Circuits for Analog System Design
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Module No. # 04
Lecture No. # 19

Gain Error Calculation in Op amp Circuits

We were discussing various errors associated with the operational amplifier in the previous lecture. We had discussed about bias current introduced error and we have also explained that with several examples. In this class, we will discuss about gain error. Gain error is an important component in error budgeting. We will discuss the same in detail.

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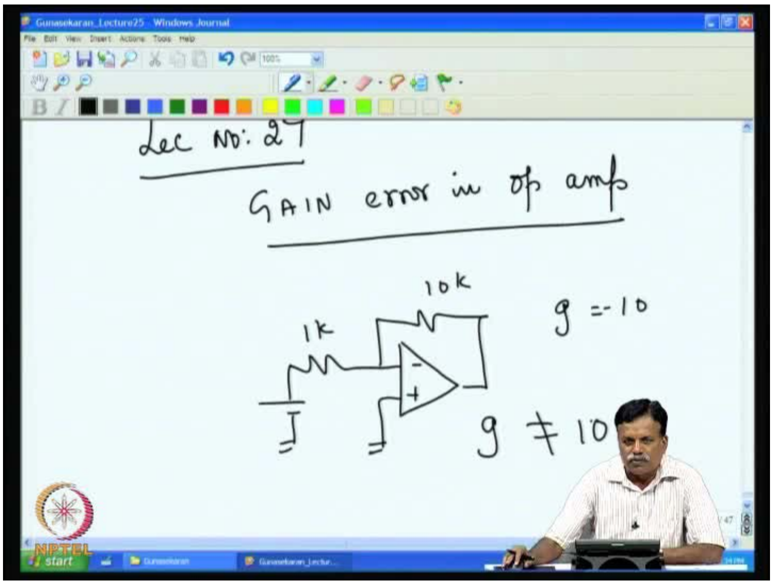

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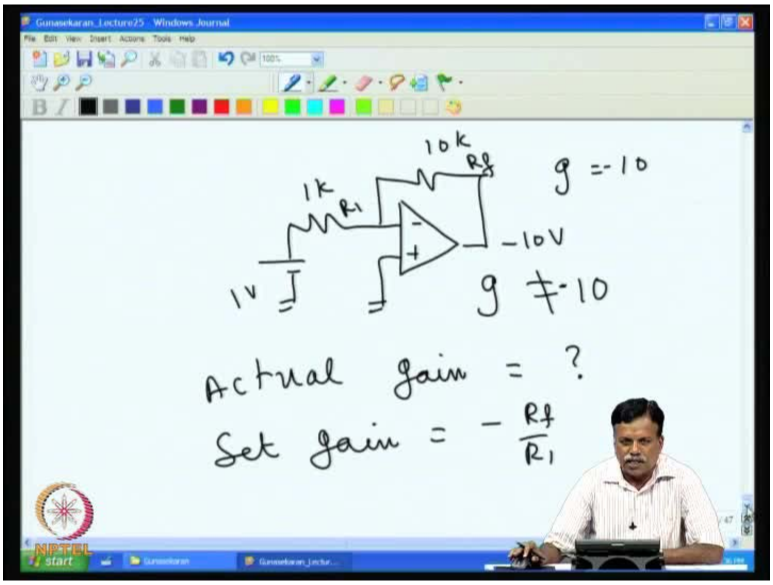

Gain error in operational amplifier

We had seen, in order to operate the operational amplifier with certain amount of gain, for example, if I want gain 10, we nearly put the two resistances with ratio of 1:10. Then, if I have 1k and 10k, you get the gain of minus 10. But this is only an approximation. With this, if we start designing the circuit, soon we will find that our circuit is not accurate enough and we get in to too many problems. For this, we are going to see this one.

In actual case, gain is not really equal to 10. This is the thing that we want to point out. What is the effect of this in the circuit applications? How to correct that? That is what you will see here.

We will fix this one in to two parts - that is, actual gain and set gain. Set gain is R_f by R_1. But what is the actual gain? Because operational amplifier is not giving the gain, which is equal to R_f R_1. For example, if I put 10k and 1k and then give 1 volt, I expected to get minus 10 volt. But in reality, you are not going to get minus 10 volt. This is going to be different. And that difference matters in most of the cases. That is our worry. And our intention here is how much is this difference and how to reduce that error. Then, we work out few examples for the significance of this error. We will see it in this class.

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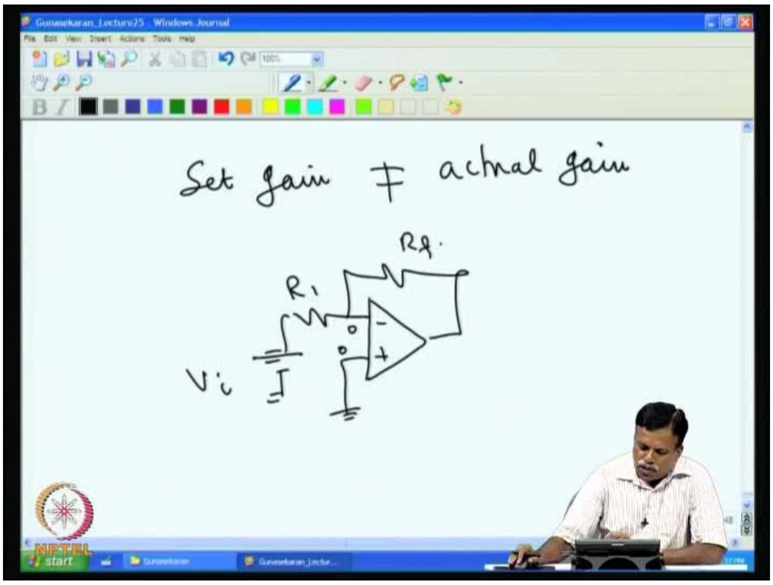

Set gain is not equal to actual gain. This problem is to be solved. Now, one may wonder where from this error had come. This error actually had come from are basic assumption that if you see our actual circuit, what you have made that we had taken this for example in actual deriving this equation, we had taken for example the input voltage is given here and then we have connected to this ground.

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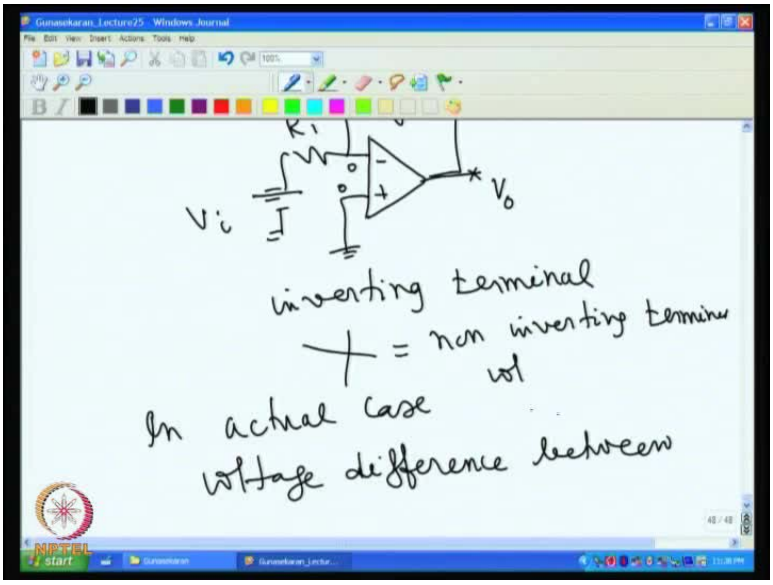

We assume that this is 0 and this is 0. You have V_i, and then this is R_1 R_f. So, we assume the inverting terminal voltage is equal to non-inverting terminal voltage.

But this is not really true because if I assume that the non-inverting terminal is 0, then we assume this is also 0 but then the output of the operational amplifier is actually V_0. This V_0 is coming from the difference between these two as the difference between the two inputs only amplified by the operational amplifier and put it at the output.

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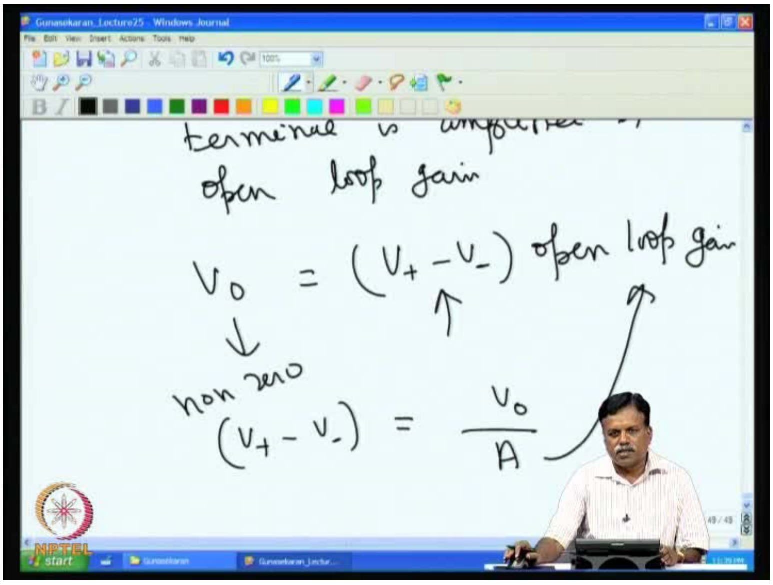

In actual case, voltage difference between non-inverting and inverting terminal is amplified by open loop gain. The other way around, V_0 is actually nothing but V plus, minus V minus into open loop gain. It essentially means if V_0 is some finite value then this cannot be 0. Plus V_0 is non-zero. Hence, this this cannot be 0, that is, V plus and V minus cannot be equal. There will be a difference.

