Analog Electronic Circuits.
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Lecture-49.
Correction to Gilbert Cell Analysis and Op-Amp Imperfections.

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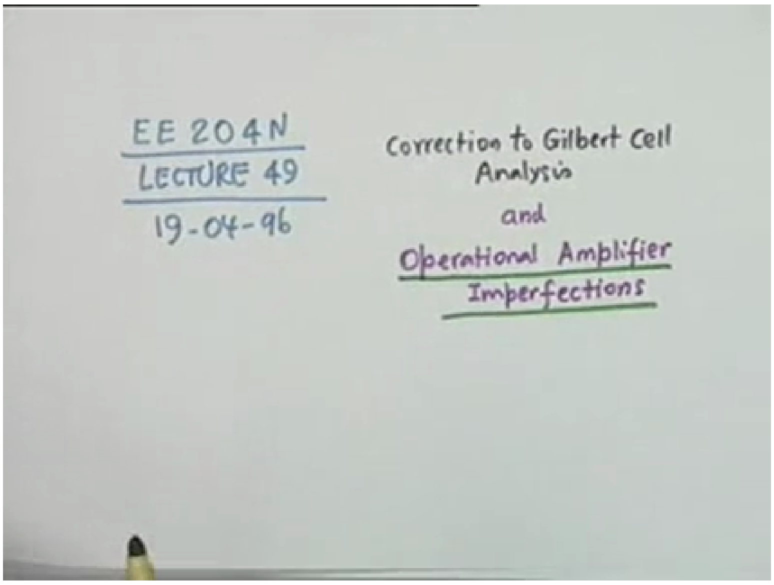

No I did not know, I did not expect. 49th lecture, we made some mistakes yesterday and we will have to make that correction, correction so Gilbert cell analysis. There was a small mistake but I have found out that the source from which I extracted the material did have that mistake, it was not my mistake but I should have thought it, I should have taken it carefully. And then after this correction we will go to operational amplifier imperfections. This I believe has never been taught to you. In the 110 class, in the previous class we simply took the Op-Amp as an ideal one and showed its applications in various situations.

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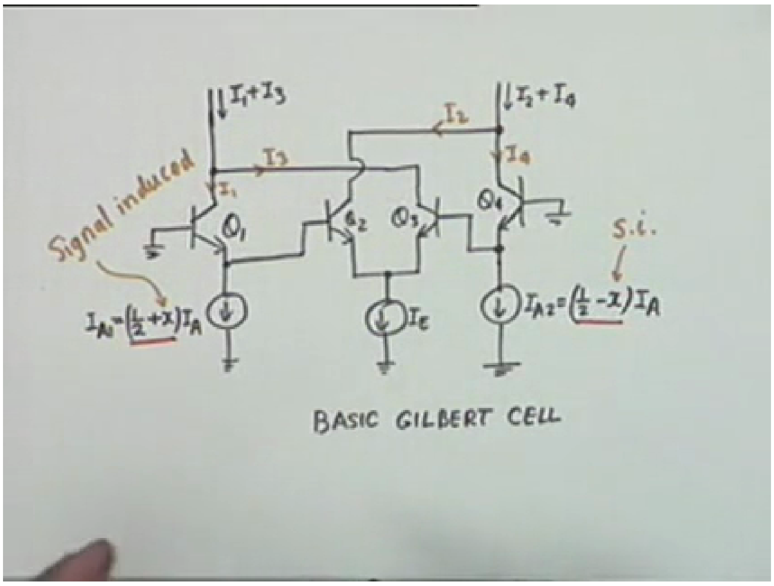

But this is very important, this is a very important topic for an electronics engineer. Operational amplifier is the most often used linear analog integrated circuits and one should be careful. The corrections are as follows. If you turn your page and look at the basic Gilbert cell, the circuit is the same, we did not make a mistake in the circuit. But in the assignment of the currents I A1 and I A2, we have written this as X IA and we have written this as 1 minus X IA and then the differential input current had a DC component, had an IA component which is the mistake.

