Circuits for Analog System Design
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Lecture No. #22
Error Budgeting for Different Circuit

Earlier classes, we had seen error due to input reasons, error due to output reasons and then offset voltage drift and bias current drift, so on.

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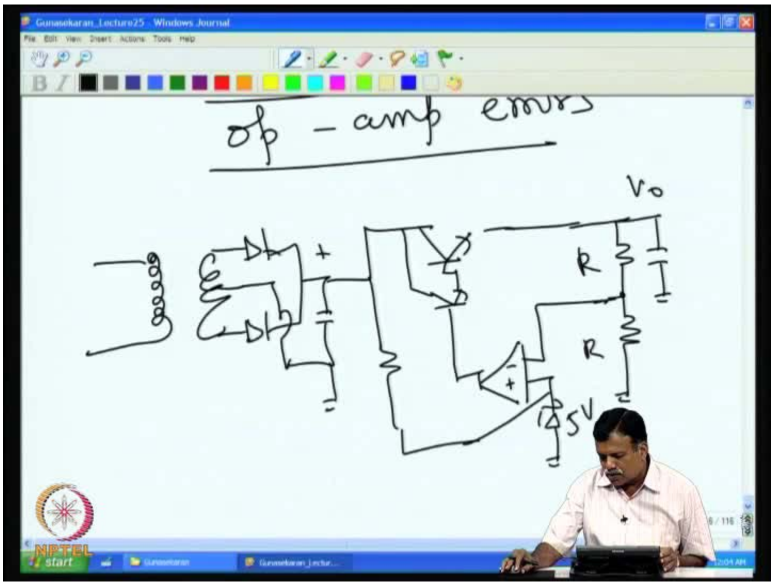

Now, let us see how to calculate these errors in a bird's eye view. So, I will see the calculation of various errors, calculation of op-amp errors. So, I will take different circuits and see how these errors are varying out, compute these errors in given circuit. So, let us take, for example, our voltage regulator; to start with, we had this transformer and then had a rectifier and we get a DC voltage and we see our regulator circuit.

So, we add this operation amplifier, then error amplifier gets reference voltage through the reference Zener; so, we connect this, then this; so, this is the voltage regulator and this is the output voltage. So, if these resistances are equal and this a 5 volt, then the regulator output voltage is 10 volt; so, we see the V output actually comes as 5 volt in to 2; that actually comes as 10 volt.

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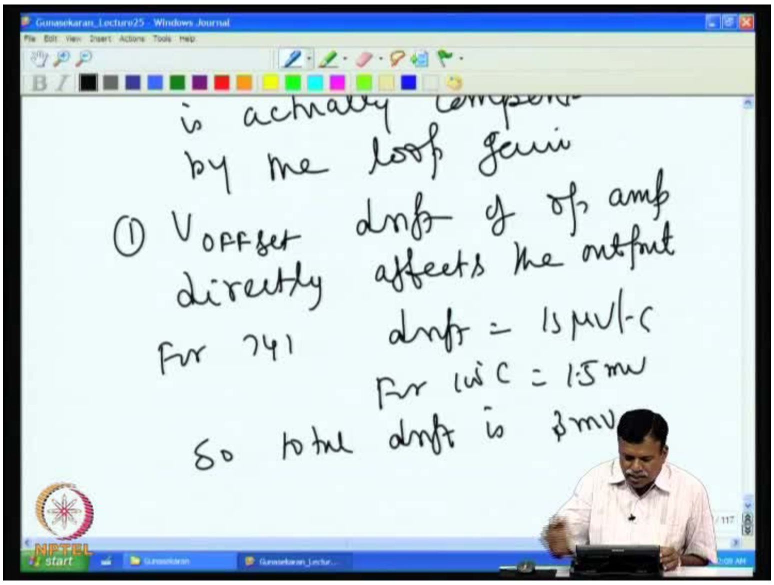

Now, what is the temperature drift error in this circuit? Let us assume, I have put here 100 k and 100 k, this two resistance 100 k and 100 k; now, the base emitter voltage drift of these transistors are not a issue, because this in a closed loop. So, if I take this circuit, that have a 5 volt here and any change at the output is compared at this point respect to the 5 volt. If the voltage goes up above 5, then automatically this voltage is comes down and output also comes down.

So, base emitter voltage drift of these two transistors is T 1 and T 2, if I take T 1 and T 2, base V BE drift of T 1 and T 2, V BE drift of T 1 and T 2 is actually compensated by the loop gain. Loop gain, in this case, is actually open loop gain with a op-amplifier divided by 2; so, since the loop gain is very large, then drift of d 1 by d 2 has negligible effect on the circuit, because of this closed loop.

Whereas offset voltage drift of the op-amp, it will directly affect the output. So, offset voltage drift, V offset drift offset drift of op-amp directly affects the output. For an example, previous 741, in that case, the offset voltage drift would be 15 micro volt per degree C; for 741, drift equal to 15 micro volt per degree C, for 100 degree C temperature change this comes 1.5 milli volt. So, 1.5 milli volt drift at the input, 1.5 milli volt drift comes at this point, now that equivalent link 3 milli volt drift at the output. So, if it is the 3 milli volt drift at the output, so total drift at the output would be. So, total drift is 3 milli volt at the output, this is due to offset voltage drift.

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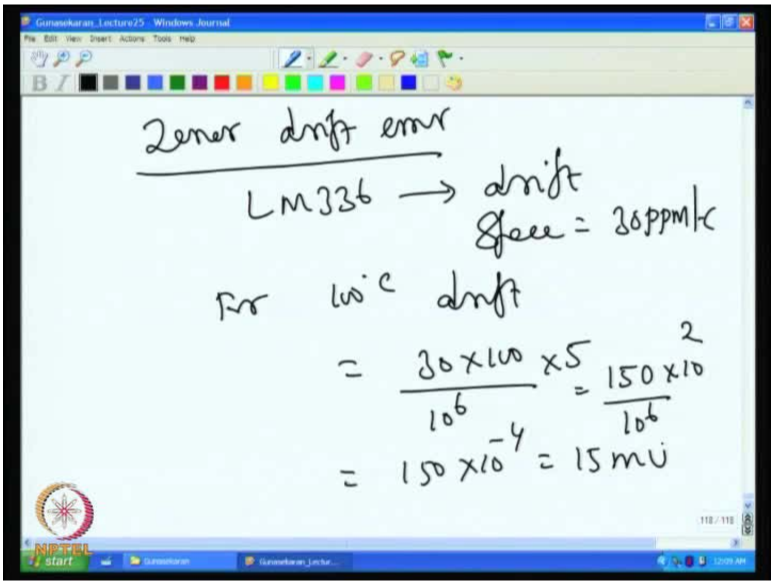

Similarly, if we see this circuit the Zener drift, Zener also drifts; so, Zener drift directly affect the output, if Zener is 30 PPM Zener then for 30 Zener. Next, we can see the Zener drift, Zener drift error, if you look at the spece of the Zener, for example, if it is LM 336 drift is actually drift spece is 30 PPM per degree C.

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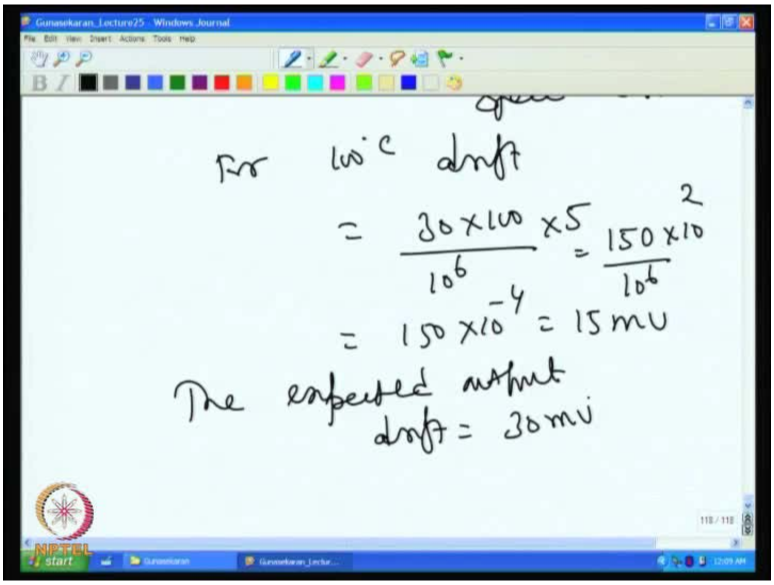