So, the difference actually is V plus minus V minus. The difference between the 2 input terminals is nothing but V_0 by A, where we take A as open loop gain. This is an important difference that one have to understand that the two input terminals are not exactly equal, and there is a difference, and A is the open loop gain. Normally, the open loop gain is very high. For example, if you take 741, the lowest gain is 20000; if it is again 20000 and V_0 is, say for example, 10 volt for A is equal to 20000, that is the minimum gain specified for 741. We take that 1.

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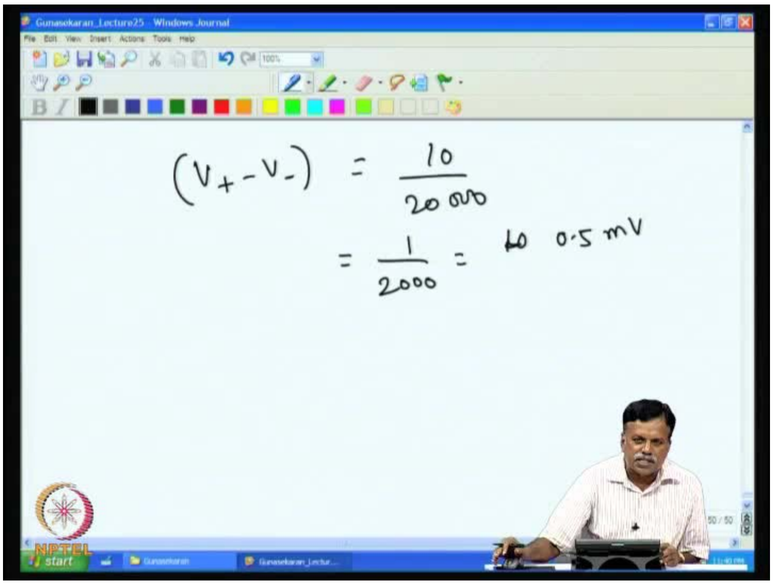

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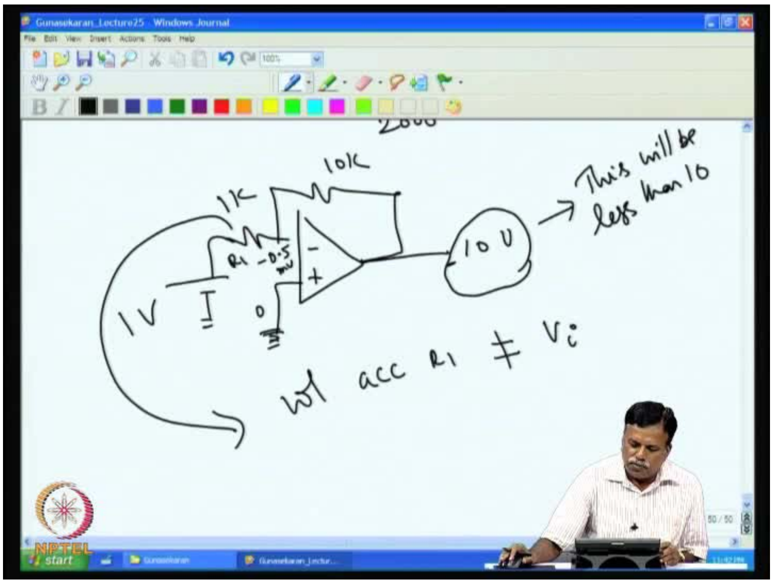

You will get V plus minus V minus, the difference between the two, will be equaled 10 divided by 20000, which actually comes out to be 1 by 2000. If you take in microvolts, then this is coming in volts, so that is coming 0.5 millivolt. You will have 0.5 millivolt difference to produce 10 volt output. That means, these two points are not at the same position. That is, if you look at the op amp input now, if I ground this one, then either if I keep 1 volt and then I have 1 k and 10 k, then I expect nearly 10 volt. Then this is 0 but this is minus 10 volt.

Minus 10 volt. This is sitting at minus 0.5 millivolt. So, minus 0.5 millivolt is the difference you have between these two points. And this 0.5 millivolt is amplified by the open loop gain 20000. It is what appears at the output.

In our derivation, we assume that this is also 0, but actually this is not 0, this is at 0.5 millivolt. The net result is our actual gain is not 10, but it will be less than 10, and the output is also not going to be 10 volt, it will be little less than 10 volt. So, in actual case, this will be little less than 10. This is because the voltage across this is R_1. R_1 is not equal to V_i. This is the main issue actually. The voltage across is not equal to input. This creates the error. How much error it creates? And is it possible to right a general equation to find out what is the error equation? And then, we also have to see, how to apply this error equation in our design? This factor has been forgotten by most of the designers today. In practical world, this has a great implications while doing the error budgeting.

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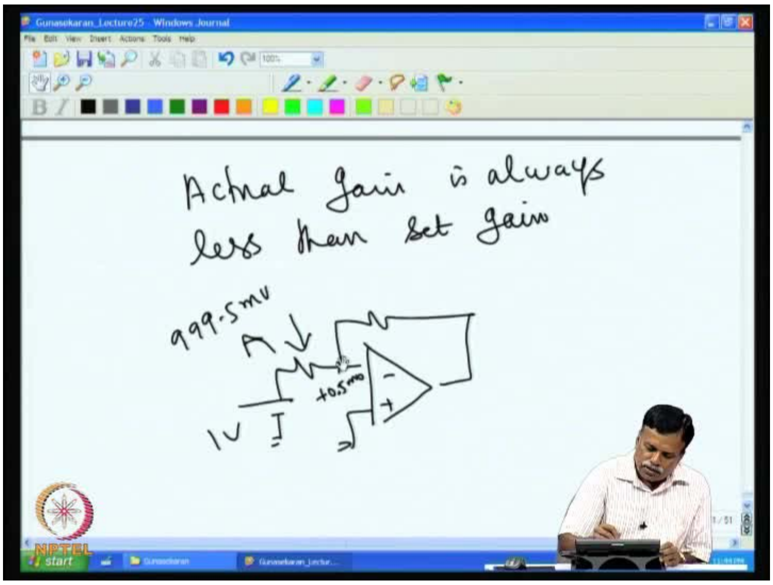

So, one has to aware of this error and then how to apply this. The net result is your gain. The set gain and the actual gain are different. In fact, what really happens is that actual gain is always less than set gain. This is to be plus 0.5 millivolt, not minus, because this voltage has to output has to minus means this has to be plus, so this voltage is plus 0.5 millivolt.

If we see the voltage across this resistance, we have 1 volt, and if this sitting at plus 0.5 millivolt, then voltage across this is not 1 volt. A voltage across this is 999.5 millivolt, instead of 1 volt. This voltage only produces the current. Originally we assume, if it is 1k, 1 milliampere current is flowing. Now, it is not 1 milliampere, it is less than 1 milliampere, same thing happens, the current flowing through is also less than 1 milliampere. The net result is – voltage across this is also less, that is, why the actual gain is always less than the set gain.

Now, we try to derive a general equation to find out what is the relation between the set gain and the actual gain. If I take that, I will take this as 0 volt. Instead of 0.5, take it as a general value as x.

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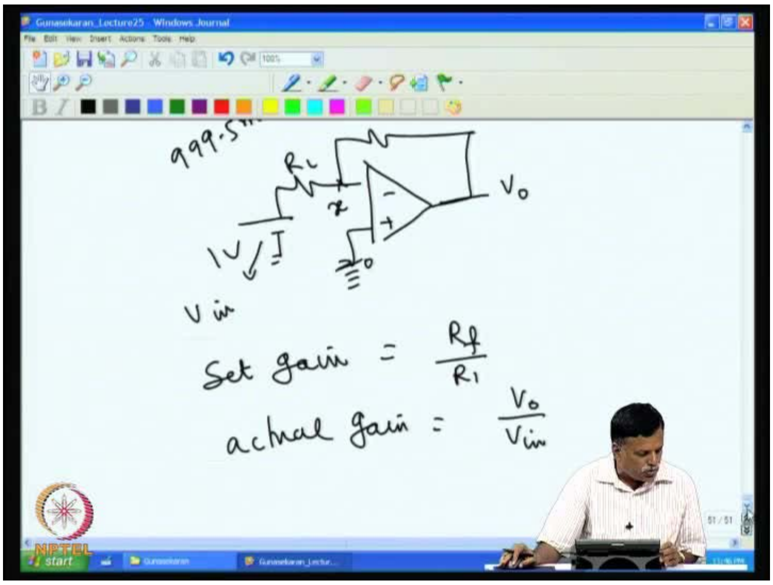

Here, I will remove this and put this as x. It is not sitting at this is sitting a 0 and this is sitting at x and take this as V_0, and then this is R_f and then so this is R_1. Hence, you have R_f R_1 and V input. this is we take it as V input and that is V_0. So, set gain is R_f by R_1.