You know, if there was no signal, then X is 0, this X is signal induced. And therefore of the IA as I had shown you earlier, this is also a differential amplifier basic current source biasing IA, half of which should go to one of the transistors and a half of it should go to the other. And there is the signal, that is then unbalanced is created between the 2 base voltages, between the 2 base voltages, then one of the current increases and the other decreases. The one for which VBE increases, the current increases, for the other it decreases.

Now X could be positive or negative but the sum of the 2, the sum of the 2 must be equal to IA and the difference must be only proportional to the signal induced quantity, okay. The difference between them is 0 if there is no signal and therefore the difference must be proportional to the signal induced quantity. The differential input current is obviously twice X times IA, okay. So this is one of the corrections. And then this continues, this continues in the analysis.

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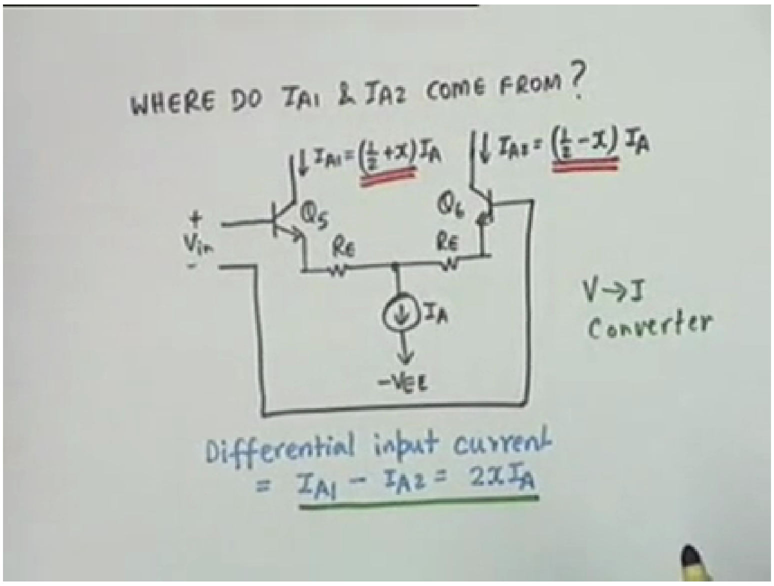

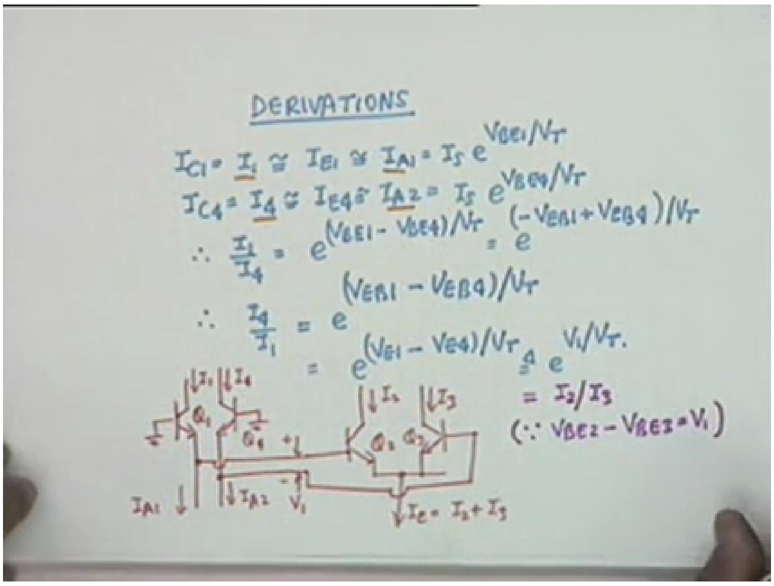

Where do I A1 and I A2 come from? Well, as I had drawn the circuit, the circuit is the same, except that these 2 currents are half plus X IA and half minus X IA, that is the correction. So in the 2nd diagram that you drew yesterday, please do indicate decoration. Then the differential input current is twice X IA, there should not be a DC component in the differential input current. And as I said this is a voltage to current converter. Gilbert cell essentially is a current amplifier, current to current and since our obsession with voltage amplification or voltage signal processing, we have a voltage to current converter at input.

