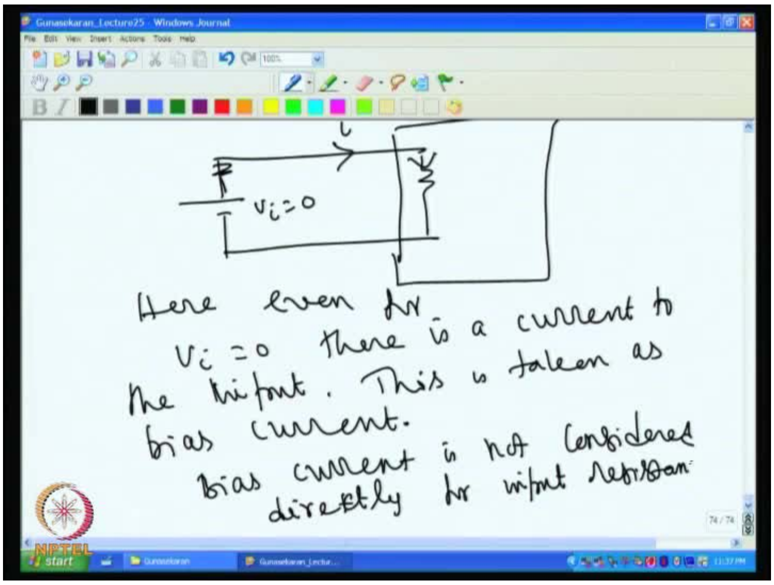

That means in case of op amp, even for V_i is equal to 0, there is a current. That means, if I assume, this is operation amplifier based instrument, then they have a resistance here. Even for V_i is equal to 0, you will find there is a current i. So, there is a current actually flows through this, which is not the case given when V is equal to 0. Here, even for V_i is equal to 0, there is a current to the input. That means, this is taken as bias current. We are not considering bias current for calculating the input resistance. So, bias current is not considered directly for input resistance calculation.

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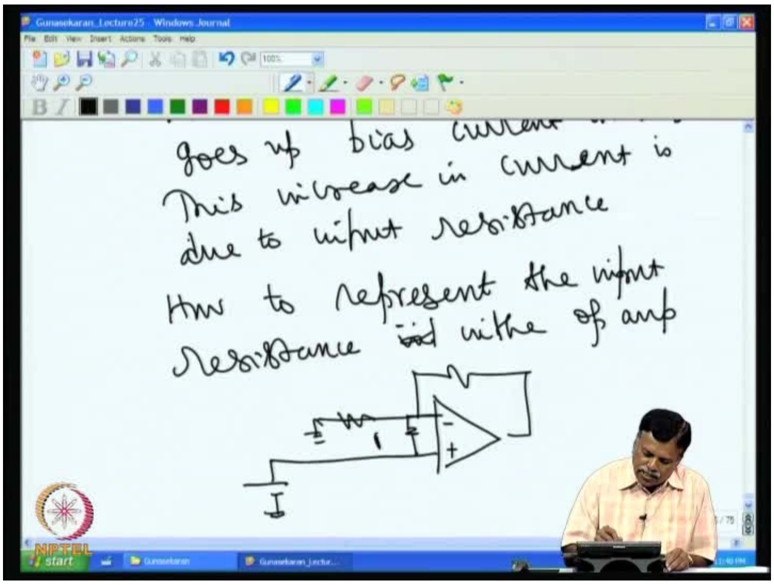

However, when the input voltage goes up, bias current increases. This increase in current is due to input resistance. Actually the increase in current will be taken as an effective to the input resistance. So, at present, we assume there is no bias current. Ideally, if you want to represent the input resistance in the case of op amp, I will put it like this. How to represent the input resistance in the op amp? We can represent it in the following way. What you can do is that you have plus minus and you have the input source, then there is a current from plus to minus. When the voltage is increased, the current is increased and that current actually increases the current flowing through this. So keeping that bias current constant, then the extra current can be taken as flowing through this.

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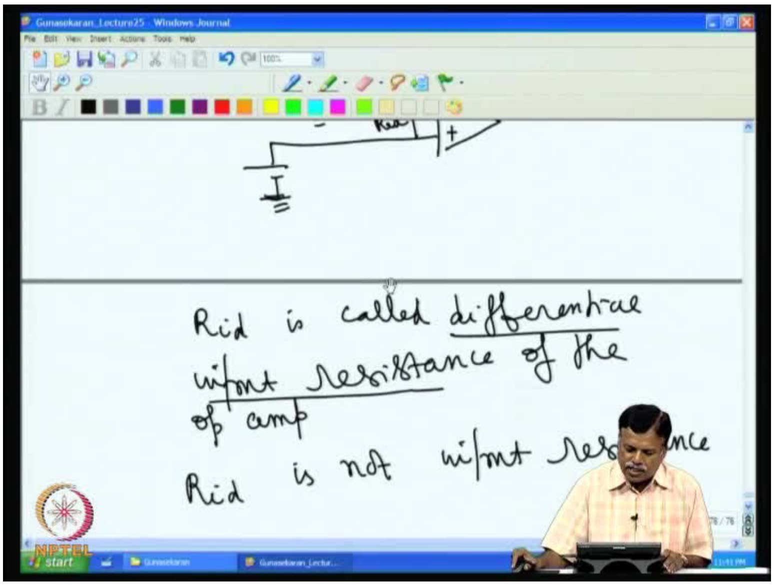

This is considered as equivalent of R_{id}. These are the two gain set resistances – R_f and R_1. So, R_f and R_1 is a gain sitting resistance and R_{id} is taken as an equivalent input resistance. R_{id} is called differential input resistance of the op amp. The increase in voltage essentially actually increases the current and that current actually flows through R_{id}. But R_{id} is not the input resistance, it is a differential input resistance, that is a resistance present between the plus and minus input. Now, you have to find out what is the equivalent input resistance?