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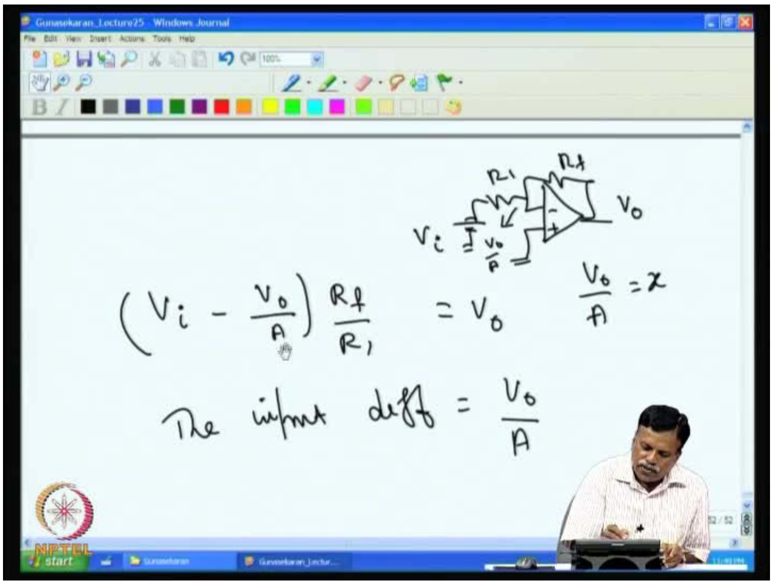

The actual gain is V_0 by V input, that is, what we want actually. Now, if I take this as x, this is as x voltage, then the current through R_i can be computed. I can take the current through R_i as V_i. So, we will have, I put the circuit at this corner, so I have as V_i. We have output as V_0, so this voltage actually, we can say, V_i minus V_0 by A into R_f by R_1, is equal to V_0. This is coming mainly by this factor because R_f by R_1 is your gain. I try to find out what is the voltage that we have apply? here it is V_i and then you know voltage at this point is V_0 by A. That is your x. So, V_0 by A is equal to x, that we have defined at this point. This is nothing but V_0 by A. But why x is V_0 by A? The reason is that if I have get to V_0 here, then I need a difference between these two points. The difference between the two points amplified by open loop gain is what we get as output. If I have to get V_0 here, V_0 by open loop gain is the difference that is the excepted here. The input difference equal to V_0 by A. That means, this point is at V_0 by A, that is why V_0 by A into A gives you V_0 here. So, I had to take this as V_0 by A. Once it is V_0 by A, we have to take the applied voltage. If you go by our earlier formula, applied voltage is taken as V_i and multiplied by the gain. Now, applied voltage is naught, it is lesser by V_0 by A. We have to take the applied voltage V_0 minus V_i by A into R_f by R_1. This is our output voltage.

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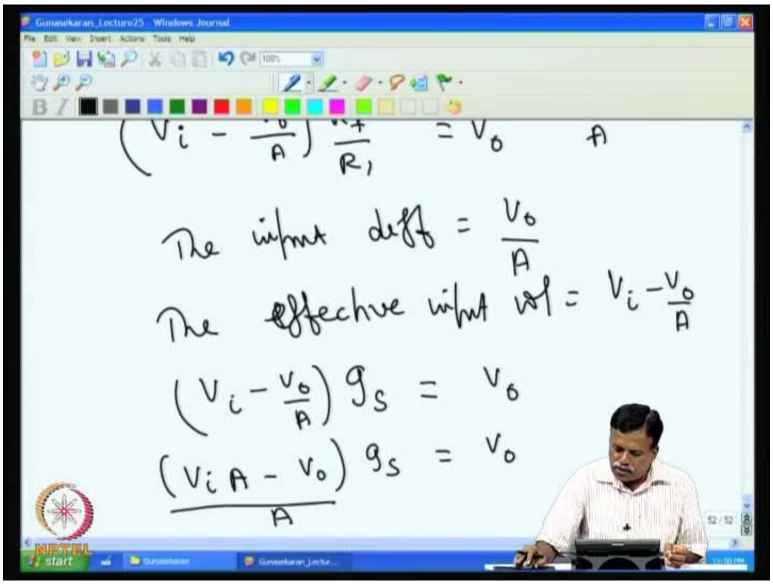

The input to that means the effective input voltage. Input voltage is nothing but V_i minus V_0 by A, which we are taking as V_i. That is why that the effective input voltage V_i minus V_0 by A into gain set, that is, R_f by R_1 gain set is equal to V_0. Now, we have to now simplify this to get the form that we want because we have to get the actual gain that is actually required. We will simplify this by multiplying this A, so V_i into A minus V_0 into g_s. If you divided by yA, that gives you V naught.

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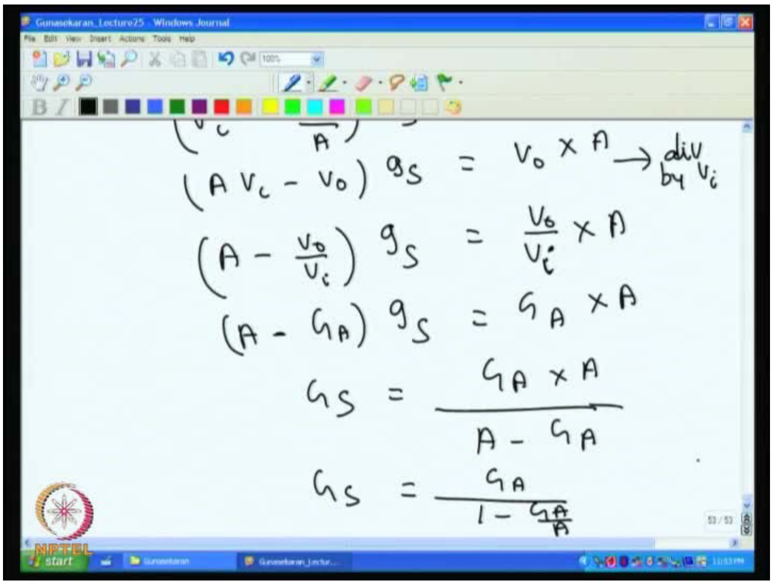

Now we can write the actual gain - V_0 V_i. So, V_0 by V_i can be written as actual gain, that is, equal to gain A. If I simplify this equation, you will get A minus, and we can simplify this here itself to get V_i minus V_0 by A into g_s, that comes as V naught. Now, I can write this 1 minus or I can write A into V_i minus V_0 into g s equal to V_0 into A. If I divide both by both sides by V_i, then I will get V_i into g, that is, actual gain. We can write V_i A minus. We will get V_0 by V_i here so that will come g_S. That is actually V_0 g_A and I write in two different forms. Divided by A, we get V_0 $V_{i.}$ So, I will get g_s minus V_0 by V_i into A. I merely divided by V_i. And you will get this. So I divided all the terms by V_i then that is what it comes.

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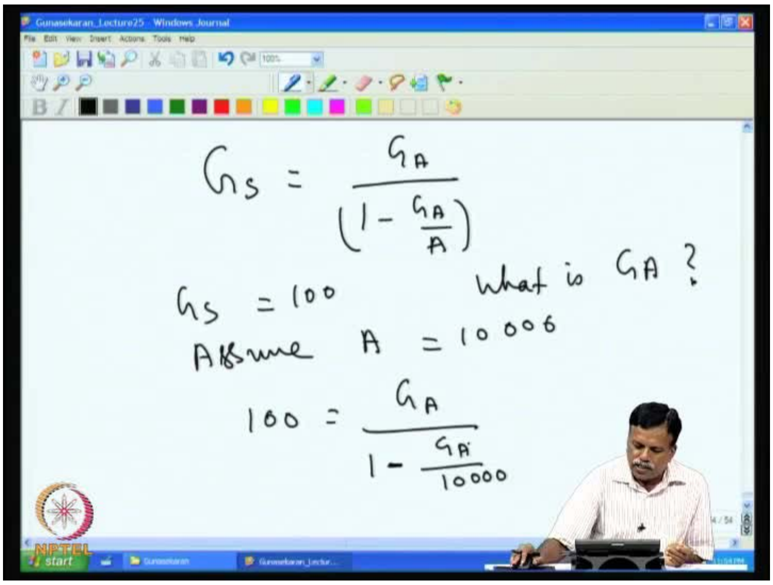

We can now put V_0 by V_i as the actual gain. So, A minus G actual into g_S comes G actual into A. Now, if you can simplify this that appears as $G_{S.}$ Set gain is actually G_A divided by A, then you get A minus G_A. On simplification, G_S will end up as you get G_A divided by 1 Minus G_A by A. Now, we get into the next page, so we will get a the set gain is actually equal to actual gain divided by 1 minus G_A by A. This is an important relationship. For example, if I have to take, for example, typical op amp of 100 gain, then if G_S is equal to 100, what is G_A? Assume A is equal to 10000 open loop gain, then you will get the set gain 100 and it is actually $G_{A.}$ That is what we have to get, that comes out to be 1 minus 100 divided by 10000. Actually G_A here this is not 100.