Input is applied between the 2 bases and that is what causes and unbalancing of the 2 currents plus X minus X. Then in the analysis, to review quickly, the current I1, can you see this part? The current I1 is the collective current of Q1 and therefore this is related to IS e to the VBE 1 by VT and this is the same as IA 1 ignoring the base current of Q2, beta is high has been assumed. Then I1 by I4 we have shown or I4 by I1 we have shown that this is V1 by VE 4 and this is the voltage V1, defined as V1, applied between the bases of Q2 and Q3.

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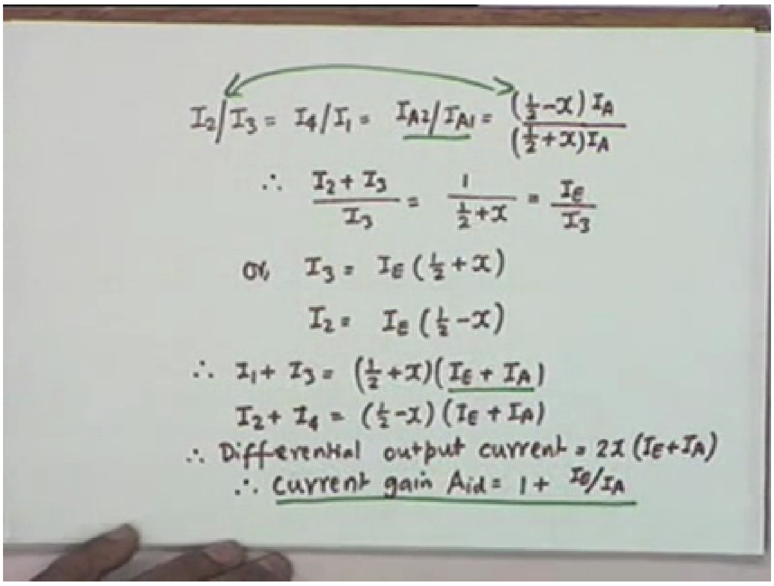

And for a similar, by similar arguments we show that I 4 by I1 is the same as I2 by I 3 because VBE 2 minus V BE3 is also equal to V1, E1 and E3 being a common point, okay. So the ultimate relationship is that I2 by I 3 is equal to I4 by I1 which is the same as I A2 by I A1. So instead of X by 1 minus X it is half minus X IA divided by half plus X IA. Make this correction, half minus X IA diverted by half plus X IA. And then we add 2, add 1 to both sides I2 plus I 3 by I 3 as equal to 1 by half plus X, I hope I am right. When I add 1 to this, I get 1 by half plus X which is the same as I2 plus I 3 which is the total emitter current IE and therefore this IE by I 3 which gives me I 3 as equal to half plus X and the rest of it goes to of I2, IE that will be half minus X.

In other words the proportioning of the current is the same as in the input current proportion is the same. And the 2 outputs currents I1 plus I 3, this is half plus X IE + IA this is the total bias current IE plus IA and the other output currents I2 + I 4 is half minus X IE plus IA and therefore the differential output currents is, should also be proportional to the signal, this twice X IE plus IA, there is no DC component, that is the mistake that we made. And therefore the current gain is 1 plus IE by IA. In this analysis we did not consider the frequency effects at all and the analysis only assumed that which is much greater than 1.

In practice we can go up to beta equal to 10, even then the analysis should be valid. Also you notice that in this analysis we did not assume the size of the signal, we did not put any restriction of the size of the signal. So this gain should be valid even for large signals, it is another advantage of current signal processing, okay. Even for large signals this gain should be true and this is the basic widebanding by Gilbert cell. The total circuit, the complete circuit now I shall draw, please try to draw with me. The complete circuit in which voltage is the input and voltages the output, okay.