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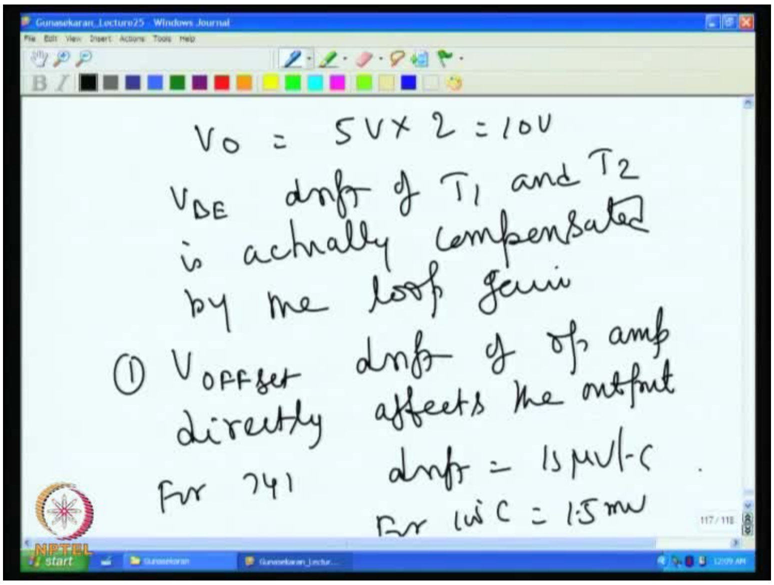

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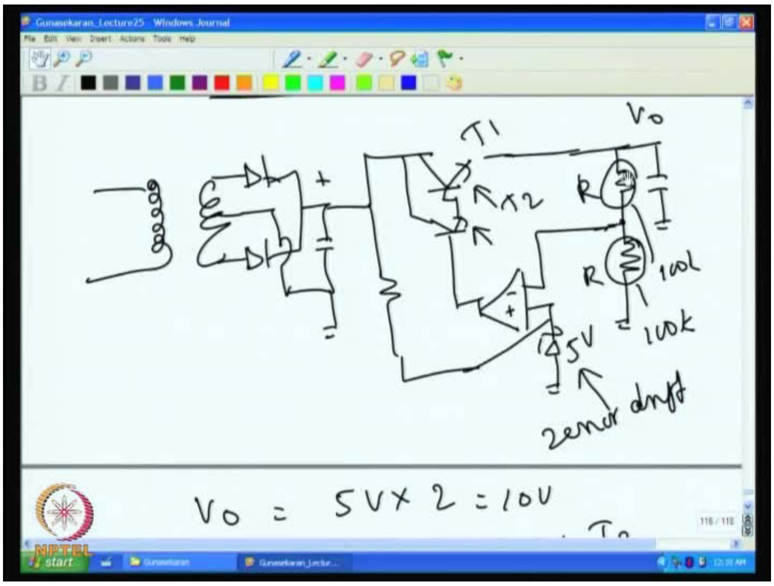

So, for 100 degree C, drift would be 30 into 100 divided by 10 power 6 into 5 volt, that actually comes, 150 into 10 power 2 divided by 10 power 6, that turns out to be, 150 in to 10 power minus 4 that is 15 milli volt; so, the expected output drift is 30 milli volt. Similarly, you have drift due to resistance, was the resistance change will also produce a drift and the bias current change also will add the drift, the resistance change already calculated.

If you use for example, 10 PPM resistance or 25 PPM resistance, then we are take one is increasing and another one is decreasing and then accordingly we are find out, what is the output voltage drift. Then, similarly, the bias current that is flowing through that, it will have an error, because there is no equivalent resistance in the pulse side because this bias current whatever is flowing through this, have to go through this, bias current actually have to go through this.

So, the bias current went drifts then the current flowing through this is changing. Consequently, voltage across this changing and output also will have a effect; so, for that keep this distance lower is 100 k, keep this distance lower, then you will have less due to bias current.

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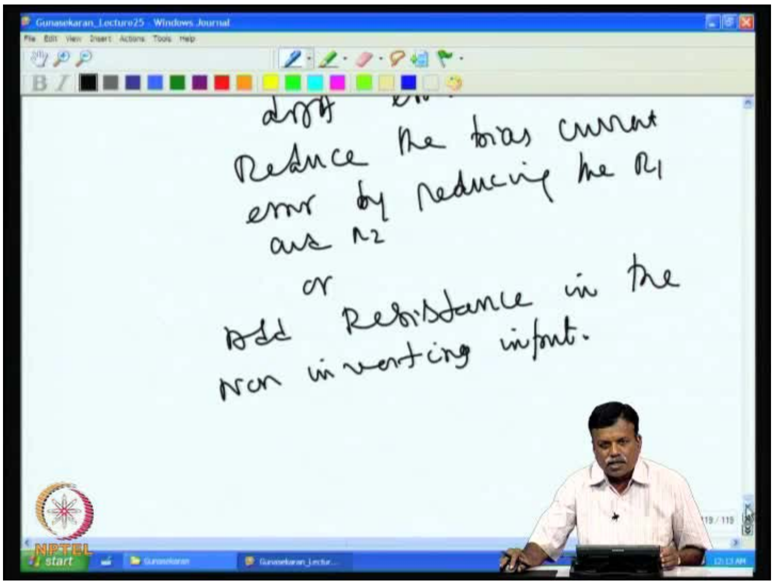

Similarly, so, we have the other errors is bias current drift resistance that is a resistance drift error; so, we have third one resistance drift error and then fourth one is bias current drift error bias current, this is only R 1 and R 2, let us bias current drift error.

Here, again R 1 and R 2 only a matters, because if we take other resistors, for example, in this case, this resistance is, this resistance no effect even if this drifts. So, the R 1 and R 2 drifts matters and then the bias current that is flowing throw this; actually it is not compensate that actually creates problem because of R 1. If we want to reduce the error then I add another resistance here, so that, they both have same ways of current and same R I can put here; so, that reduce the bias current error.

I am not calculate here the bias current, but the bias current contributed by this, reduce the bias current error by adding; a reduce the bias current error by reducing the R 1 and R 2; is R 1 and R 2 are alternatively or add resistance in the non-inverting input.

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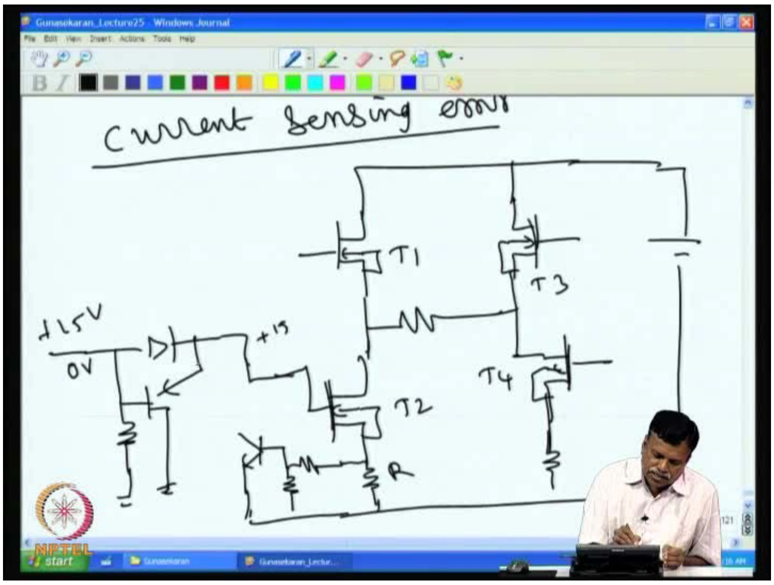

So, this is the error that is comes in the voltage related. Let us see some other circuit, how to compute the error in other circuit. Like, take for an example, current sensing; so, assume that we are having H-bridge switching and then we want limit the short circuit current; like, take for an example, we take the second circuit 2 H-bridge drive.

We calculate the current sensing error, current sensing error, in this case, what we are trying to achieve is that, assume that we have a H-bridge, a MOSFET base, here we know T 1, T 2 and then T 3 and T 4, there are four switches, the load is connected here; so, this is the supplier here.

Now, if you want provide a short circuit protection then normally what is done is, I will add the resistance, so I will explain, this little bit in the ground side. So, what I do is that I will add the resistance here; I will add the resistance here; now, this I connected to ground. For short circuit protection what I do is, I will add the current that is adding the resistance here; for example, I will put one transistor connect to this to ground then I connect the resistance here.

So, assume that we have a pulse coming at this point, then what is normally done is that you switch on the giving a pulse to this; so, it switches on and then make it off by connecting this. So, in this case, when the plus 15 volt is given here, the plus 15 volt actually is applied to the gate and then gate actually 10s on the MOSFET, the current actually flows through this; so, we have this sense resistance R here.

So, this sense resistance and current flowing throw that produce a voltage at this point. So, when similarly when the 10s this is 1 to 0, then since this is 0 and this already charge to plus 15; under this transistor conduct and discharges that way that MOSFET switched on and off.

In case of the short circuit of the load or if this transistor turned on when it is suppose to be off, for example when this is on this is transits should be a, when this is on this should be off, but when this is on, if this comes on for some reason or the resistance is shorted then I current flows through to that; we want to protect this from the damage, so we have done; we would sense resistance voltage across this, it is applied to this.