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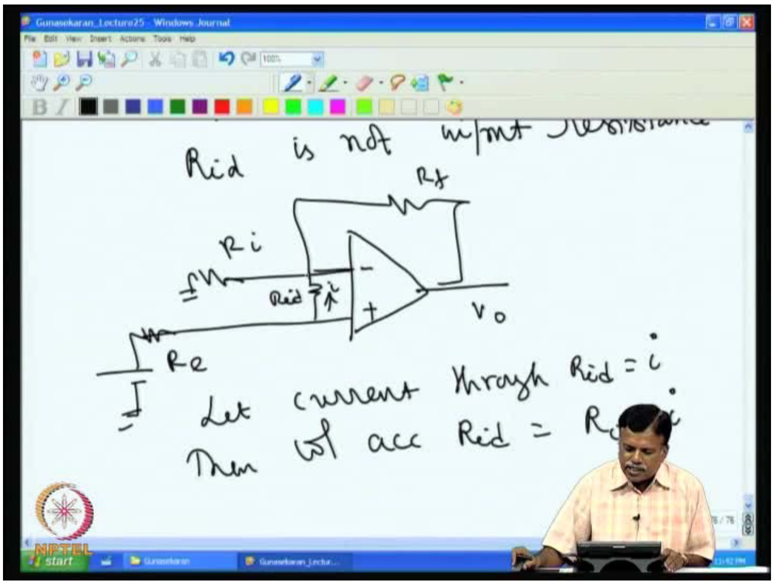

That means R_{id} is not input resistance present at the input. If I have to convert in to an equivalent input resistance, I have to split this R_{id} effectively to the ground side. So, what is the current flowing through R_{id}, I have to find out and then only I will be able to find the input resistance. We can determine this by assuming current i in R_{id}. How to find the input resistance? We can do this in the following manner: Taking this circuit, assume this has some internal resistance and R_{id}, and R_i, and this is R_e, the output. So assume current i is flowing here.

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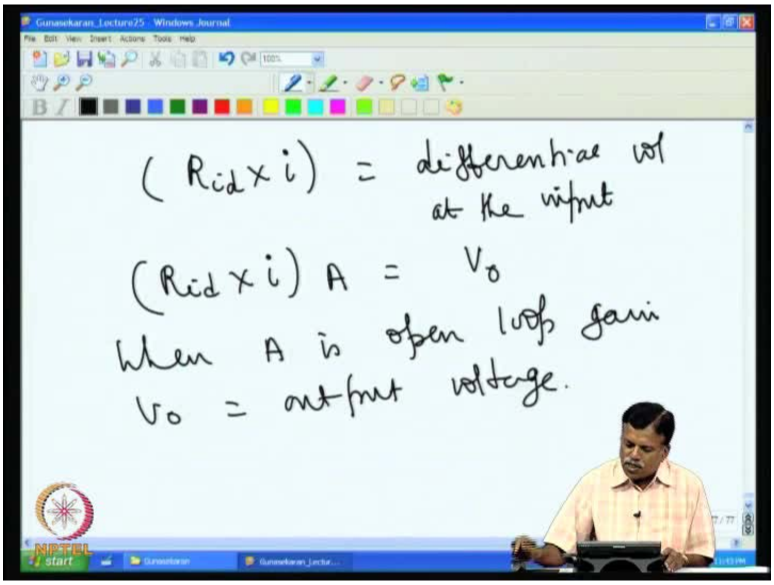

So voltage let current through R_{id} is i. Then, voltage across R_{id} comes R_i d into i. That is the voltage that you get across this. This is nothing but the difference between plus and minus. That means, R_{id} into i must be the different between these two. It is the differential voltage at the input. That means, R_{id} into i into A would be equal to output voltage, where A is open loop gain and V_0 is output voltage. So, essentially R_{id} into i is the input voltage, multiplied by open loop gain is the output voltage, is equal to V_0.

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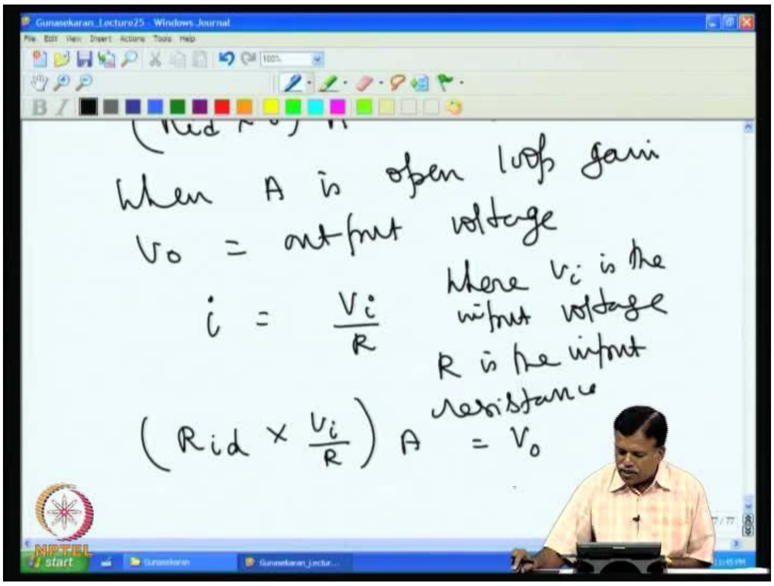

Now, we also have to now find out what is i comes out to be? If I write for the value for i, then i is nothing but V_i is the input voltage. Then, I will take R as the equivalent input resistance, and we can write the value of i would be V_i divided by R, where V_i is the input voltage and R is the input resistance. We are looking for input resistance. If I substitute that in the equation here, we substitute for i here, then this will appear like this, R_{id}. Because we have one the input soil substitute in equation one the for i, so that you will come V i by R that actually a that appears to the v naught. Now, I can bring out the V naught at other side.

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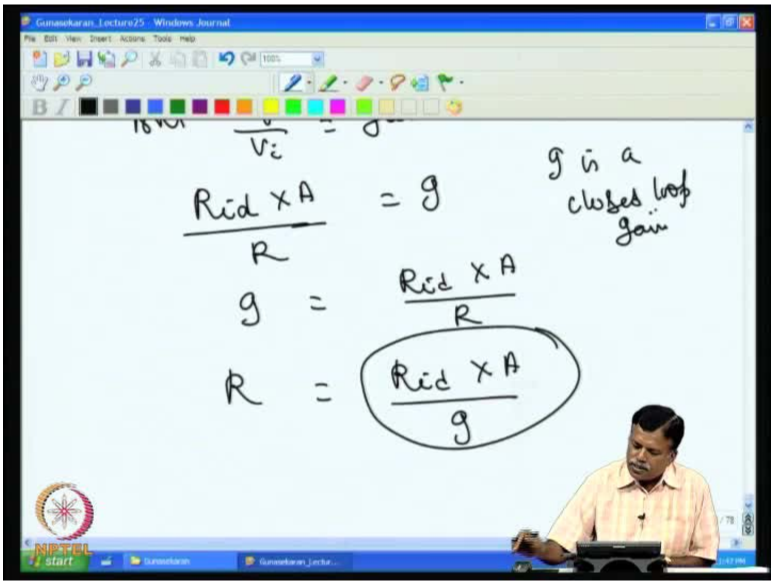

From this equation, you will get back R_{id}, which is the input resistance divided by R into A. That comes out as V_0 V_i. This is nothing but the gain that actually comes out. That means, you will get R_i d into A by R, actually comes out to be g. If I can shift the other way around, then I will get g is R, the input resistance. R, that what we wanted then appears to be R_{id} into a divided by g. That means, now, input resistance appears in terms of R_i d, differential resistance and the open loop gain and closed loop gain g. So, g is a closed loop gain. That means, input resistance offered by the op amp, which is R, actually depends on the closed loop gain that we have set.