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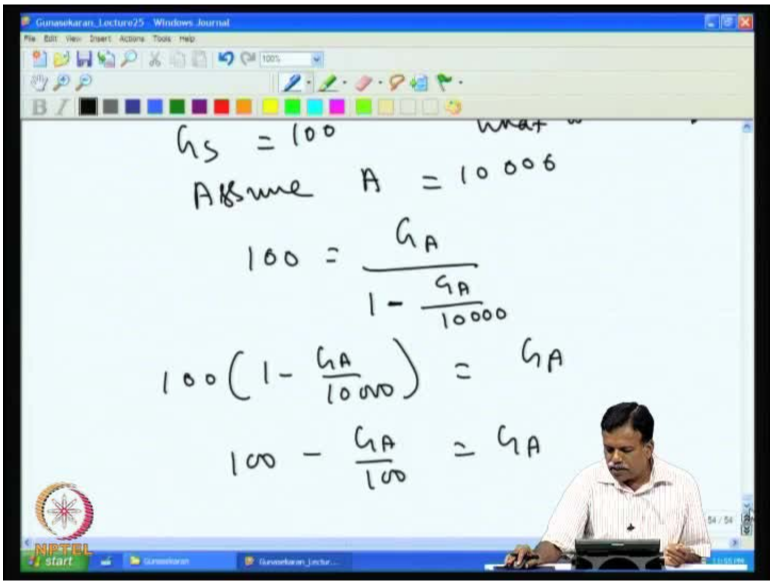

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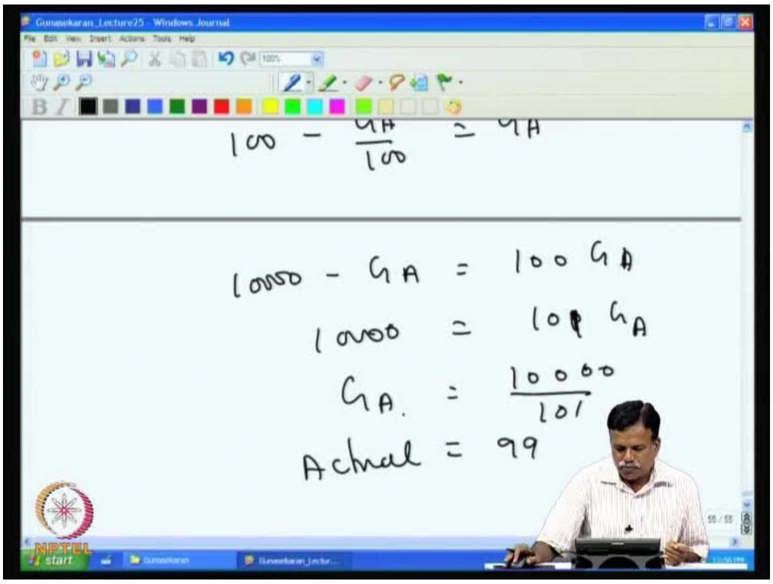

We are applying in this. So, you get G_A by 100. If I multiply this, you will get 100 1 minus G_A by 10000, it gives you G_A. That makes, for example, 100 minus G_A by 100, it gives you the actual gain. If I see this one, this come as the actual gain as 10000 minus G_A. That comes 100 G_A. So, 10000 comes as 101 G_A.

Actual gain would be 10,000 divided by 101, which will be close to 99. Instead of getting 100 gain, we are getting only 99 gain. So, the actual gain is actually little less. Now, if the gain is little less than 100, it is not a serious issue. But actual problem comes not because of this small deduction in gain. This 99 gain. Is it stable? The gain 99 is not stable that is the main issue. That is what we going to explore now.

The first step that what we had done is that the set gain 100 that we are not really getting it as 100. The set actual gain what we get is actually less than 100. And that relation is actually given by this equation. This equation defines what is the relation between actual gain and set gain. Now, the difference between actual gain and set gain will be more, if the open loop gain is less. For example, if the open loop gain A is very large, then this term become negligible and then you will get set gain is equal to actual gain. But this will be negligible only when A is much larger than actual gain. That is what you going to get. So, the open loop gain in op amp is very large, then set gain and actual gain will be small.

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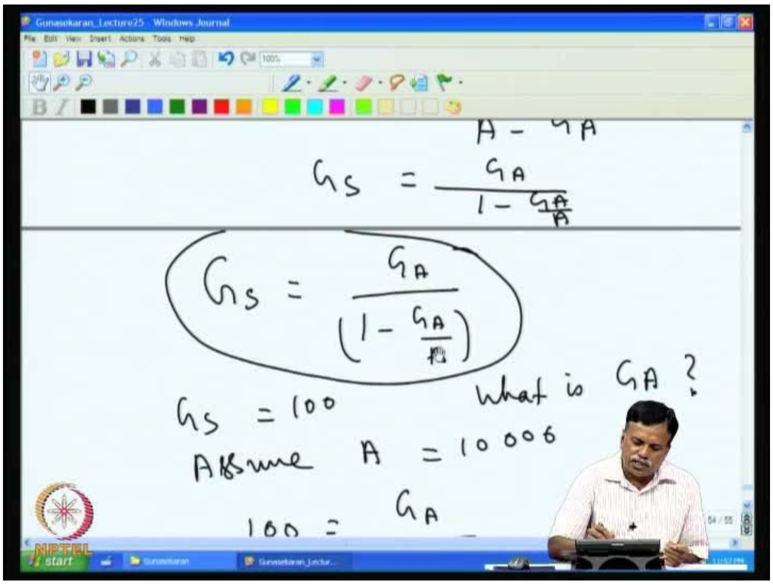

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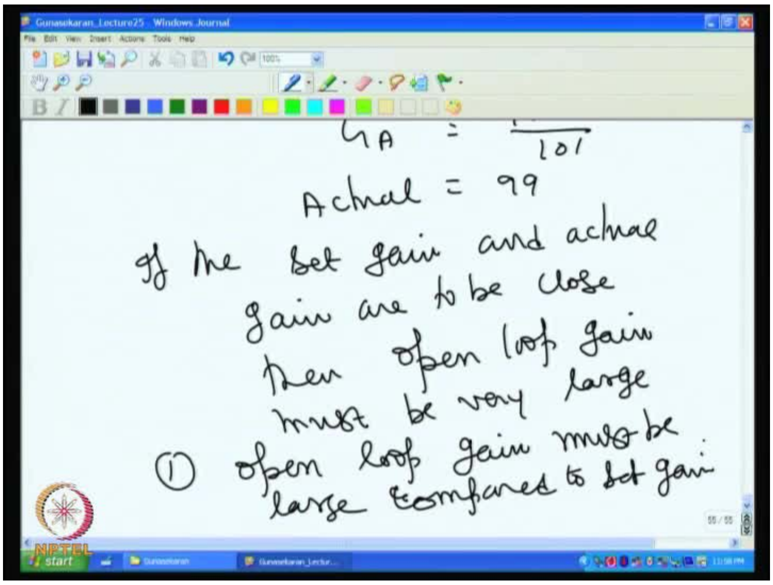

Now, one has to remember that A is the open loop gain, that is not a constant factor. For a given op amp, it changes with temperature. This is the main issue in actual case. If the gain has to be stable in the op amp, that means, if the set gain and actual gain are to be close enough, then open loop gain should be very large. Open loop gain must be very large so that is one condition. So, first condition is that open loop gain should be very large. Must be large as compared to set gain. Other way round, you should have only less gain to be set from the op amp.

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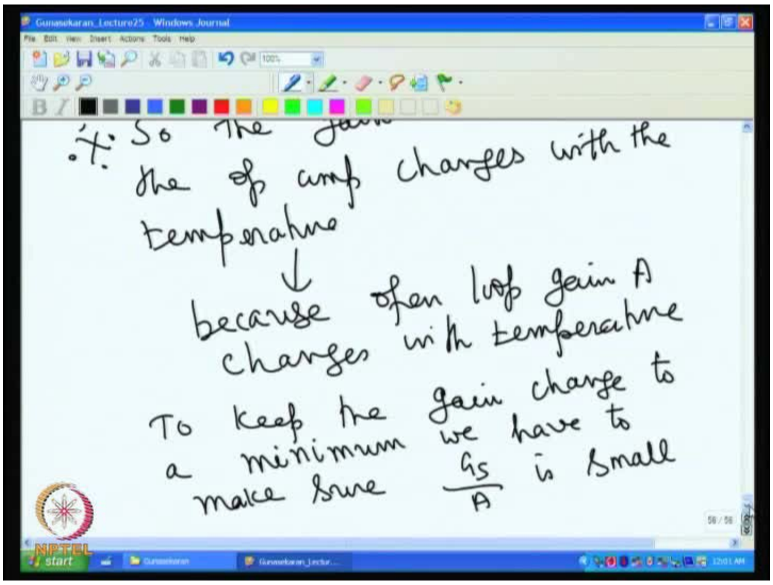

Then the second point is if the open loop gain A changes with temperature. Because higher the temperature, the open loop gain be higher. So, for given a op amp, if the open loop gain changes, then the actual gain also changes, even though we are not changing the set gain. The gain obtained from the op amp changes with temperature. Now, this is a very important point that we had realized. That is, whatever gain that we are getting is not constant, that changes with the temperature. This is because A_e changing with temperature. Because open loop gain A in A changes with temperature.

That means, the gain that what we are to get actually changes with temperature. Now our aim is we want to minimize the change. That means, if our ratio between the set gain and open loop gain is very small, then the change also will be very small.

To keep the gain change to a minimum amount, we have to make sure the set gain by A is small. That means, one should not try to get large gain in one single op amp. That is the thing that we have to remember.