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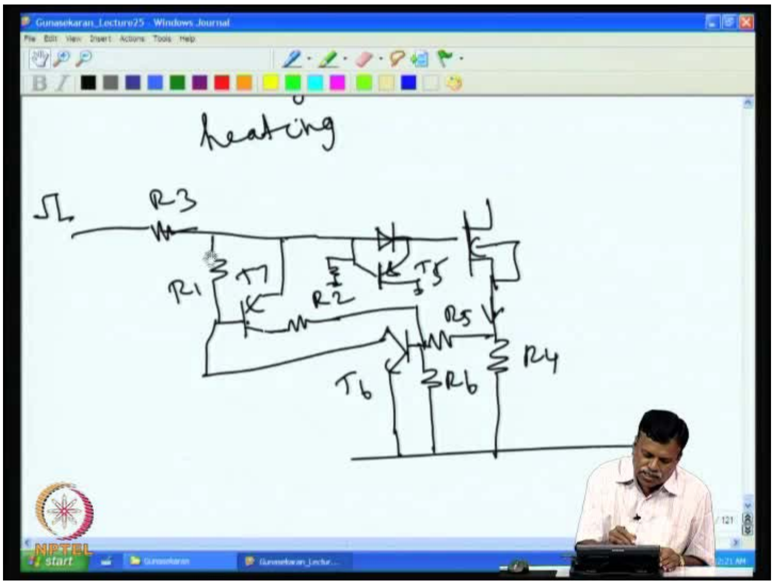

So, when voltage is at this point, it goes more than 0.6, then distance will conduct; so I can connect this here, but if a connected like this, the problem is that limited to 0.6 and the conduction will take plus. Assume that I have small resistance here; so, the voltage drop such that always 0.6, goes 0.6 is a at this point, you have 0.6 at this point and then this transits T 2 will be taken to in a linear region. So, by this is a conversational in a regulator current limited, in this circuit will limit the current but it will damage the T 2 because of heating.

So, we are to latch the pulse, so that is to be done; so, we can add a latching circuit to the above, so what we can do is, I redraw this lost path alone; so, we have the MOSFET and then we have sense resistance here. Now, what can be done is that we can have sense resistance and then that this connected to this; so, if the voltage, at this current goes high, the voltage at this point increases and that will make this transistor to conduct. Now, what to do, is to make this transistor to latch the pulse, that incoming pulse; what do is, will have, for example, we have circuit like this, assume have a resistance here, so what can be done is we can have a latch spur, that can be designed in this way, will have the and then this can be connected to this.

So, essentially I will name it now R 1, you have R 2 and this R 3, it is the incoming pulse that is coming here and this is R 4, R 5, R 6 and then we have our we will have this the input pulse, then will have regular switching off mechanism what is there here, so will have transistor say T 1 or T 5.

So, transistor T 5, this is T 6, we put it as T 7; so, when pulse comes on here that turns on the device and current flows through this. So, we are trying make, a provide a short circuit protection; so, the large current that is flowing through this will develop a voltage here and that voltage appears here and that once it goes more than 0.6 then transistor T 6 conducts. Once transistor T 6 conducts then the voltage across R 1 exits more than 0.6 then T 7 will conduct and that voltage will appear at this point.

It will make this T 6 to go on continuously and then the heavy current that is flowing here will make this voltage to drop and the transistor will go off, but once it goes off, its continuity be off, because this voltage, whatever is there that will be continuously driving this transistor and make the current to latch actually.

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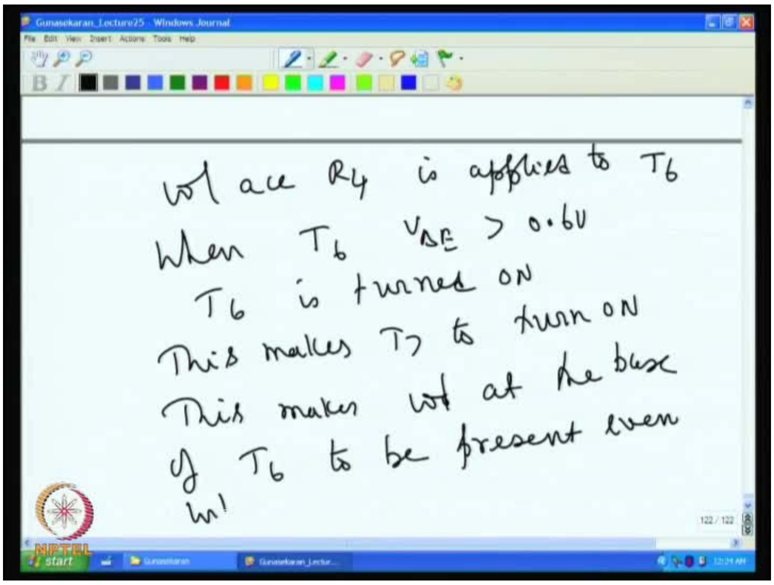

So, essentially this is for short circuit protection. So, T 6 is the one which senses the current; so, the T 6 that is voltage across R 4, so if I take this, so volt voltage across R 4 is applied, is applied to T 6. So, at based an voltage is more than 0.6 than that makes current flow R 1 and T 7 is turned on and then voltage applied back to T 6, so applied to T 6. When the voltage is, when T 6 V BE is greater than 0.6 volt, T 6 is turned on, T 6 turned on, this makes T 7 to turn on, because, then T 6 is turned on, when T 6 is turned on then T 7 will be turned on.

Once the voltage across R 1 goes above 0.6, this makes, this makes T 7 to turn on. Then, once T 7 turn on T 6 get latch, this make T 7 to turn on; this, this makes voltage at the base of T 6 to be present even without the current that is T 6 is latched, that means, transfer that is our power transistor that is this one that is T I think this power transfer named as T 2.

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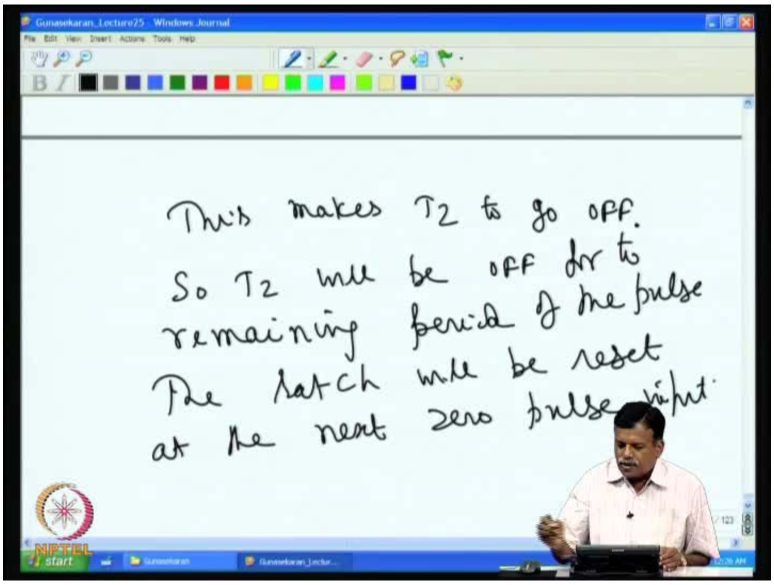

So, the power MOSFET power transfer T 2 will be off, this makes T 2 to go off. This latch will continue up to, next pulse, next pulse comes, R 1 the pulse input 10 to the 0, then the latch is because there is no current flow through T 7 and then the latch will be reset that is once current exits this makes T 2 go off.

So, T 2 will be, T 2 will be, will be, off for the remaining period, remaining period of the pulse. The latch will be reset at the next latch will be reset at the next zero pulse input.

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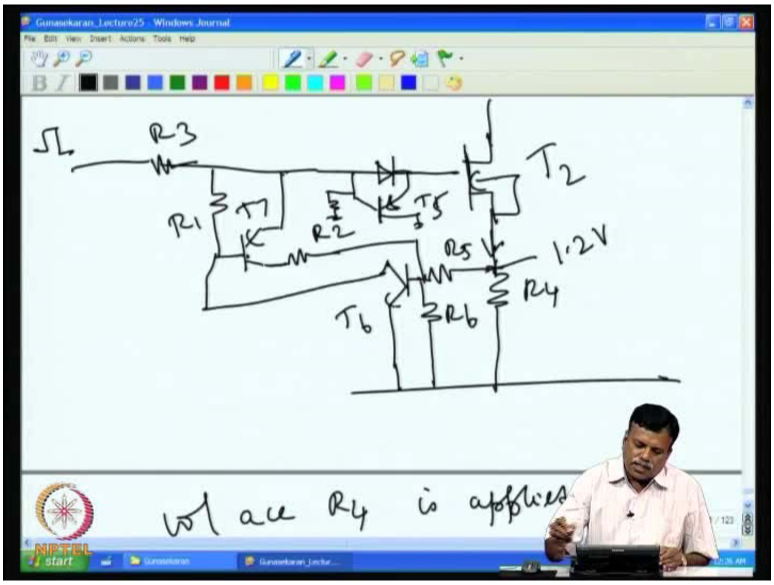