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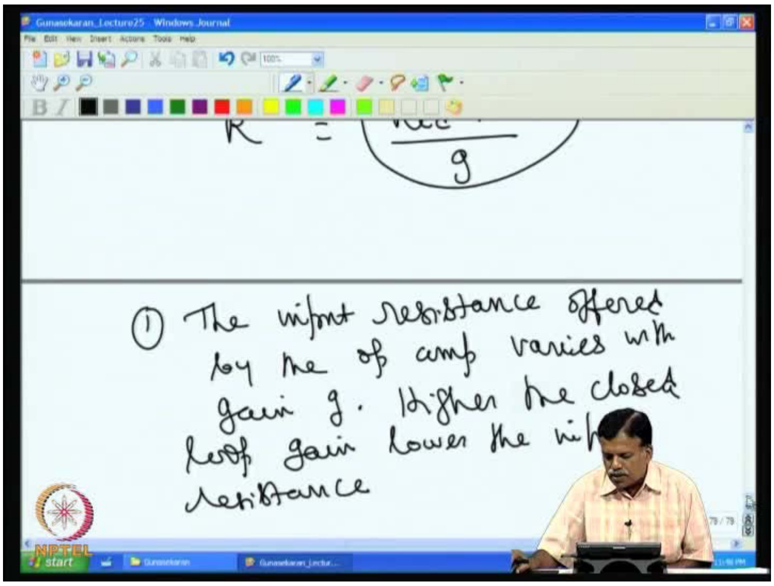

For example, if I give very high gain, then my input resistance will be low. For example, if the open loop gain is 20,000, and g is 10,000, then you get 2. Then, the closed loop input resistance will be R_i d into 2; where as if I keep g as 1 then I will get input resistance very high.

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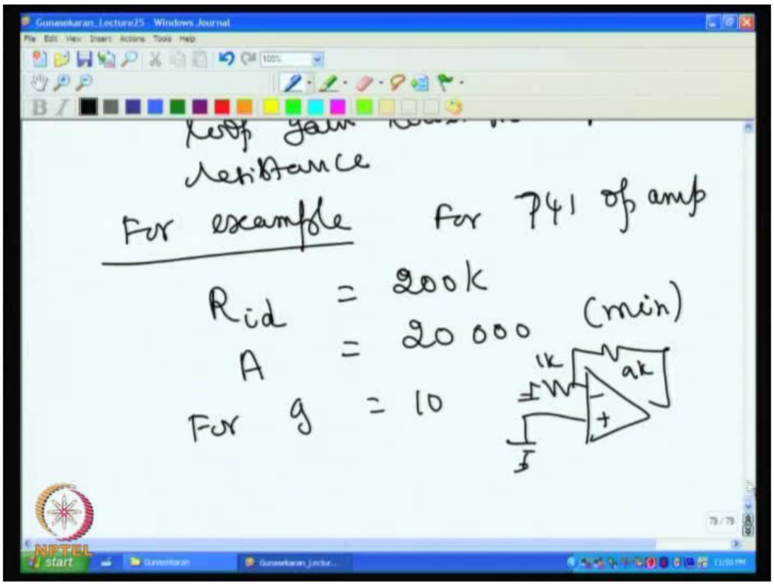

The input resistance offered by the op amp varies with gain g. Higher the gain, lower the input resistance g. Higher the closed loop gain, lower the input resistance. Now, this is to be realized because we try to get, for example, 741 op amp, we look at the data sheet, R_i d is given as 200 k and open loop gain A is as minimum of 20,000.

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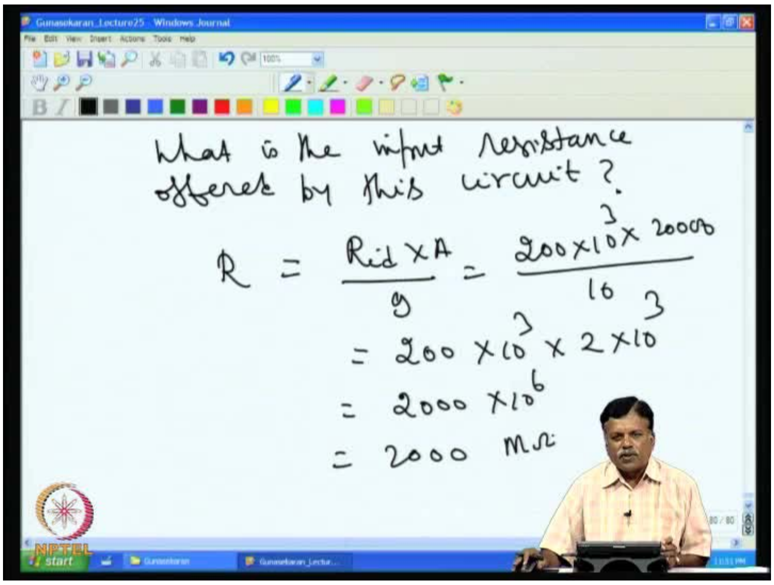

For this case, if I put gain 10, for g is equal to 10, and use non-inverting amplifier like this. That is, if I put here 9 k and 1 k, that means gain 10, what is the input resistance offered by the 741? And what is the input resistance offered by this circuit?

If I calculate, that comes that R will be R_{id} into A by g. That comes out as 200 k and A is 20,000, and g, in this case, is 10, that come to be 200 into ten power 3 into 2000 actually, that is 2,000 mega ohms. In that case, input resistance offered by the op amp is 2,000 mega ohm, not infinity, which normally we think.