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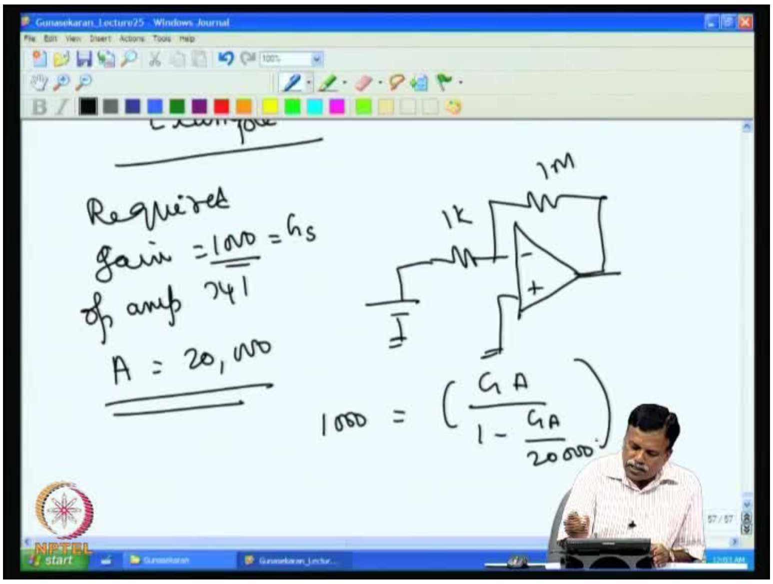

Now, let us work out 1 or 2 examples to illustrate this point. For example, in this case, we want to have a gain of 1000. Assume the required gain is 1000, assume we use a op amp 741, the A is equal to minimum 20000 per 741. So, A is a 20000, the required gain is 1000. What we get is a set gain. You want a set gain as 1000. If I take this, to get a gain 1000, what I do is I will put this. Assume I keep here 1 mega and then 1k, and now the signal is given here. So, the gain the set gain is 1000 is there.

Now will I get the actual gain 1000? Or, how much I will get? And, what will be the effect of temperature for this? And then, we will show the second example that if I modify the circuit, the error that I am going to get will be very small. For this, let us work out the gain error.

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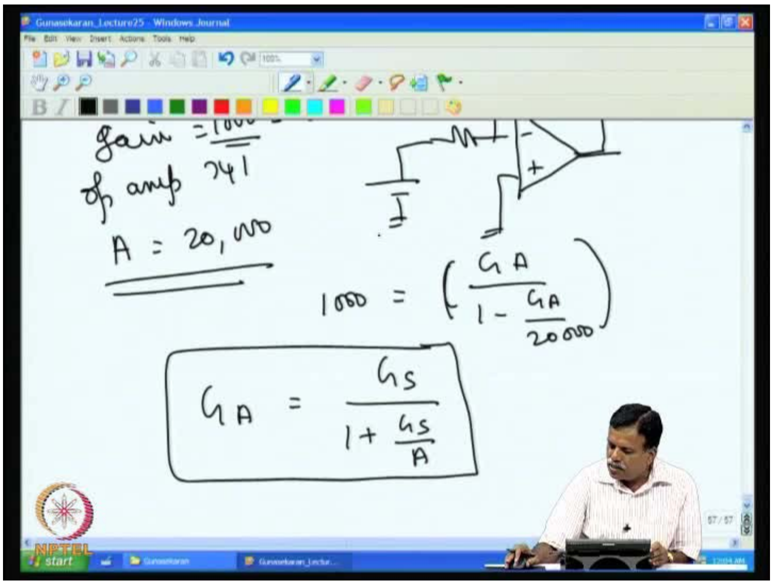

If I calculate the gain error, for example, this set gain in this case is 1000, so you have 1000. But actually I do not know what is the actual gain. So, I put this divided by 1 minus G_A by 20000. That is what actually it comes so the actual gain. So we will have... Actually, even this formula can be rewritten in the following way. that is we can also show in the derivation that derivation Actual gain for this can be written in terms of set gain. I can also write in terms of actual gain: 1 plus G_S by A. This also can be derived from this equation. That is no problem that you can rearrange the terms then you will get it in this problem.

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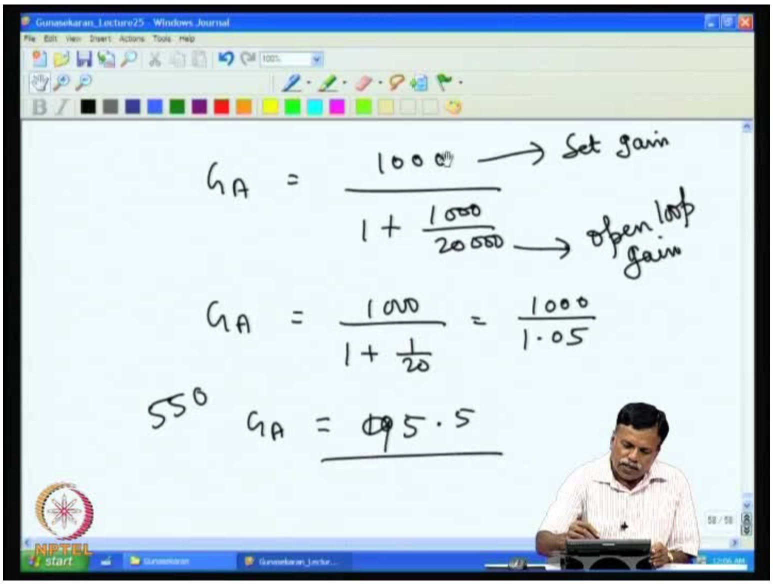

So, the actual gain that you get will be in terms of set gain one can obtain. So, if I apply this equation, if I apply these qualities in this equation, then you will get, for example, actual gain would be a gain of 1000, then I have 1000 plus 1 plus 1000 divided by 20000. This is actual gain that you get. This is the set gain. This is the open loop gain.

You will get 1000 divided by 1 plus 1 by 20, which actually works out be 1000 divided by 1.05. That is actually the gain. It will be actually, if you would take this, you will get 9 times, so 945. So you will get 55 into 0, and that will come as 5 times. You will get around 95.5, you will get the gain.

Actual gain is not 100 but it is actually only 95.5. Now this had happened because we have to get large gain here. If the gain is put lower gain, for example, 10, then the gain error will be small. As they increase the gain more and more, the gain error is increased.

As such having a lower gain then what we want is not a serious issue. If we want 100 gain, I can put 105 and get the required gain of 100. But the question is whether this gain 95? what is there? Is it constant? Is it steady? The question is – is it stable against temperature? That is the question actually. Actually, this is not stable and as the gain changes, this also changes.

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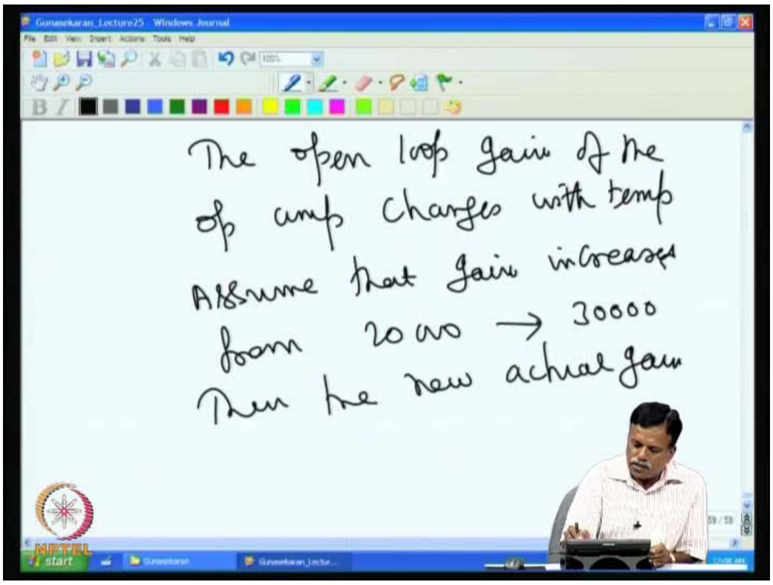

For example, assume that op amp open loop gain is increased to, instead of 20000. The open loop gain changes with the temperature. Because in all the cases, the open loop gain of the op amp changes with temperature. So, the open loop gain of the op amp changes with temperature.

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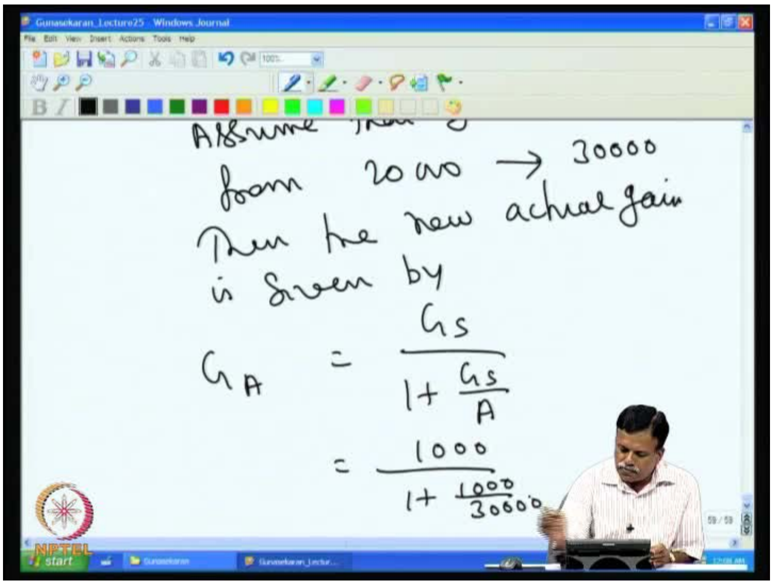

For example, assume that gain increased from 20000 to 30000, then if I calculate the gain, the new actual gain would be actual gain, which is given by... So, you will have the gain set divided by 1 plus gain set divided by A. If you have to apply this, then we will apply this now. This we will get here. This is 1000.