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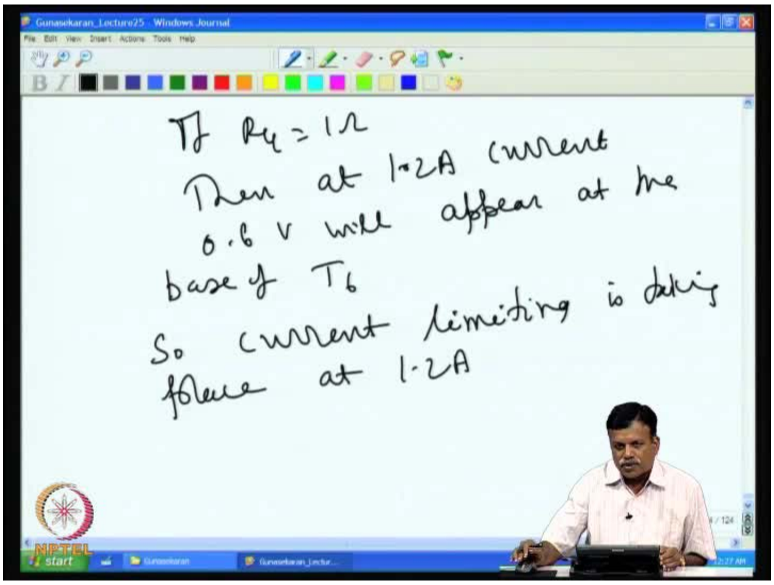

Now, in this case, what is the drift? Because we are taken the 0.6, it will be reset; so, if I take for a example, R 5 and R 6 are equal then if this voltage is 1.2 volt, assume that this voltage is 1.2 volt, then the T 6 base will be 0.6; that means, the latching operation will be initiated at 1.2 volts. Suppose, if it is 1 ohm resistance, power 4 is 1 ohm; so, if I take R 4 as a 1 ohm, if R 4 equal to 1 ohm then at 1.2 ampere current, 0.6 volt will appear at the base of, it is T 6, that means, at 1.2 ampere latch will take place.

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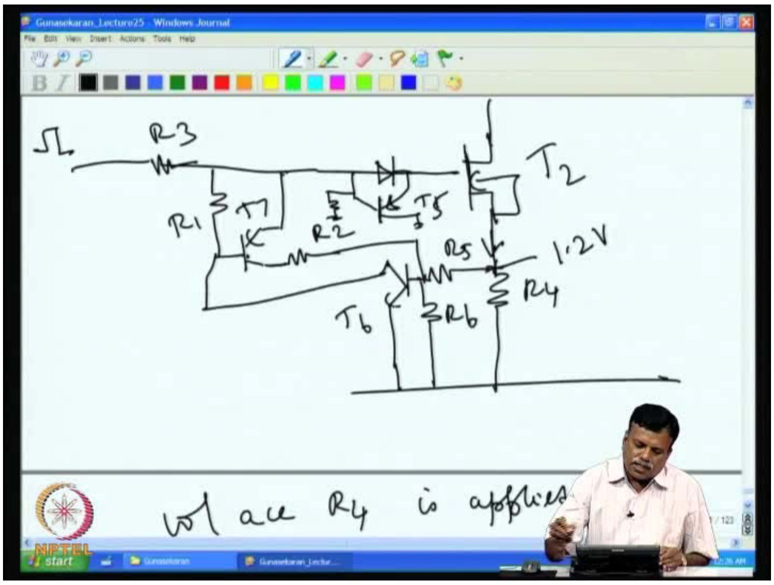

So, current limiting is taking place at 1.2 ampere, but when temperature, this will happen at 25 c degree ambient because at 25 c degree ambient only at 0.6 actually the transistor T 6 conduct because when the voltage is 0.6 at this point, the transistor T 6 connects for when the temperature of this device goes up say at 80 degree then it needs much lower voltage because of 2.2 milli volt per degree C.

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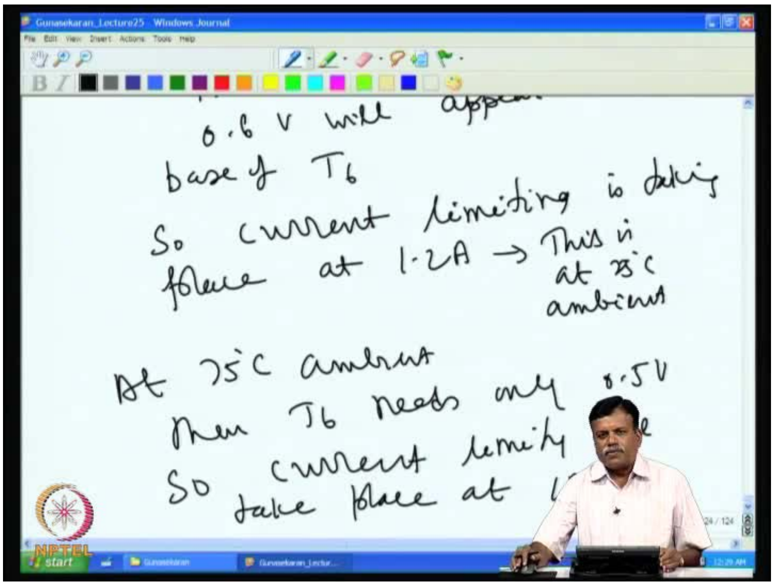

So, at 50 degree will loss 100 milli volt; that means, at 0.5 volt, only at 0.5 itself T 6 will be conducting; when the temperature of this is at 80 degree, the remains 0.5 need, means, we need 1 volt here, that means, at 75 at 80 degree we need roughly it connectivity will takes pulse an 1 amps, that means, this is at 25 degree C ambient; at 75 degree C ambient then T 6 needs only 0.5 volt; so, current limiting will take place at 1 amps.

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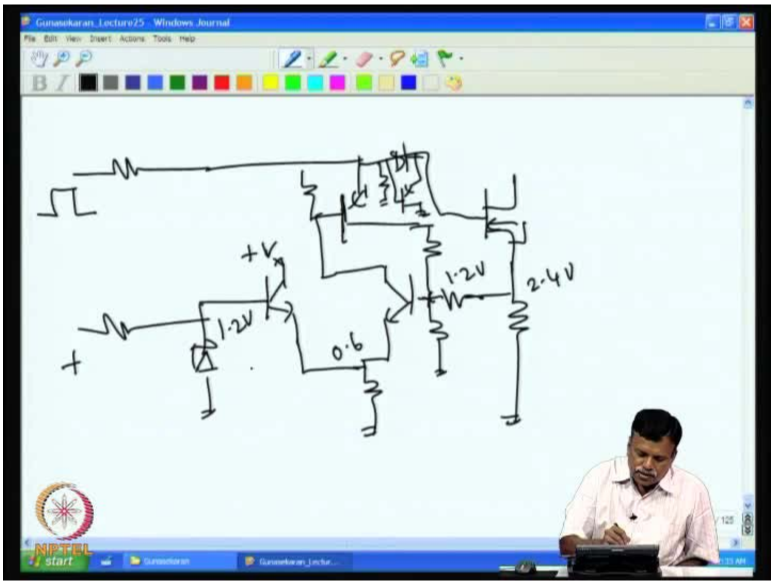

So, obviously with temperature current limiting is changing; so, we want to avoid this, so how will you modify this current limiting the drift that is occurring due to T 6, because base emitter voltage drift now affects the current limiting. Now, the circuit can be modified in the following manner to compensate for the temperature drift, for example, the trick that was using op-amp can be used, again here to remove the base emitter voltage drift in this case. So, we can redraw the circuit, there is we can have the switching trans here and with a resistance.

Now, what can be done is that, this can be applied in the similar manner to the transitor here and then we can also apply this and here we can have a V reference then the latch function can be return as it is; so, what we can leave, the this transistor latch function can be added; so, we can have a device here and this can connected to this and then output of this can be connected to this, this can to be even connected to supply.

So, in this case, the temperature drift that was affecting the current limiting function can be removed by adding this additional transistor that is we have added it. Now, this transistor to compensate the V BA drift of this, because, in this case, if the current goes high then voltage of at this point will go high and the voltage of this point will go high then this will be start conducting, but then we are kept this one at reference voltage because this is a connected to pulse supply, assume that we are kept this one at 1.2 volt Zener.

If it is the 1.2 volt Zener then this will be start conducting only when it is above 1.2 volt, otherwise it will not conduct, because if assume that room temperature that is 0.6 volt is drop, then this will be sitting at 0.6 volt and this will start conducting only above 1.2 volt. So, above 1.2 volt this transistor will be conducting that when this transistor conducts the current will flow there is above 1.2, the conduction will take place through this. Once it conducts then this voltage will come and this voltage will come permanently high and make the, produce the latching function actually and this can be given for the drive. Of course, we also at add the reset function here that can be done in the regular manner; so, this reset function can be provide at in a regular manner.