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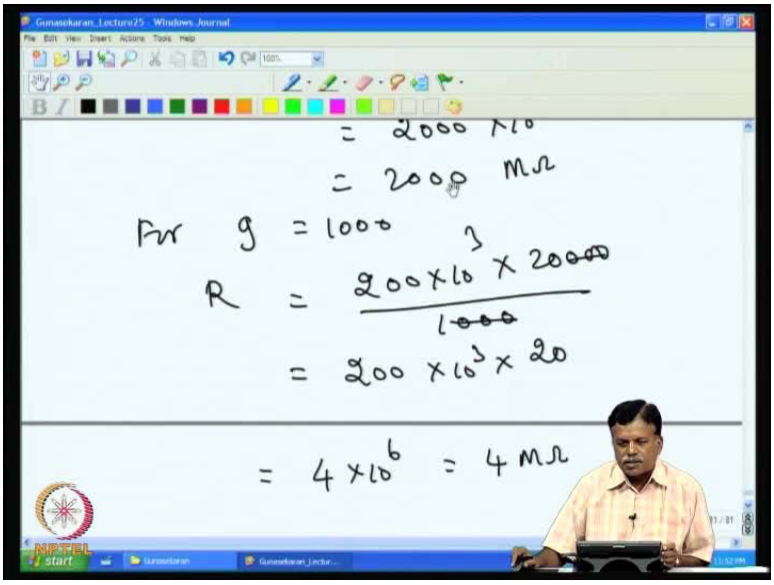

Similarly, for example, if I put gain as 1,000, g is equal to 1000, then R comes out to be 200 k into 20000 divided by 1000,, which works out to be 200 into 10 power 3 into 20. This works out to be 4 into 10 power 6, that is, 4 mega ohm. So, if I have a 1,000 gain, input resistance comes down to 4 mega ohm; whereas if the gain was 10, the input resistance was 2,000 mega ohm. That shows that if you want a high input demands, then you have to give as low gain as possible.

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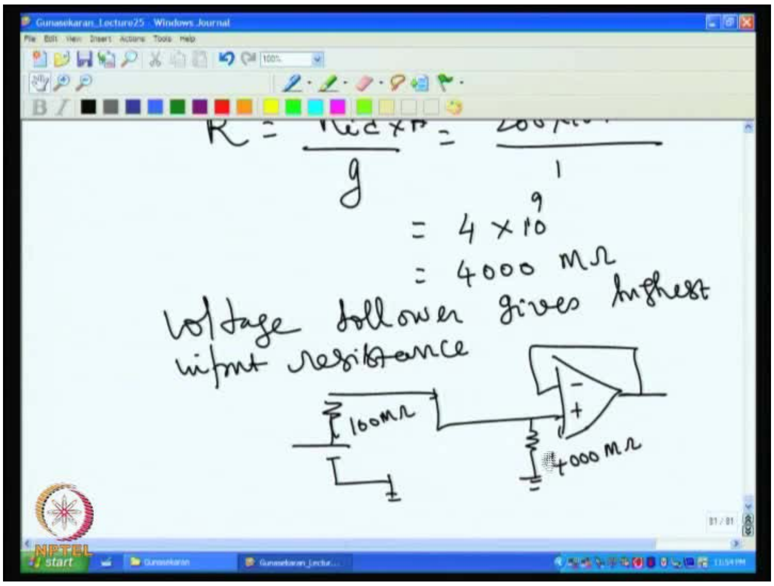

The best case would be for voltage follower, where the gain is 1 follower, then R comes out to be, g into A, that is, 200 k. R_{id} into 20000 divided by 1, comes as 4 into 10 power 9, or that is equal to 4,000 mega ohms. That means, voltage follower is the one which gives the highest input resistance. That is why when you are dealing with, for example, PH probe, then it is better to have unity gain at the input stage. If it is, for example, 100 mega ohm, internal resistance that the circuit gives will be 4,000 mega ohm resistance. Equivalent resistance stilling is 4000 mega ohm.

So the input resistance that is given by this circuit is equal to 4000 mega ohm. They give a unity gain. If I use gain here, in this stage, then the input resistance would have come down and then most of the voltage would have been lost on the internal resistance. Because when the internal resistance is high we have to keep this resistance high. For that purpose, we have to go for voltage follower at the input stage.

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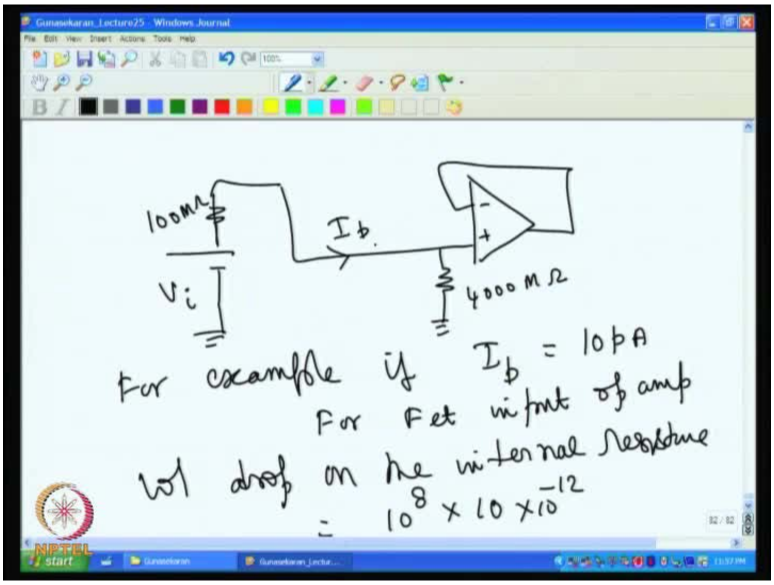

You may wonder that what happen to the bias current? Is that also to be considered or only the input resistance will be considered? In fact, when I am using with op amp, we also consider the bias current error, in addition into the input resistance error. For example, if I take the case of PH probe, where we have 100 mega ohm resistance here, and then we are giving this to the input. Similarly, I have put a voltage follower, and I know that we have 4,000 mega ohm here. Whether this 4,000 mega ohm present or not or whether this V_i is here present or not? There is a bias current flowing here I b. The bias current that is flowing through this will drop a voltage. There is a current that is flowing through this, that current also added to this, so totally I b plus is what actually flows through this. One may have to consider the voltage loss for both the cases.

For example, if I b, the bias current, is equal to 1 Pico amps for Fet input op amp, because you will have very low bias current, so we have to use a Fet input op amp. Assume that we have taken 1 Pico ampere or we can take say 10 Pico ampere. In that case, voltage drop on the internal resistance, that is equal to 10 power 8 into Pico ampere, is 10 power minus 12. So we have 10 power 8 into voltage of 10 power 8 into 10 into 10 power minus 12. That comes out to be 10 power 9 into 10 power minus 12. That is equal to 1 millivolt.