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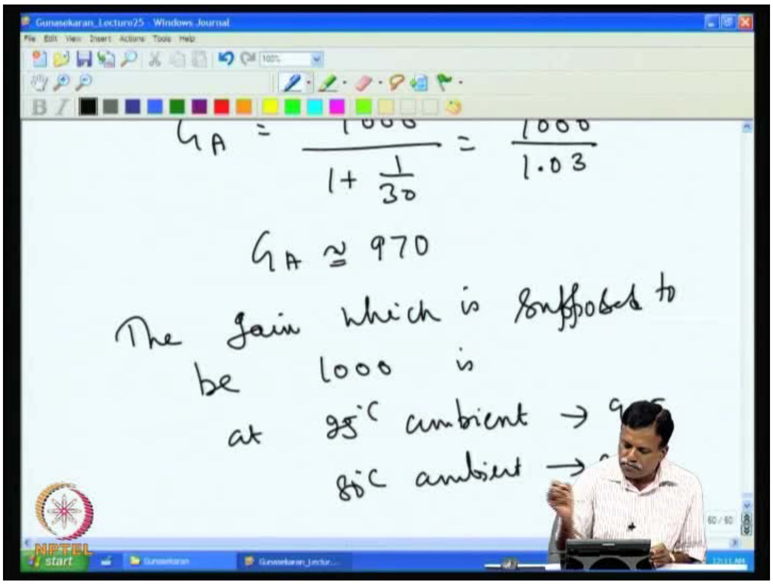

Now, 1 plus 1000 divided by 30000, this works out be actual gain. It would be 1000 divided by 1 plus 1 by 30. That comes 1000 divided by 1.03. So we had actually 1.05. That actually will become 1.03.

Now, if you calculate this, there will be a 3 percent decrease, and you will have that actual gain would be around 97. Earlier, it was 95, now the gain had become 97, that means, for example, with op amp temperature change, the room temperature changes, and the gain shifted from 95 to 97. If have that is so the actually this 970 sorry this becomes 970 it becomes 970 here also this has to be 955 actual gain would be 955.

The gain supposed to be 1000 had become only 955 in this case. And then the gain supposed to be 1000 here, have become 970. That means, the gain has drifted from 955 to 970.

Actual gain, which is supposed to be 1000 is at 25 degree, for example. 25 degree c ambient it had become 955. At 80 degree ambient, it had become 970. That is, the gain is actually changing with the temperature. This problem looks like a trivial, but actually it is a serious problem circuit design, which is not understood by many of the designers.

You have the gain of the op amp. First of all, if you say 1000, it is not going to be 1000, this will be something different actually. And that also changes with temperature.

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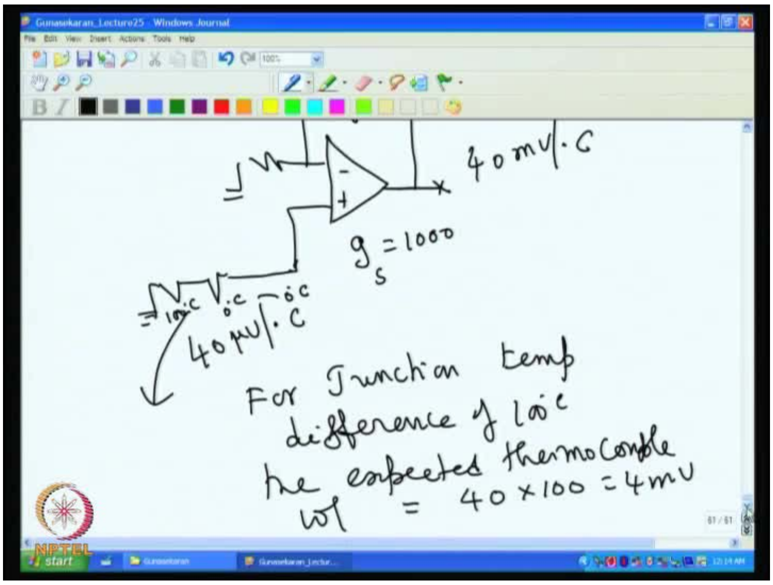

Now what is the expected problem because of this? This gives a problem because, for example, if I want to amplify some signal – thermocouple voltage, so I have a thermocouple amplifier, I put this, a thermocouple voltage is given here -- single junction thermocouple. Take an example of thermocouple amplifier. Take this as example 2. Take thermocouple amplifier and then assume that this gives you 40 microvolt per degree c. If I give, for example, gain is equal to 1000, that is, I set the gain at 1000, then what I want here is actually 40 millivolt per degree c. Every 1 degree difference in temperature will produce 40 microvolt here and if I give a 1000 gain, I would expect 40 millivolt at this point.

For 100 degree change, for 100 degree room temperature, for junction temperature for 100 degree... To avoid confusion if you want, you can also have two junctions 1 0 degree c 1 at 100 degree c. So I can put it in two junction. Also those, who are not familiar, need not worry about this single junction thermocouple. For example, if this is 0 degree c and if this is 100 degree c, then the difference is 100 degree c.

For junction temperature difference of 100 degree c, the expected thermocouple voltage is 40 into 100, that is equal to 4 millivolt.

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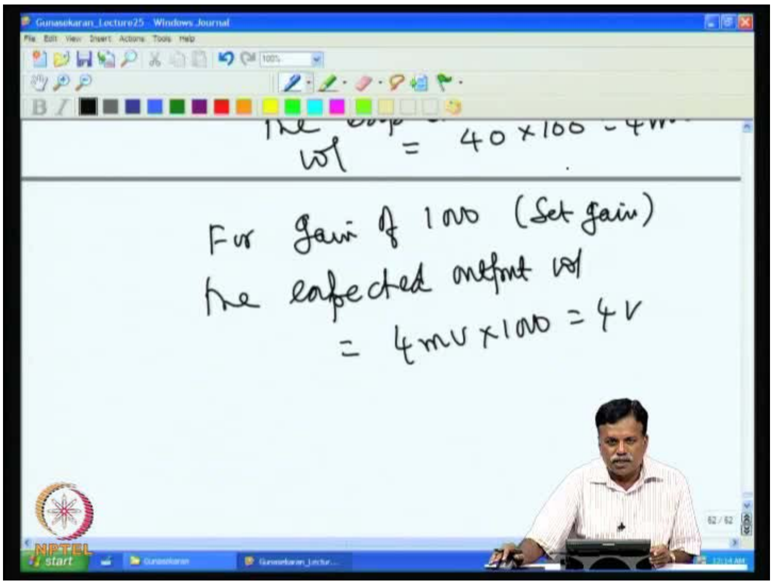

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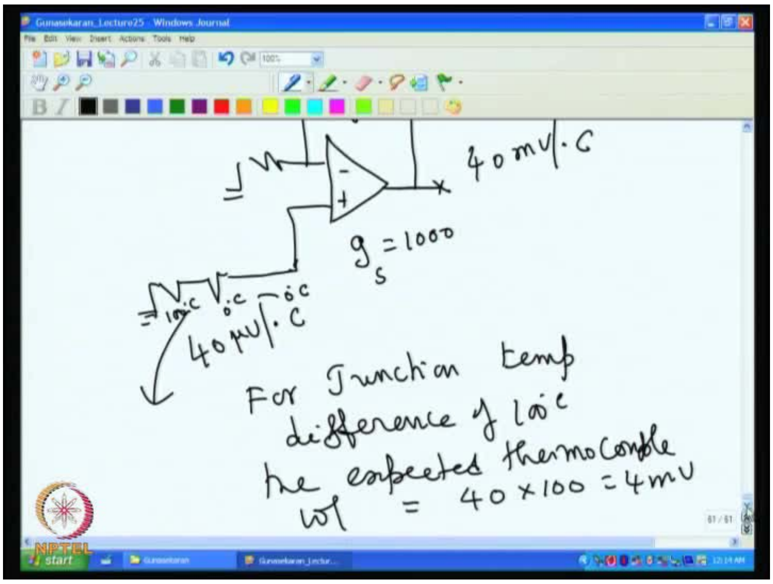

We expect it at 1000 gain. For gain of 1000 set gain, the expected output voltage is actually 4 millivolt into 1000. That is equal to 4 volt. So, expected voltage is 4 volt. But what actually happens is when the … But we know that we had shown that if it is a 741 gain of 20000 at room temperature, then the open loop gain of 741 actually goes up to 30000 at 80 degree c. So when the open loop gain is 20000, then the gain will be 955, and when the temperature goes high that 80 degree the gain goes to 30000, then the actual gain increased to 970.

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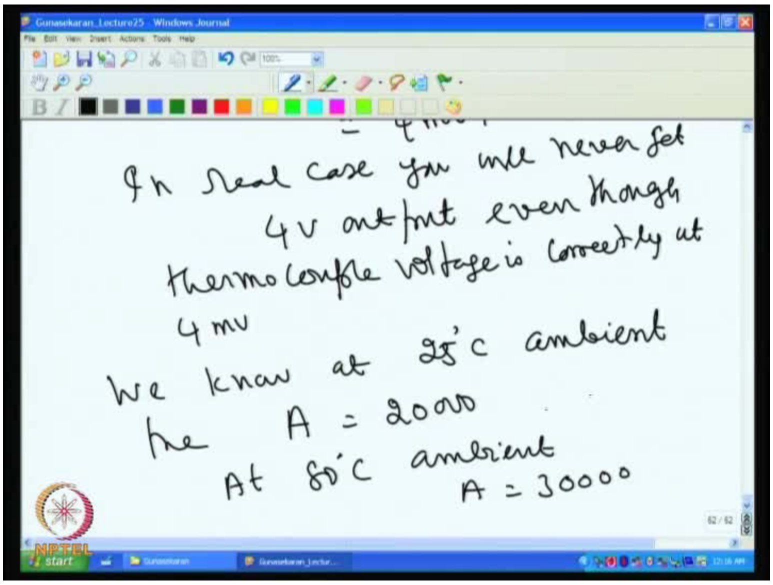

That means, at 25 degree c, when the... But in real life, in real case, you will never get 4 volt output, even though thermocouple voltage is correctly at 4 millivolt at 25 degree c. We know at 25 degree c ambient, the A is equal to 20000; at 85 degree c, 80 degree c ambient, A is equal to 30000.