So, once this voltage closed above 2.4, then this will go above 1.2, then this will be conducting and then this current will be latch and then that trans will be turned off fully up to the next pulse, because when the pulse goes to 0 and this latch will reset and then it is ready for next short circuit production. By incorporating this transistor, we are avoided the drift produced by this base emitter voltage; so, we call this one as T 8 and then this we are named it earlier, we are named it as a T 6; so, put, we put it, this is T 6.

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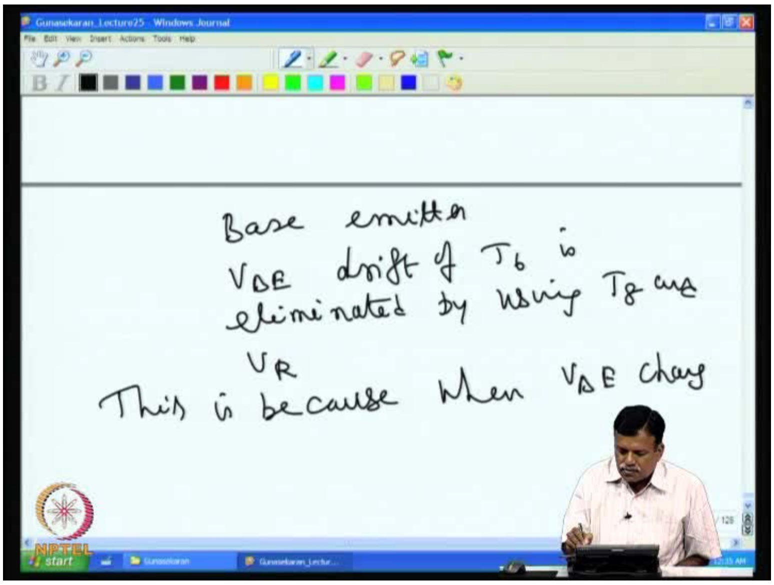

So, we have T 6, so by adding T 8 and the V reference voltage V R avoided the drift of the base emitter voltage drift of the T 6. So, what is done is, base emitter, base emitter in the V BE drift of T 6 is eliminated, is eliminated by using T 8 and V reference. Now, because for example, if the temperature changes, suppose if the temperature goes high then we need only 0.5 volt difference here and since this also needs only 0.5 volt at higher temperature instead of 0.6, then this will shift to 0.7; for example, high temperature, this is shift to 0.7 because if needs only 0.5, so this will see at 0.7 and again this also needs only 0.5 volt.

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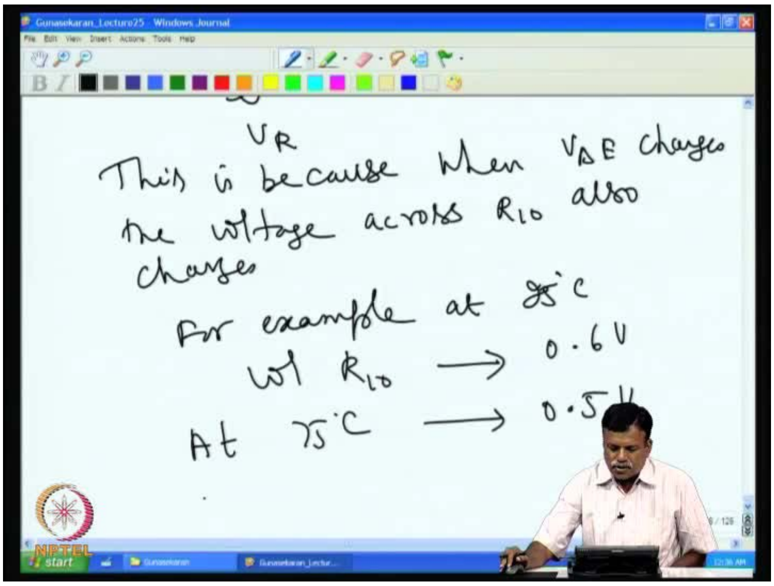

So, again if high temperature which also if limited at least only at 1.2 volt, so if temperature drift as no effect on the current limiting. This is because when V BE changes, I call this resistance as R 10, voltage across R 10 also changes, the base voltage across R 10 also changes. For example, for example, at 25 degree C voltage across R 10 is actually 0.6 volt, at 75 degree it comes nearly to 0.5 volt, because now the base emitter voltage decreased, so at high temperature it only becoming, it had become 0.7.

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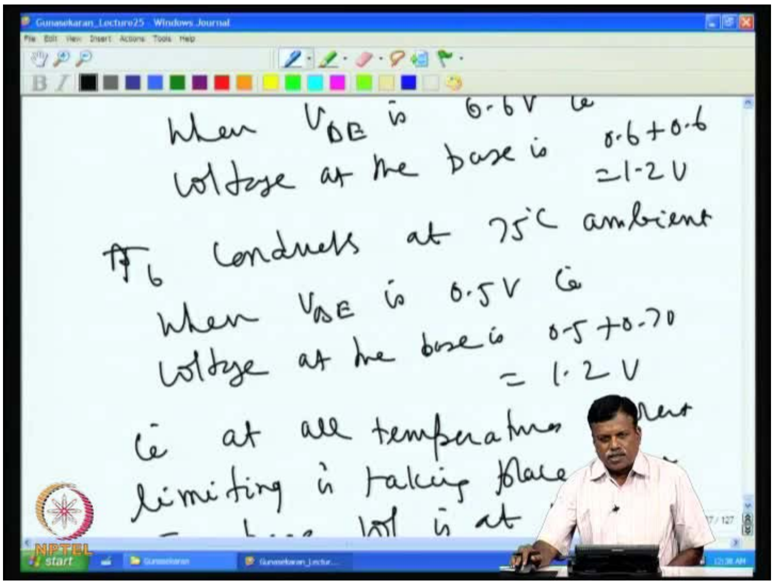

Now, the T 6 also needs only 0.5 volt. So, T 6 for example, now T 6 conducts at 25 degree ambient when V BE is 0.6 volt that is voltage at the base is 0.6 plus 0.6 that is 1.2 volt. Then, at same thing T 6 conducts at 75 degree C ambient when V BE is 0.5 volt that is voltage at the base is 0.5 plus 0.7 that equal to 1.2 volt again.

So, all the time it limits the current only at 1.2 volt that is - at all temperatures current limiting is taking place current limiting current limiting is taking place is, when T 6 base voltage is at 1.2 volt; so, drift as no effect in this case this. So, in the operation amplifier also the drift was cancel, which we are already discuses; so, we can compensate the current drift of the transistor in this way.

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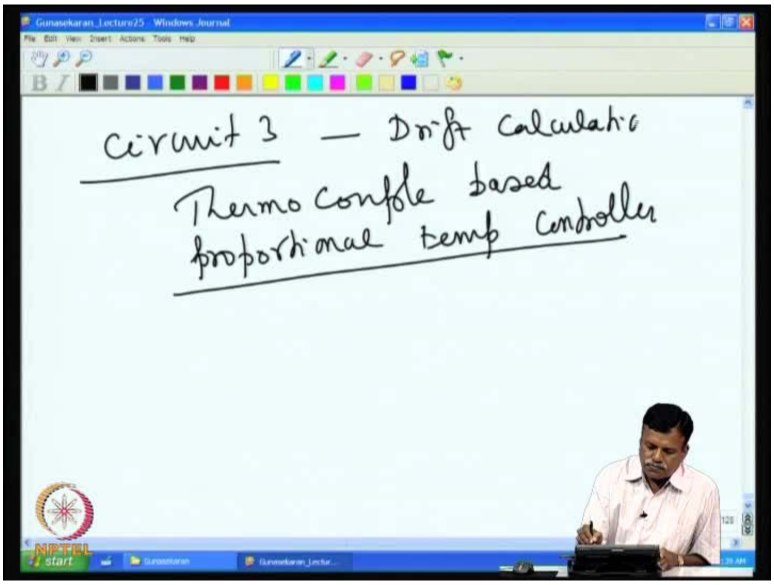

Let us see another circuit where in op-amp is used and how the drift is calculated, take the example circuit 3; so, I will take a next example circuit 3. In this case, we take a proportional temperature controller and we use sensor as thermo couple; so, thermo couple based proportional temperature controller, we take in this example, thermo couple based proportional temperature controller.