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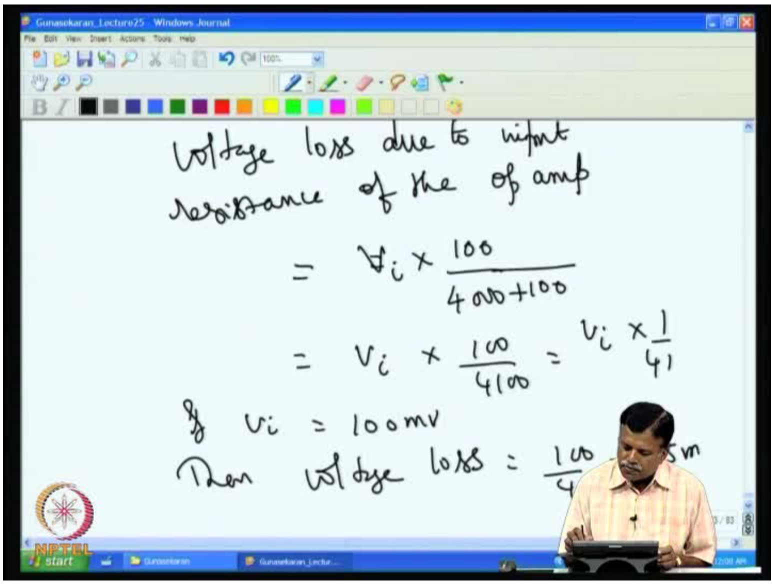

Due to voltage drop on the internal resistance due to the bias current, it is one millivolt, because we have taken I b as 10 Pico ampere. So, you have a loss of voltage 1 millivolt due to bias current. In addition to this, there will loss of voltage due to the sharing of the due to the input resistance, which is 4000 mega ohm. So, voltage loss due to bias current is equal to 1 millivolt.

We have to find out voltage loss due to input resistance of the op amp? That would be V_i into what is the voltage across the 100 mega ohm. In case of 4000 plus 100, that is in voltage mega ohm, that is the voltage across 100 mega ohm. Because V_i is shared between 100 mega ohm and 4000 mega ohm, so we want to find out what is the voltage drop across this 100 mega ohm for V_i. In this case, it will work out to be V_i into 100, I assume, that will work out to be V_i into 1 by 41.

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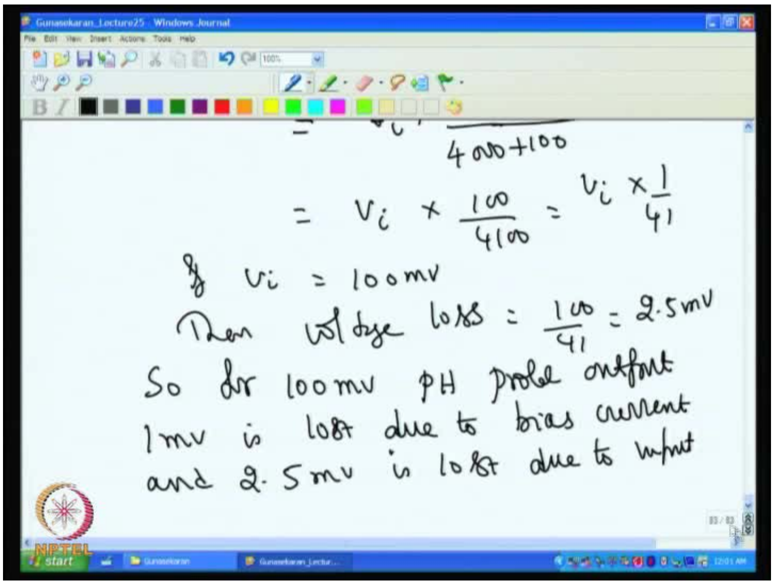

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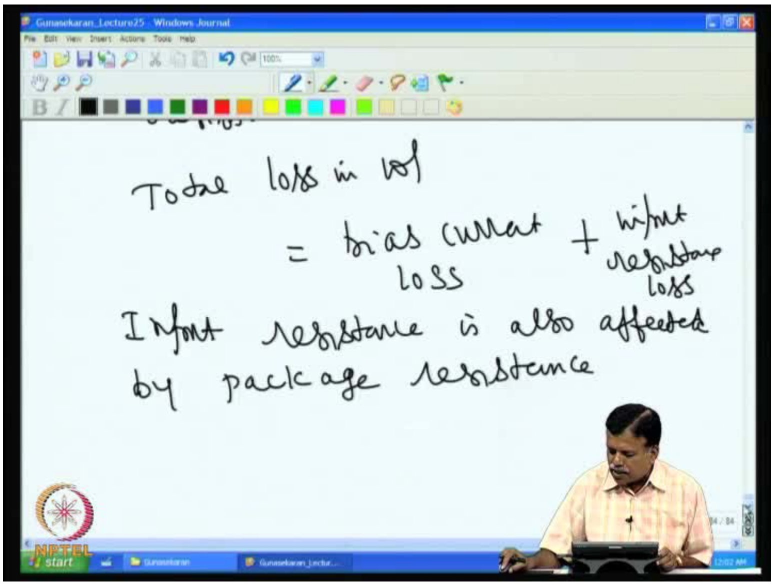

If V_i is equal to say 100 millivolt, then voltage loss equal to 100 divided by 41, which is roughly 2.5 millivolt. So, if the PH probe output is 100 millivolt, then 2.5 millivolt is lost due to the input resistance effect and 1 millivolt is lost due to bias current. For 100 millivolt PH output, 1 millivolt is lost due to bias current and 2.5 millivolt is lost due to input resistance. The total loss in voltage is equal to bias current loss plus input resistance loss. This must be understood clearly in order to calculate the loss at the internal resistance, due to bias current and input resistance.

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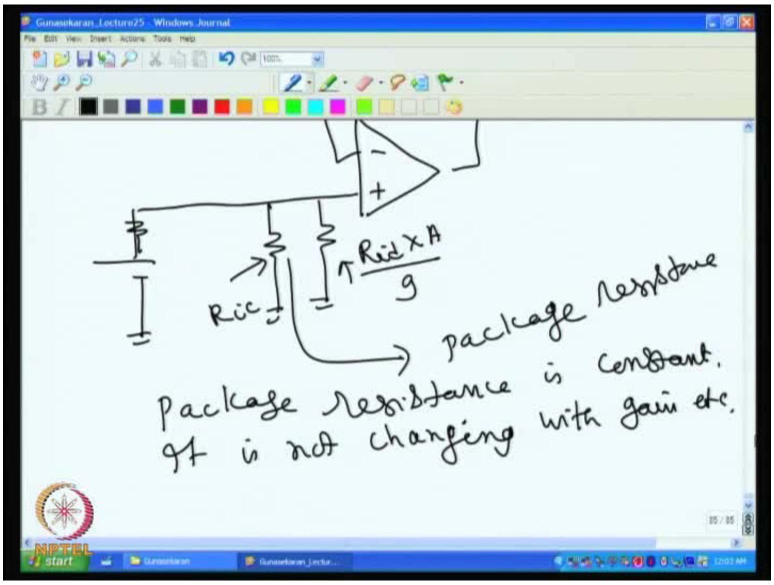

There is one more issue in the input resistance. Because there is a package resistance, in addition to the current that is flowing into the circuit terminals of the op amp, so we have to consider what is the package resistance loss? Input resistance is also affected by package resistance, that is, if I draw the equivalent circuit, it will looks like this. That we have the input voltage and it is the internal resistance. This is R_{id} into A by g. There is our package resistance, which is called R_ic, that is common resistance. This resistance is coming due to package. So package resistance is constant, it is not changing with gain, etc.