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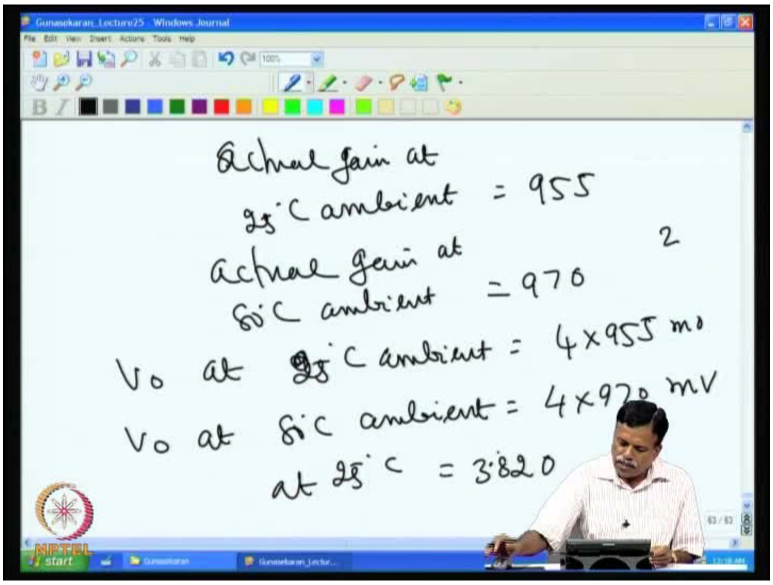

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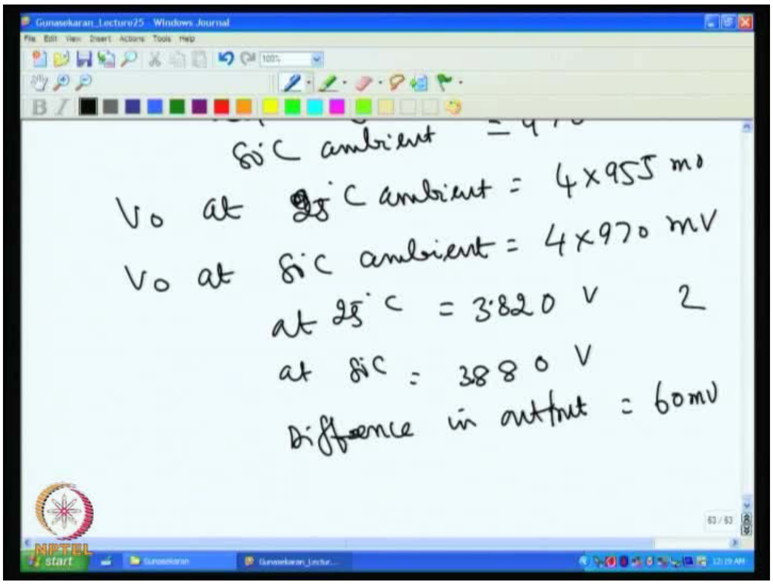

From our earlier calculation, the actual gain at 25 degree c ambient is 955. Actual gain at 80 degree ambient is equal to 970. That means, output V_0 at 25 degree c ambient would be 4 into 955 millivolt, V_0 at 80 degree ambient would be 4 into 970 millivolt, which actually means it appears as if as the ambient temperature increases, the output voltage also increases. That is what it means that this is the voltage that you get. If you calculate this at 25 degree c, it comes out to be 3.82 volts, at 80 degree c, it turns out to be 3.8 volts.

We see the difference of 60 millivolt. The difference in output is equal to 60 millivolt because this is 3.820. This is 3.8 volt. That means, output voltage drifted by 60 millivolt for the ambient temperature change of 25 to 80 degree, that is, 55 degree change created 60 millivolt change at the output, where the output is 4 millivolt. It is 1 degree c because at the output we have 1000 gain and the input, it is 40 microvolt, which is 1 degree c, at the output of the op amp 4 millivolt is 1 degree c.

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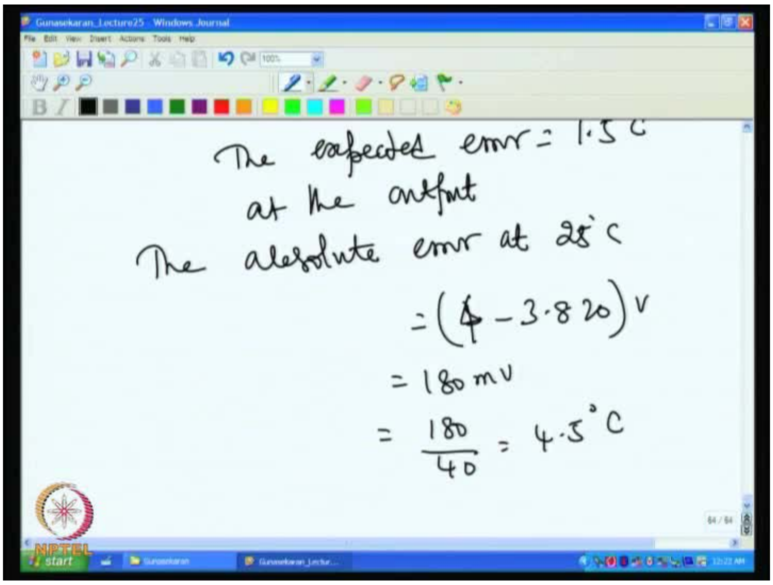

At the output of the op amp, sensitivity is equal to 40 into 1000 microvolt, because 1000 is the gain, so that comes out to be 40 millivolt. Sorry. It is actually 40 millivolt, it is coming as a 1 degree c here the output. Actually we have 4 millivolt here, 4 millivolt into 1000 actually comes as 4 volt, instead of 4 millivolt, which is actually 100 degree c. It is supposed to come as 4 volt. If first of all we got only 3.82 and at that to increase to 3.80. That is 60 millivolt increase because 1.5 degree error had come at the output.

The error, the expected temperature drift, expected error error is equal to 1.5 degree c at the output. This error had come purely because of gain drift. If you calculate the total error, this is only change in error. But if I take the real error, for example, at this point of 4 volt, you are getting only 3.82 volt. So, in terms of absolute error, the absolute error is only a difference error of 1.5 degree. The absolute error would be the absolute error at 25 degree c, it would be 4 minus 3.820 volt, that is 180 millivolt. This is equal to 180 divided by 40, that is 4.5 degree error.

So, absolute error is high and with temperature, that is changing. And that error is 1.5 degree. That difference error is 1.5 degree. So that means, if I try to use op amp and I put two resistors to get a gain 1000 and I haven't got the gain 1000; in that case, instead of showing 100 degree c, it will be showing only much less than 100 degree, that is less by 4.5 degree c. It will show only 95.5 degree c. 100 degree temperature will be shown as 95.9 degree and that to when ambient temperature changes, that will change to 97 degree.

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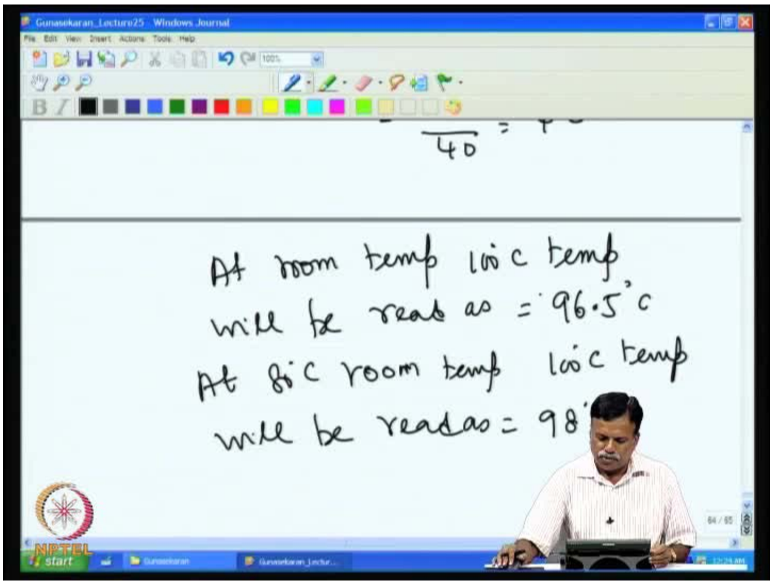

At room temperature, 100 degree c temperature will be read as 96.5 degree c because you have 4.5 degree error at room temperature. At 80 degree c room temperature, 100 degree c temperature of the thermocouple will be read as 91.5 degree. will be added up, that will be actually we will have three point one twenty. So, 120 will be 3 degree away, so that will be 98 degree. Actually, this is to be 4.5 degree error. 100 minus 4.5 you have to add 1.5, that will come as 98. So, if I add this one, it will show as 98 degree c.

First of all, the temperature is wrong and the reading also changes with ambient temperature. Now, that is actually coming because I think there is a mistake in this calculation. This difference is actually coming as 820 60, and 1.5 degree error is coming. So nevertheless, you see that temperature changes with ambient temperature change. This had come because the op amp gain is changing. If you do not want this to be this to happen, one easiest way is do not get all the 100 gain in one single stage. Get the required gain in multiple stages.