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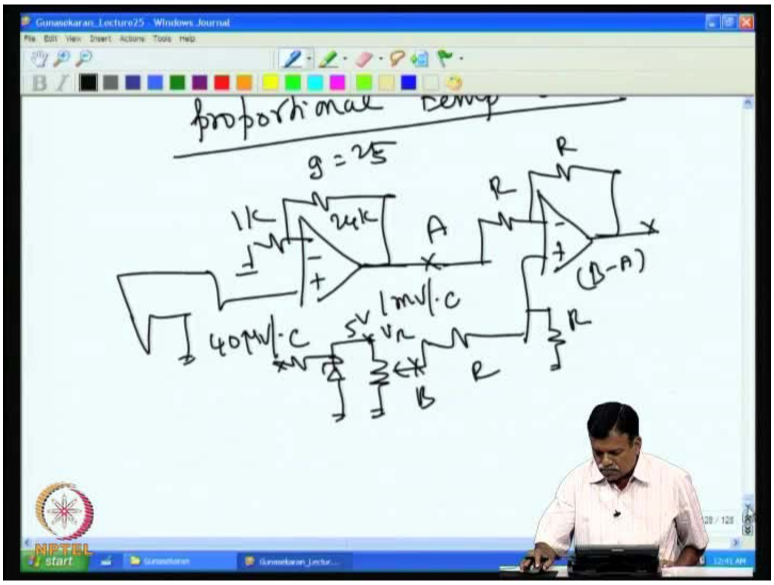

Let us calculate the drift, so drift calculation. So, take the input stage that we have the thermo couple and thermo couple amplifier is there, assume that we have one amplifier like this, gain of 25 that is 24 k and 1 k. So, thermo couple gives 40 micro volt per degree C and that makes 1 milli volt per degree C sensitivity at the output because the gain is 25 and when it is amplified by 25 times, the signals becomes 1 milli volt. Now, we want to make a proportional controller; so, we find the different between the reference voltage and the actual temperature. So, we have a difference amplifier here which as set temperature that is a V reference.

So, this is a V reference say 5 volt and we set whatever voltage that is required. So, we have A and B; so, A gives you the actual temperature and then A gives you actual temperature, B is the set temperature and then if put for example, the values are equal and then I will have a error voltage so the which is nothing but difference between A minus B or B minus A is what it is coming at this point, so that is called error voltage.

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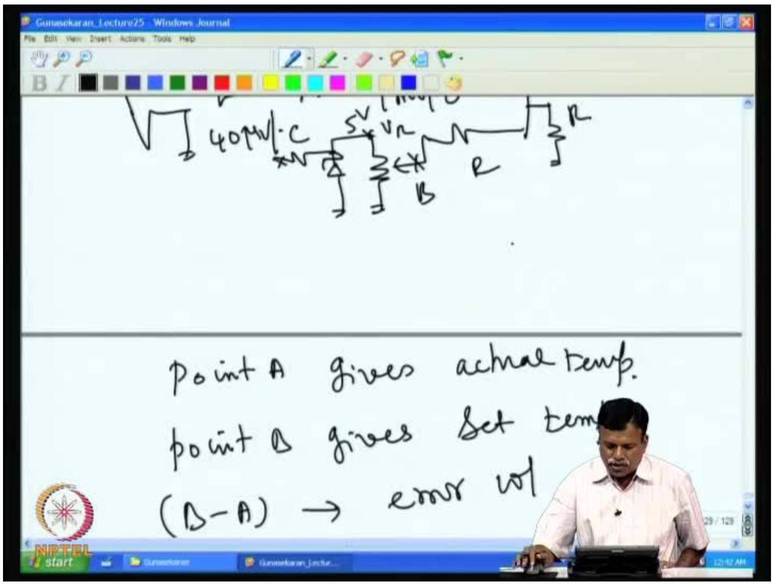

So, A is actually in the actual temperature. The point A gives the actual temperature, point B gives you gives reference set temperature that is - set temperature. B minus A, error voltage, the difference between the two; it is a difference between set value and the actual temperature is coming as a error voltage, this error voltage is amplified and given to the heater to make it as a controller.

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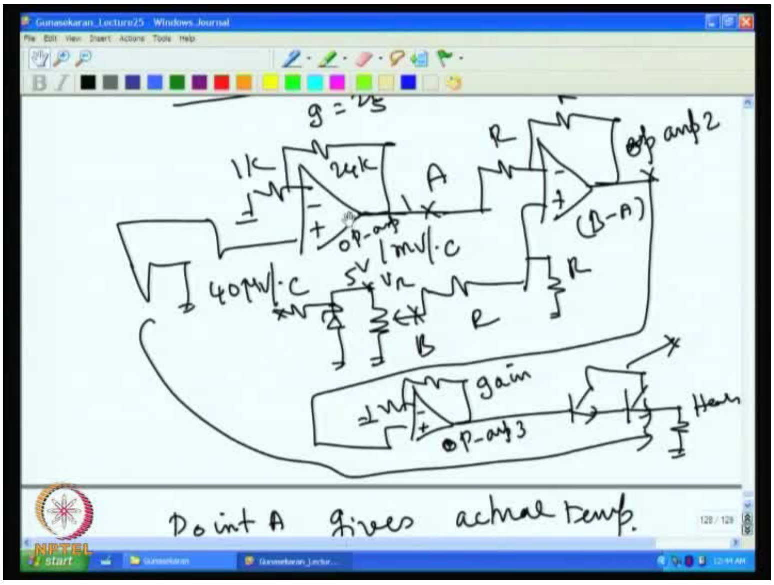

So, normally what is done is, this output is given to the next stage; so, the next stage consistence of an amplifier, so the output of that given to this, then this is given driven in the heater. For example, I can have a heater circuit here, this heater and this sensor is linked to this direct, physically to the sensor is linked to the heater. So, this forms complete proportional controller, so we have here pulse input, so this is, this is the gain stage for proportional controller gain is set by these two resistance. So, these forms are complete proportional controller.

Now, let as trying to find what are the errors associated in this circuit. Now, if it is say the stage 1 that is I will take that op-amp 1; this is op-amp 2 and then op-amp 3. Now, the stage 1 handles the lowest signal is 40 micro volt in input is actually apply to the input. So, this should give as there off set voltage drift off the op-amp 1, it is a serious concern.

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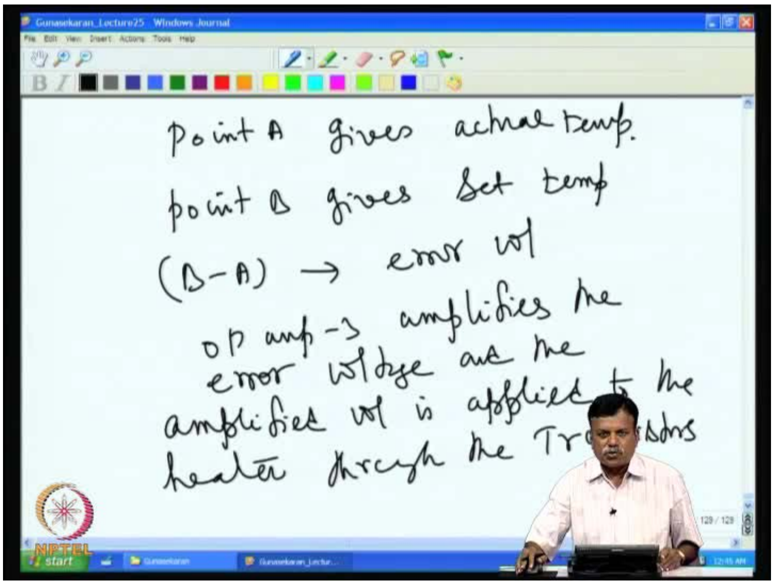

So, now, we will be continue to write the functioning of the circuit that B minus A gives error voltage then the op-amp the three amplifiers error voltage. So, I write the op-amp 3 amplifies errors voltage, amplifies the error voltage, and the amplified voltage, amplified voltage is applied to the heater is through the transistors; transitor mainly used for the current boosting.

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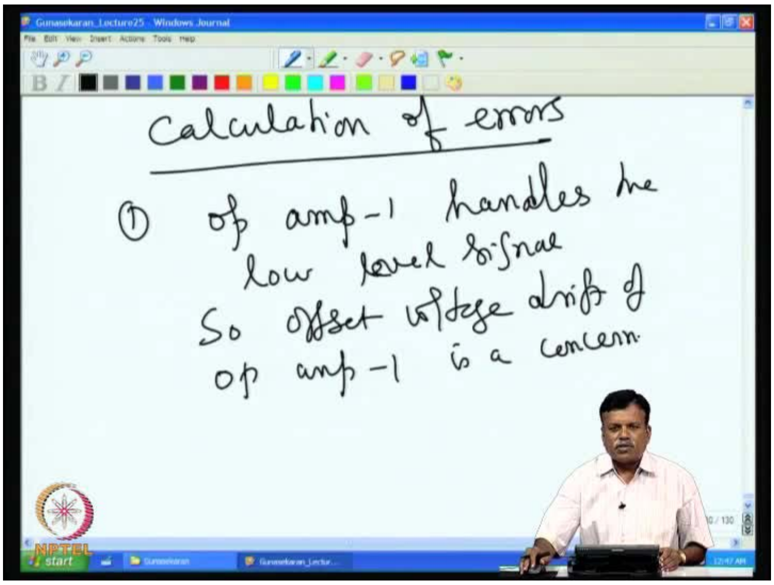

So, basically the error voltage at this point, what is coming is amplifier apply to the heater. Now, we will see the errors; so, the op-amp 1 handles the low, very low level signal, so op-amp 1, so we calculate the errors. So, we will now calculate the calculations of errors: the operational amplifier 1 handles the lowest voltage handles the low level signal low level signal.