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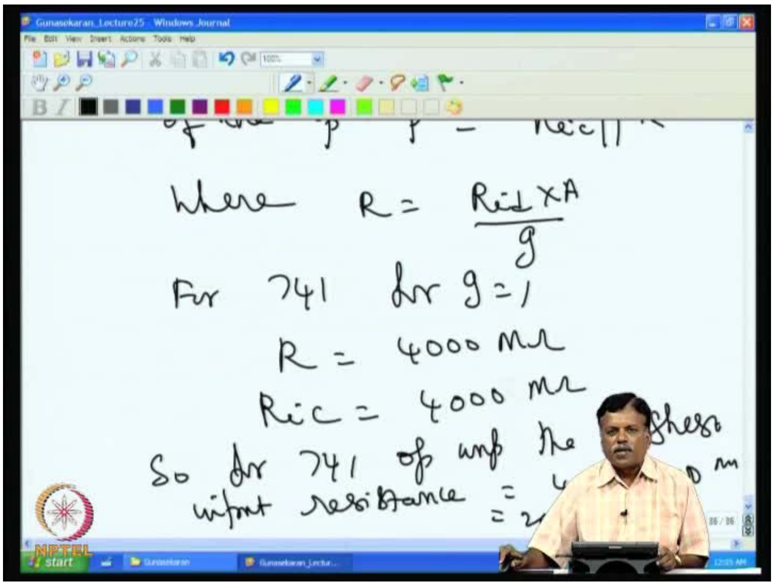

The effective input resistance op amp is in a way R_{ic} parallel R. The other way round, R is the input resistance, where R is equal to R_{id} into A by g. For example, in case of 741 unity gain, for g is equal to 1, R is 4000 mega ohm. R_{ic} is also 4000 mega ohm. For highest input resistance would be... For 741 op amp, the highest input resistance will be 4000 mega ohm. Parallel 4000 mega ohm comes to be 2,000 mega ohm. Hence if you have a unity gain, you can get around effectively 2,000 mega ohm as an input resistance.

The input resistance then coupled with bias current, what is the loss that is taking place at the internal resistance of the source must be calculated in every circuit. And invariably this effect is actually neglected by the many of the users. This is wrong particularly, if the gain sitting is very high, then input resistance can be very low. So, one should not consider that input resistance is infinite for the op amp, and neglect the effect of input resistance totally. Similarly, the bias current also should not be neglected. Sometimes bias current effect can also be a dramatically very high.

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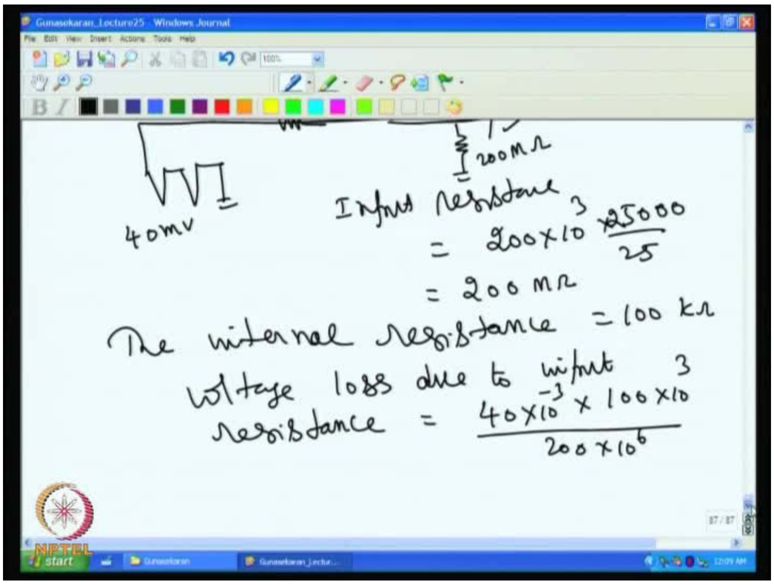

Let us take this example 2. In this case, we will show that we have a source. For example, we have a thermocouple voltage, and then to protect the thermocouple from short circuit we have high voltage coming from this. We added, say for example, 100 mega ohm resistance and then I connect this one to the operational amplifier. And then I put this. I have some gain here for, say, 25 gain, I have set here and then I try to use some general purpose op amp and then find out what is the error due to this? For example, if the gain is say 25, then input resistance would be, for example, 200 k into, if it is a 25000 is there the open loop gain and then I have 25 gain here, that will come 200 mega ohm. Input resistance will come as 200 mega ohms.

Now that means, it is equivalent (( )). I have a 200 mega ohm resistance here. If I have 100 kilo ohm resistance, then voltage drop due to the internal resistance is equal to 100 kilo ohms. Assume that this is only 40 millivolts signal, that is what maximum that is expected...

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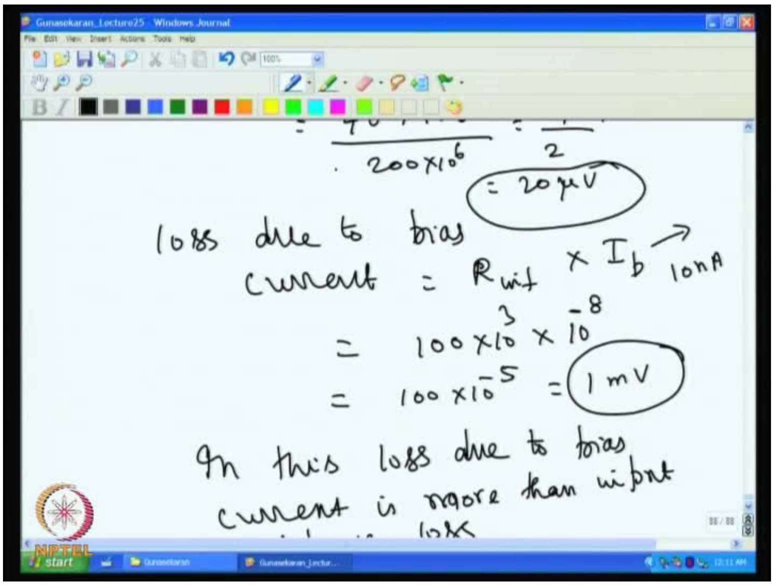

The voltage loss due to internal input resistance would be 40 millivolt into 100 divided by kilo ohm, that is 100 kilo ohm divided by 200 mega ohms. That actually works out to be 40 into 100 millivolt and this gets cancelled. Then, you have 200 into 10 power 6, that works out to be 440 divided by 2 into 10 power minus 6, that comes 20 microvolt. So the loss due to internal resistance is only 20 microvolt.