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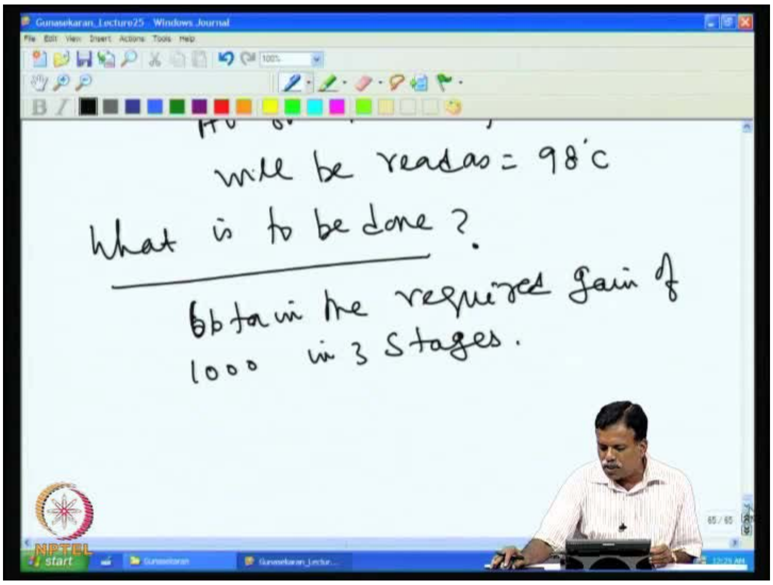

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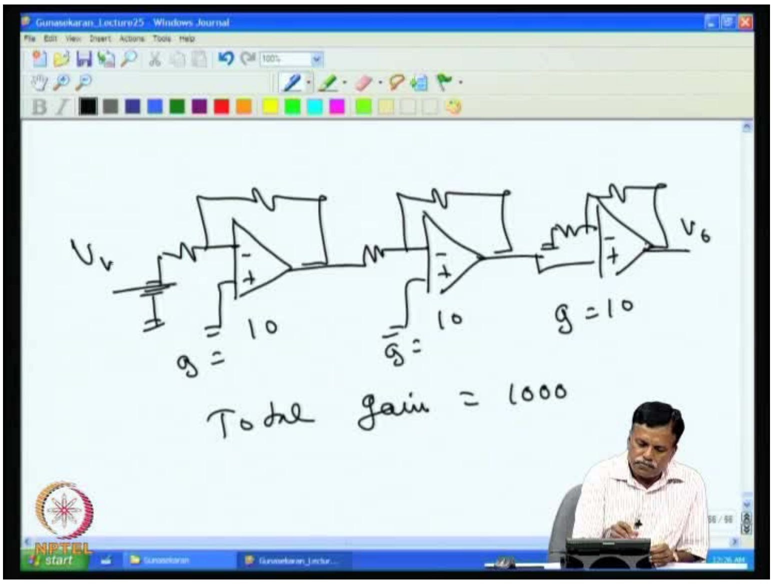

For this, what is to be done? Obtain the required gain of the 1000 in three stages, instead of one single stage. Then, you will find that the gain drift is also less, the gain error is also less. For example, I can have gain 1000 in 3 stages, for example, I can have input like this and have only 10 gain in first stage, then I put the next 10 gain in the second stage, and another 10 gain in third stage, then I can even use the... So assume, I have gain 10 here, gain 10 here, and gain 10 here.

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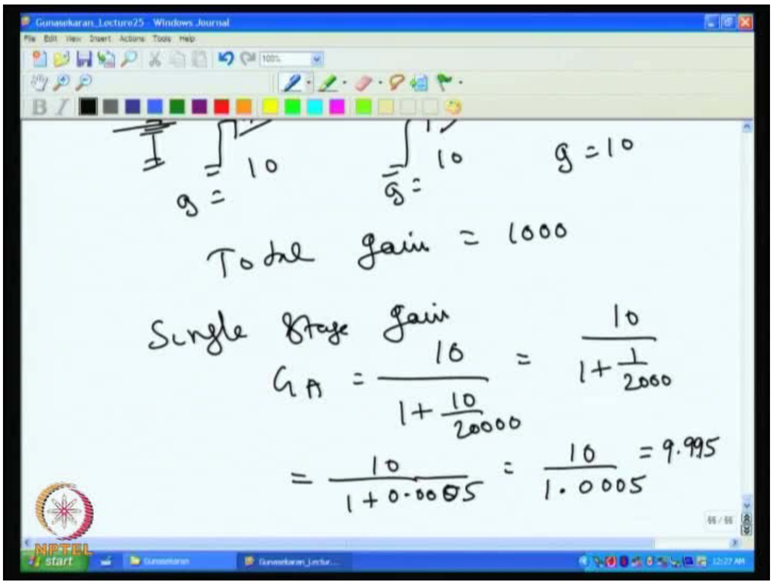

We have three stages. So, total gain is 1000. Now, if you calculate V_0 and V input, you will find that gain error is much smaller because the single stage gain. If I calculate the single stage gain, so actual gain would be set gain of 10 divided by 1 plus 10 by 20000.

That actually works out to be 10 divided by 1 plus 1 by 2000, which you will have 10 divided by 1 plus it 1 by 20000. That comes out 0.005, which will come as 1.005. And you will find this gain is coming very close to 10. You will find it as 9.995. You have to work out and see what is that actual value that it is coming.

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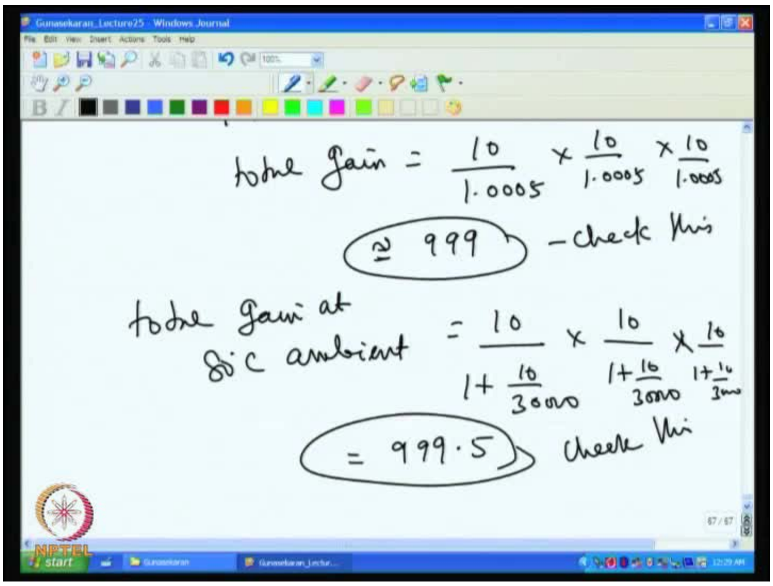

If you multiply this by 3 stage, each stage will have this. Then for 3 stage, total gain would be 10 divided by 1.0005 into 10 divided by 1.0005 into 10 divided by 1.0005. Now, if you calculate this, you will have get almost 999. Now, gain error is much smaller compared to what we had in the earlier case. So, by getting a lower gain in single stage, the gain error comes down and the drift of the gain with temperature will also be less.

For example, if I try to find total gain at 80 degree c ambient, that would be 10 divided by... You will find that 1 plus 10 divided by 30000 into the 10 divided by 30000 is the open loop gain. You will get the same thing again – 10 divided by a 30000 plus into 10 divided by 1 plus 10 divided by 30000. You will find that this is also coming very close to this. You will get 999.5. I have not calculated.

You check this. But you will find that the difference in gain is only very small. So, we will find that with the temperature, the gain is not changing much. It is better option to have higher gain obtained from many stages, rather than a single stage. That will make the gain error also small and the gain change also very small.

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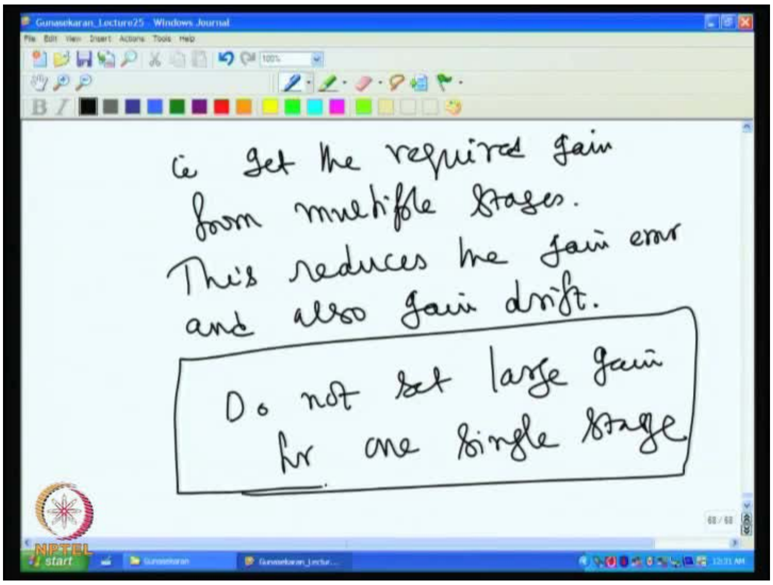

What is required to get larger gain? Use many stages. That is, obtain the gain from several stages -- smaller gain from several stages. Get the required gain from multiple stages. This reduces the gain error and also gain drift.

That is why one should not try to get large gain in one single stage itself. If we get a large gain, then you will have gain drift as well as gain error. So, the advice is do not get large gain, do not set large gain for one single stage alone or one single stage.

This is the thing that we had to remember. If you do not set large gain, if we set a smaller gain, get it from several stages. The gain error and the gain drift also will be less. With this, I will stop this lecturer. Thank you.