So, the offset voltage drift of this op-amp is very important because op-amp 1 see is the lowest voltage, offset voltage to the op-amp is a matter of concern, so the op-amp offset. So, offset voltage drift of op-amp one is a concern because we are, we, it is used low offset voltage drift op-amp, because otherwise whatever drift, for an example if use 741 in this case, we just 15 micro volt per degree offset voltage drift.

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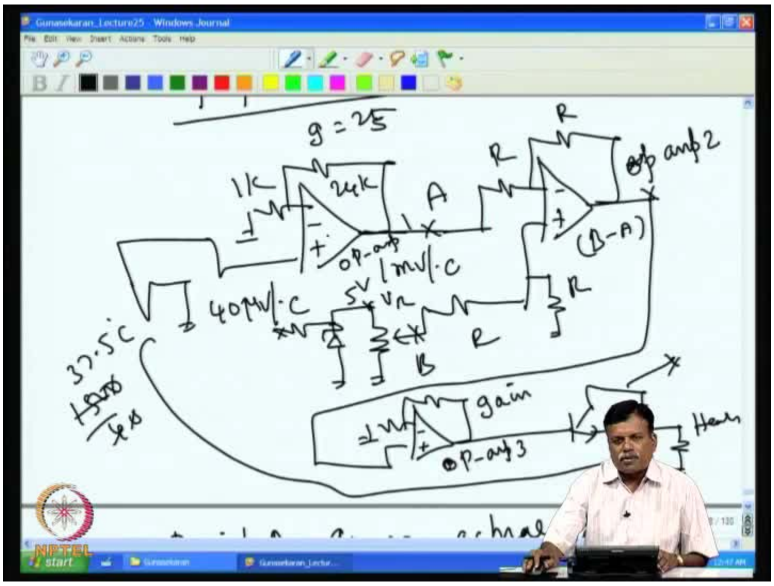

For 100 degree then to be 1.5 milli volt, 1.5 milli volt drift at the input will correspond to if a calculate 1.5 milli volt that is, 1500 divided by 40 that comes 37.5 degree error.

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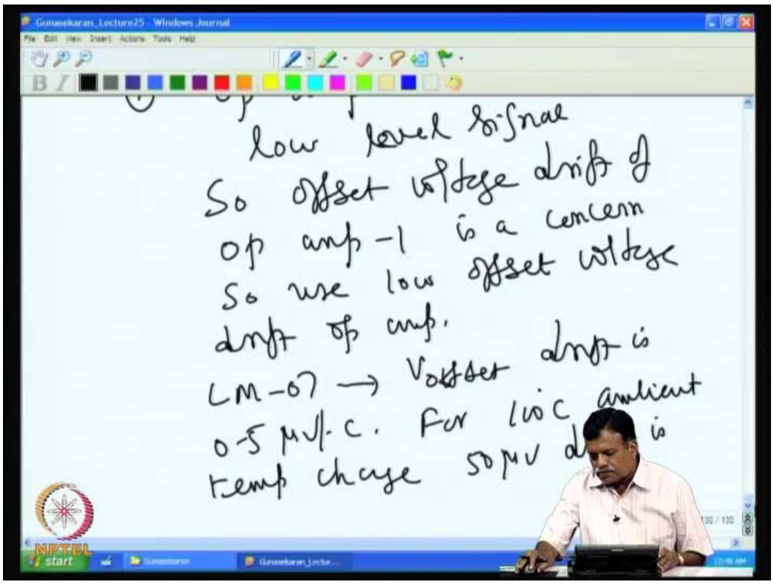

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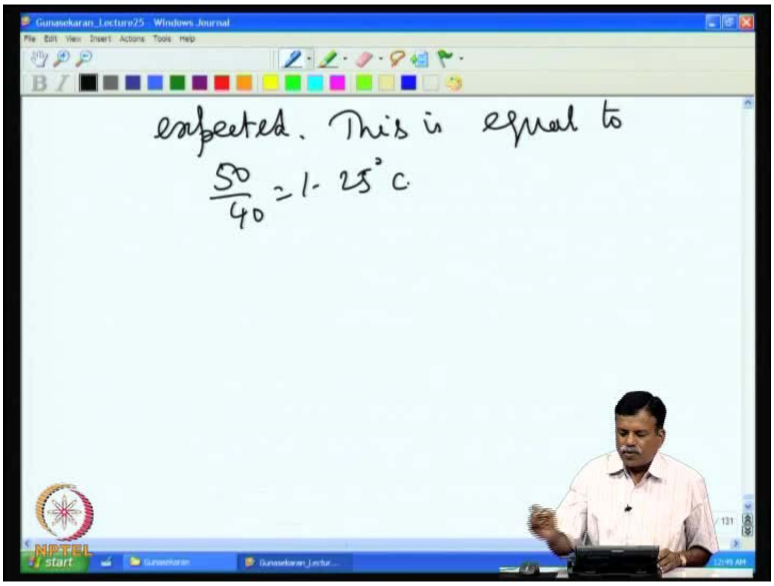

So, this should have very low offset voltage drift. So, use low offset voltage drift op-amp for op-amp 1; so, use low offset voltage drift op-amp, for example, if I use LM 0 7 V offset drift, V offset drift is 0.5 micro volt per degree C, so that will give for 100 degree 50 micro volt. For 100 degree ambient temperature change 50 micro volt drift is expected. This is equal to 50 divided by 40 that 1.25 degree error.

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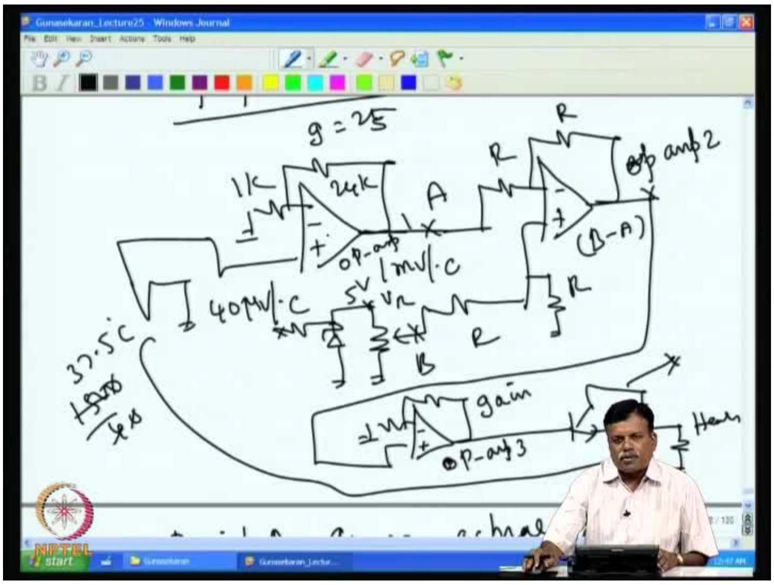

So, have to use low offset voltage drift op-amp for op-amp 1, otherwise that large error. Similarly, this resistor what we are use are actually 24 k and 1 k and if we use very high resistance, then I have to use bias current error also. Of course, it is better to add here one resistance roughly 1 k, so that the most of the bias current flowing here and equal to here that will be get compensate as this, these two should be utilized and then keep this R f and R 1 lower value; so, that even offset voltage drift is lower.

Of course, in this case input impedance is not a serious problem because the thermo couple as very low inner resistance, so input impedance error is not much. So, in this case, if consider only offset voltage drift and bias current drift itself is enough. More importantly, in such a low level signal when we are handling it is an offset voltage drift that is to be considering very often. Then, if look at the second stage that is op-amp 2, in op-amp 2 signal level is already 1 milli volt.

So, the drift of the most off the op-amp is not more than 50 micro volt per degree C. So, even for 100 degree, it is only 1.5 milli volt that look corresponds only 1.5 degree error at this point. So, this need not be very low offset voltage drift op-amp because very low offset voltage drift op-amps cost more; so, this stage need not to have very low offset voltage drift op-amp, not necessary for this, the difference only some amplified here; of course, the resistance value is used should not very high.

So, for example, I need not put vertical value; these values to be and 10 k, 10 k, 10 k, to be used; one thing that if this resistance are not matched which we are discussed earlier. When we are discussing about the concern current source, if this resistance are not match say they are 10 k's, but they may have 1 percent error if I use 1 percent resistance and may have a 10 percent error if I use 10 percent resistance, but then that will acts as a common mode error. So, this resistance must have at least 1 percent error are better to avoid the common mode the voltage, because when we are varying this then this voltage also latches of to the same value, when the loop is balance.