Now loss due to bias current. That would be R internal resistance into I b. In this case, 100 kilo ohm 10 power 3 into I b. If I use a general purpose op amp, which will be in nano amps, that will be 10 power minus 8 10 nano amps. I b will be taken as 10 nano amps. That works out to be 100 into 10 power minus 5, which is 1 millivolt. In this case, we have lost more due to bias current than the... Because what we lost is only 20 millivolt due to input resistance and we have lost 1 millivolt due to bias current. In this case, loss due to bias current is more than input resistance loss. In that case, one has to go for low bias current op amp, and then the high input resistance op amp because that will then only make sense.

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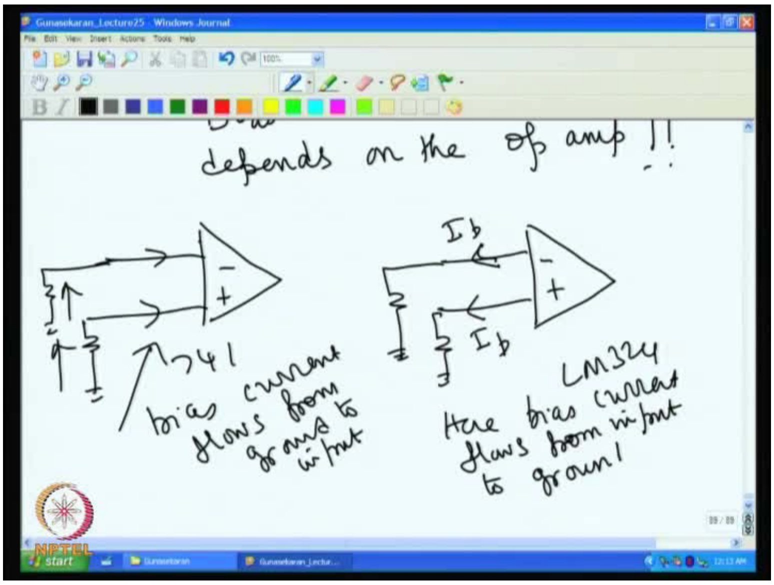

In this case, resistance that you have used is 100 kilo ohms for protection purpose. That will drop too much voltage due to the bias current. One may wonder that set loss is only the bias current loss. Is it to be only subtracted or is it can be added also? Actually the bias current direction depends on the op amp is the big surprise because, for example, if I take 741, in that case if I take plus minus, the bias current actually flows inside. If I take the resistance here, then the bias current actually flows in bias current flows, from ground to input terminals.

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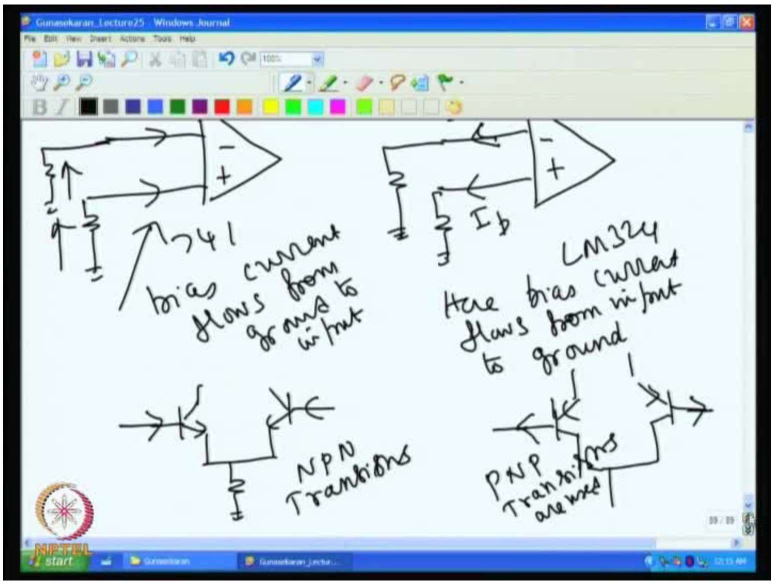

Take another op amp, which is say LM 324. In this case bias current flows out. I is I b. Here, bias current flows from input to ground. In 741, if we look at the input stage, there actually you have look at this, basically NPN transistor. So current is flowing here. In the case of LM 324, that is actually PNP transistors, which are used. In that case, bias current flows out. In this case here, PNP transistor is used, so bias current flows out.

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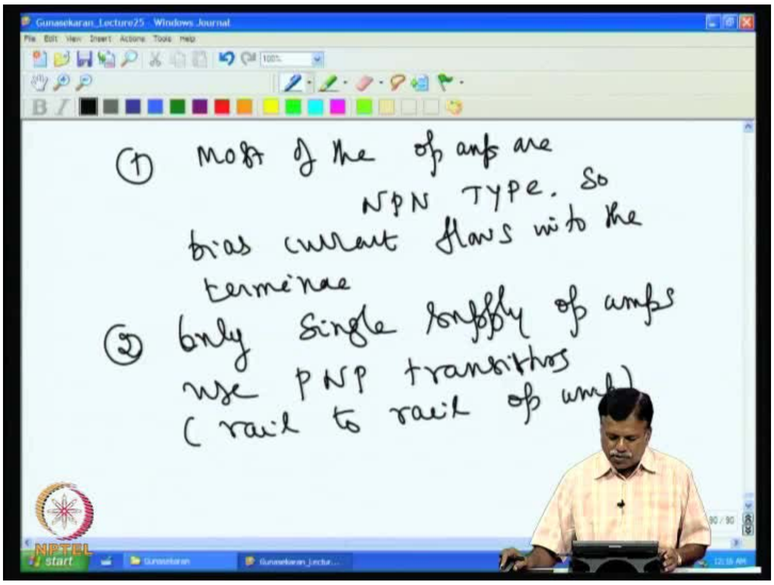

In general, most of the op amps are NPN type. So, bias current flows into the terminal. Second one is – generally only rail to rail op amp or single supply op amps use PNP transistors. That is, input and output can go up to the supply voltage. Most other would be single supply op amp. In this case, they use NPN transistor. In that case, current will be flowing out, so one has to be careful in adding or subtracting the error.

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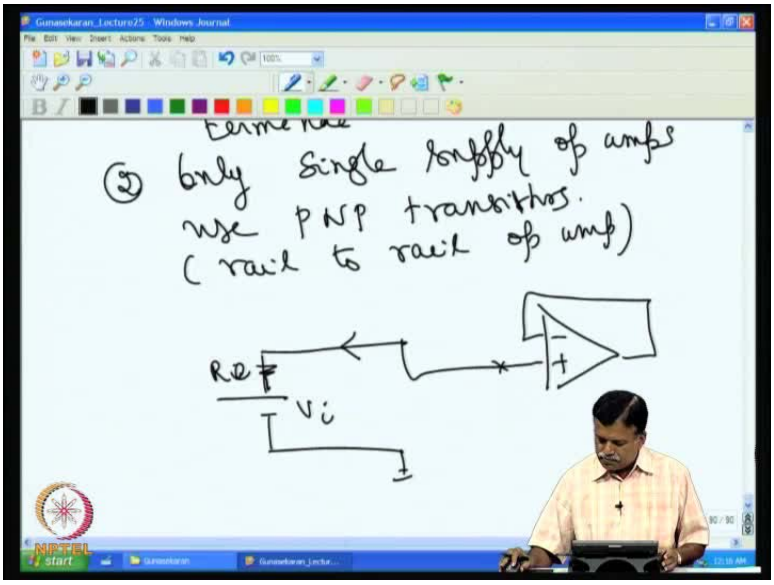

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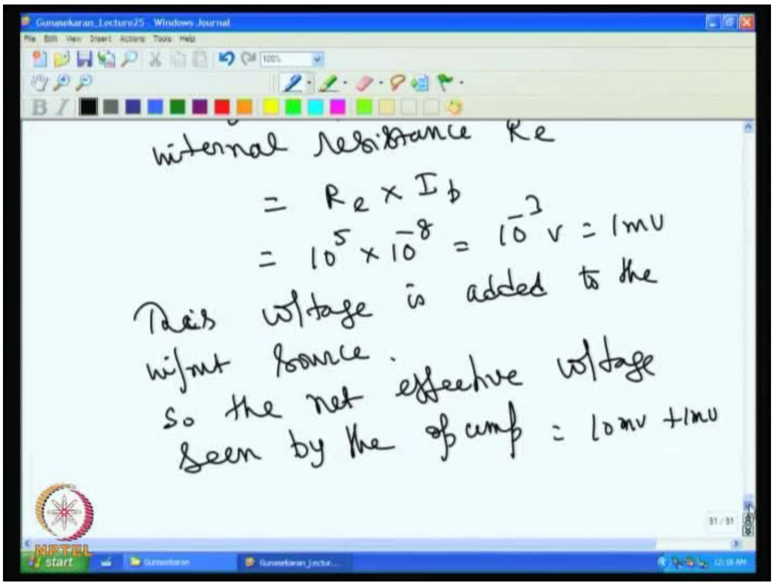

For example, I use LM 324, connect this in this case, bias current will be flowing like this, so you will have voltage at this point. Input voltage would be R_i here and then voltage drop across R_e. Voltage drop across the internal resistance R_e will be equal to R_e into I b because in this case, if I take R_e as 100 k, then resistance 10 to the power 5 into 10 nano will be 10 power minus 3 volt, which is equal to 1 millivolt.

You have 1 millivolt drop across this. Suppose, this is 10 millivolt source, then 1 millivolt goes through. This means, this is actually plus and then this is minus. It is now added to the input source. For net input voltage, this voltage is added to the input source. So the net input voltage, net effective voltage, seen by the op amp is equal to 10 millivolt plus 1 millivolt. so As compare to 741, this is totally different case. If it had been a 741 for LM 324, that is PNP-type, which is used where the bias current is flowing out for 324 op amp.

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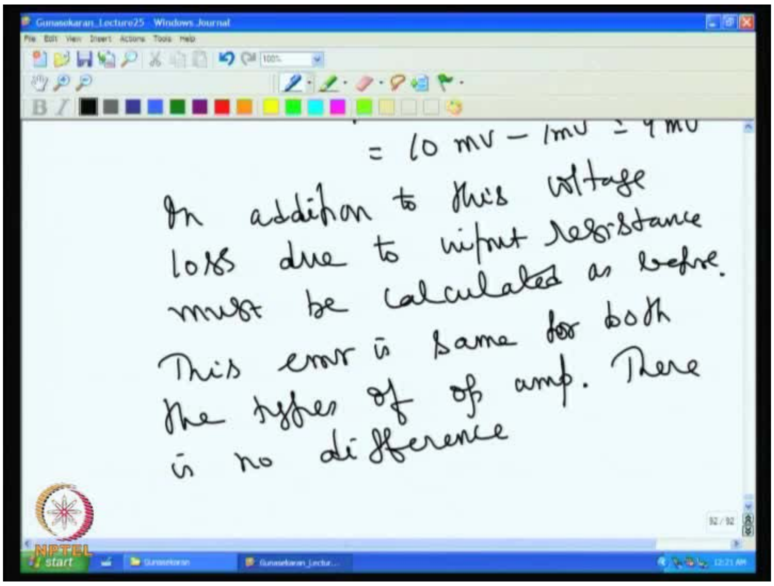

If it had been 741op amp, net voltage, the effective voltage, at the input of the input of the op amp would be 10 millivolt minus 1 millivolt, that is, 9 millivolt. One has to be aware of this difference when you are using op amp. Whether you are using NPN type or PNP type in calculating the error? In addition to this, what will have the voltage drop error due to the internal resistance?

So in addition to this, voltage loss due to input resistance must be calculated as before, which is same for both the cases. Because there is no difference between the two types for the loss due to input resistance, this error is same for both the types of op amp.

One can understand that the input resistance and the bias current complicates the matter quite a lot in the use of operational amplifier. So, one have to be very careful in calculating the input resistance. If you want high input resistance, go for lower gain. If you give a lower gain, you will get a very high resistance. The best is to go for voltage follower. If you increase the closed loop gain more and more, the input resistance will keep coming down, that is not actually what is required. You should not assume that input resistance of the op amp is infinite in all cases, and then ignore the effect of the input resistance. That is not correct. Always worry about this input resistance effect and then be successful in your circuit design. Thank you.