So, when we are changing this for certain different temperature then the common mode error will coming. So, here op-amp is not a serious issue, selection of the resistance is the matter of concern here. Similarly, we look at the op-amp 3, In op-amp 3 the signal is 1 milli volt per degree C; so, this also need not very low drift op-amp because C 1, if I use ordinary op-amp which is 1.5 milli volt due to 100 degree C, the error will be only 1.5 degree.

So, but if the error need to be kept very low then one option is use go for as a 50 gain; for a example, if I use the 50 gain here and if I use the low offset voltage then this stage and this stage error will be small; of course, keeping this resistance small, hence so lot reducing the offset voltage drift. Now, the base emitter voltage drift of this, base emitter voltage of this transistor is not a concern because they are compensates in the closed loop and error is reduced because of the loop gain. So, for example, this 15 volt say T 1, T 2, the base emitter voltage drift of T 1 and T 2 is not serious problem.

So, for example, if I use first stages as op-amp 1, it is a first stage and then if I used 25 gain then total error due to offset voltage drift can be calculated. So, we calculate total error due to offset voltage drift: stage 1, op-amp 1, here offset voltage drift error comes 1.5 k say 0.5 milli volt operation op-amp we are used; so, total drift is 50 micro volt divided by 40 micro volt degree per C that comes 1.25 degree op-amp 2.

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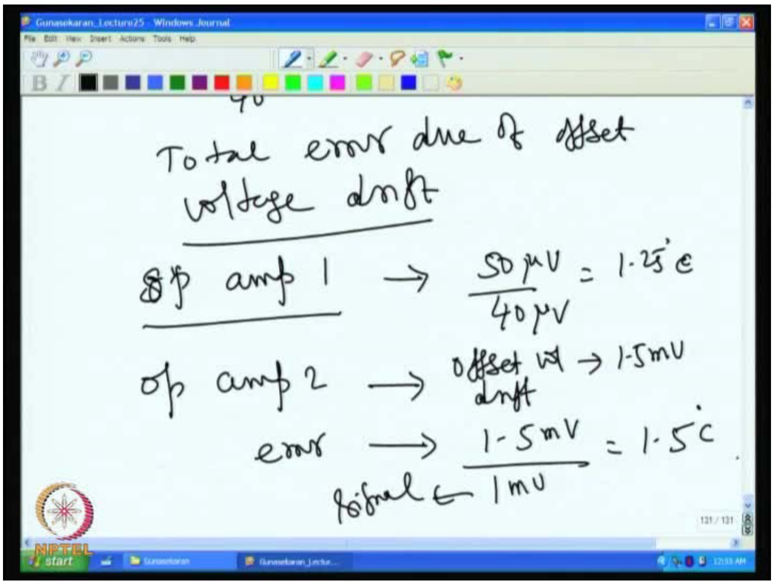

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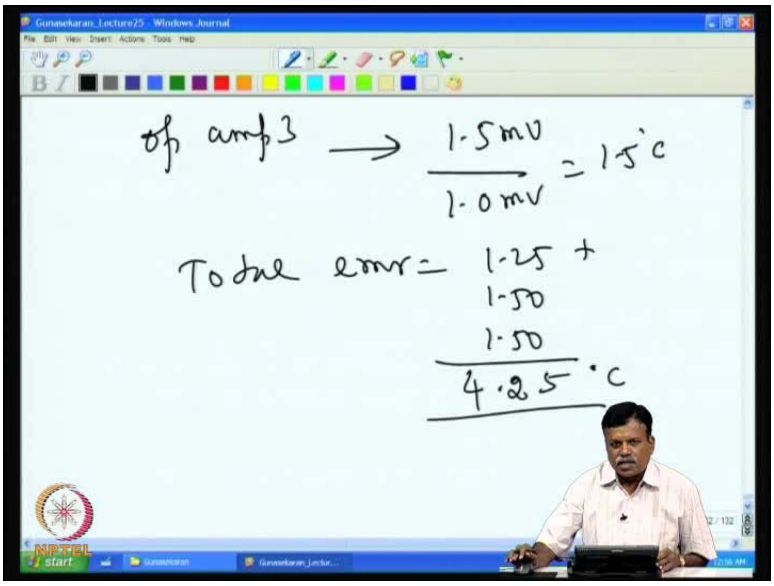

If I use op-amp 2 normal op-amp, so that total offset voltage drift is offset voltage drift comes out to be 1.5 milli volt per 100 degree C. So, error in this stage would be error turns out to be 1.5 milli volt, this signal is actually at this stage, 1 milli volt is a signal per degree C signal because 40 micro volt amplified by 25 time gives 1 milli volt, so that comes out 1.5 so op-amp second stage error will be 1.5 degree C. Third stage op-amp 3, error in the op-amp, stage 3, op-amp 3 error that works out to be total drift gain. Here, it is 1.5 milli volt and signal is 1 milli volt and again it is 1 milli volt, so that comes 1.5 degree C.

So, total error will be 1.25 plus 1.5 plus 1.5; so, the total offset drift loan comes to be 4.25 degree. If I use first stages as low drift op-amp that is 0.5 micro volt per degree drift error op-amp and two other stages are 1 milli volt, other faces are normal op-amp which is 50 micro volt per degree C op-amps.

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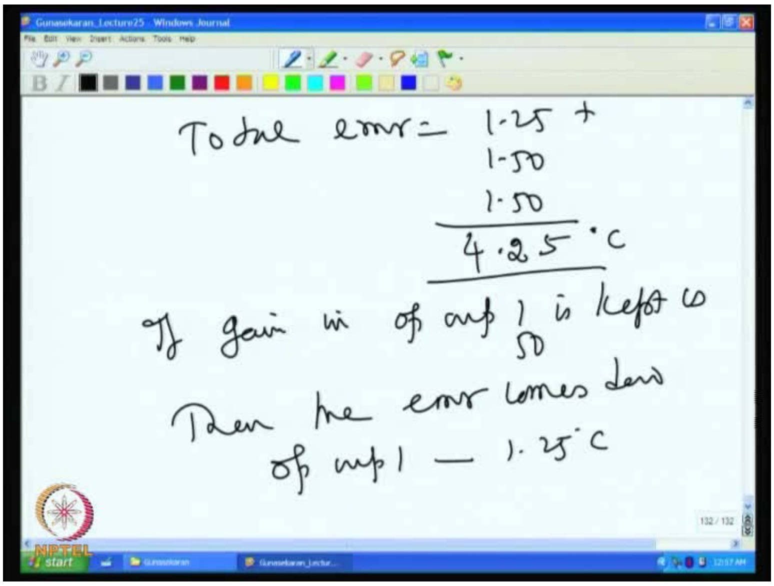

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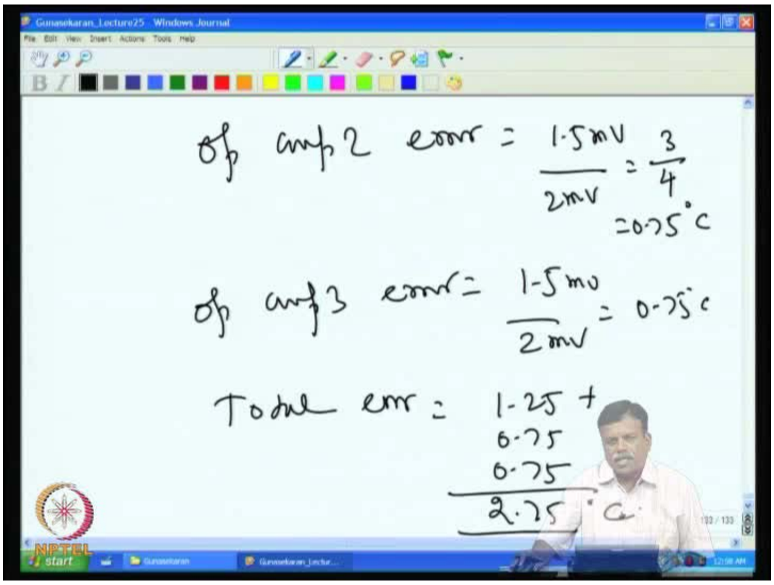

So, one can reduces these errors by increasing the gain. If gain in the first stages increased, if gain in op-amp 1 is kept as 50 then the errors comes down. In this case op-amp 1 error would be, op-amp 1 error will remain that would be 1.25 degree C. Op-amp

2 error would be now same 1.5 milli volt. Now, the signal is 2 milli volt; so, this will actually become 3 by 4th 0.75 degree error. Op-amp 3 error would be against 1.5 milli volt by 2 milli volt that again 0.75 degree. So, total error actually becomes 1.25 plus 0.75 and 0.75 that comes 2.75 degree.

So, one can reduces the total error due to offset voltage due to by increasing the gain of the first stage. So, one can closely calculate the error in each stage and then see that the circuit functions with least error this is the most critical think analog circuit design that is the error budgeting. Error budgeting is an important issue in an analog circuit and then error is another important issue that also we show in our second circuit example. So, with this, I will close this today's lecture, we will see the other issues in the next class.

Thank you.