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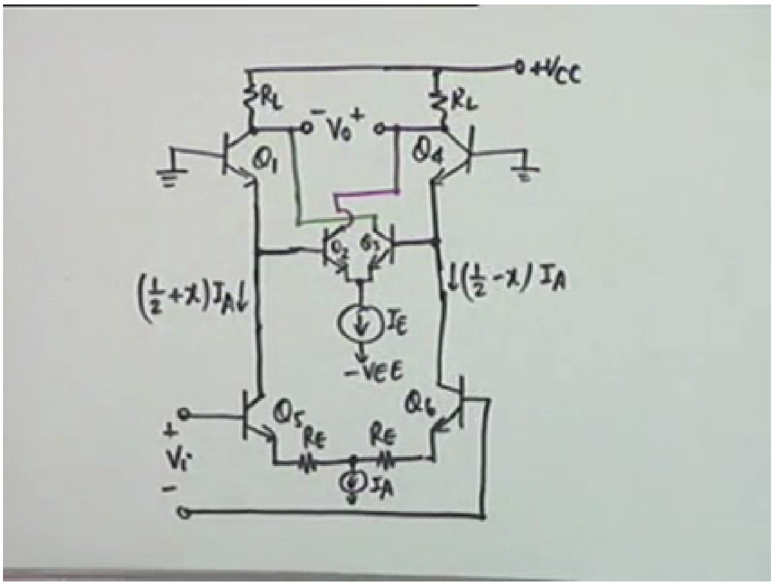

And the circuit is like this, you have the 2 transistors Q1 and Q4, the 2 basic transistors and instead of taking the currents at the output, since we have to take the voltage, we add a load to both, this goes to plus VCC, the currents are converted voltages, and therefore your output signal would be the differential signal here V0, let us say plus minus. You can assign some polarities to this, Q1 and Q4, both are, the bases are connected to ground and in addition you have the internal differential amplifier Q2 and Q3. The emitters of which are connected and this is connected to an I sub e to minus VEE and they are connected in a criss-cross fashion.

That is the collector of Q1 is connected to the collector of Q3, okay and the collector of Q2 is connected to the collector of Q4, this is a basic circuit. And in addition the emitter of Q1 is connected to, is connected to the base of Q2, yes and the method of Q4 is connected to the base of Q3, okay, this is a criss-cross connection. And these are the currents, these are the currents which are half plus X IA and half minus X IA, these are the 2 currents. And these currents are derived from a voltage to current converter. And it is like this, we have have 2 transistors Q5 and Q6, then there are 2 small resistances, nobody ask me why these resistances are there, RE and RE, okay.

You connect the voltage source, the signal source here V I here between the 2 bases and that is converted into 2 currents half plus X IA and half minus X IA and obviously I sub A is the current generator that goes here, I sub A.

Excuse me sir. In case beta is less than 10, in that case what would be instead of half plus X and half minus X IA? I have to take them the (())(12:01).

No, you see as far as these 2 currents are concerned, they are not affected by beta.

The total (())(12:11).

That is right, if this current IE 1, if beta is less than 10, then I E1 cannot be equated to this, then the whole expression shall change, the whole expression shall change and you will not get the gain 1+ IE by IA. Now the beta will be less than 10 at very high frequency and therefore the expression shall not be valid at high frequency, that is all that it means. In other words the gain at high frequencies will decrease. Okay…

(())(12:48).

Why do I need this, well you know that in an Op-Amp, in a differential amplifier there are 2 supplies that are needed.

Even IA is going to (())(12:58).

That is also going to minus VEE, yes, this is also going to negative supply. Also this is not essential but I have also explained the reason why 2 supplies are used. In Op-Amp there is no ground terminal, there is no reference, an Op-Amp does not provide a reference, it provides several terminals, input 2 terminals, output one terminal, one terminals for positive supply, one for negative supply, where is the ground then? The reference is between the common point of the 2 supplies plus VCC and minus VCC, usually they are equal, okay. And therefore since 2 supplies are available as a differential amplifier is based on that. With 2 supplies…

(())(13:50).

What about the bases of Q1 and Q2, they are grounded because, yes…

(())(13:58).

This has to be connected to, you see these 2 bases will be connected together and the terminal will be brought out. In the IC chip of the Gilbert cell the terminal will be brought out which you will have to connect to ground, right, you will have to do that externally, there is no ground supplied in the IC chips, okay. This is the total circuit, this is the chip you that you can take. Now there are modifications in very simple modifications, one of them is that these loads may not be actual resistance. If you want a very high gain, then these loads will be replaced by an active load, a current source, okay.

In a similar manner Q1 and Q4, the betas, if they are not adequate, then you might use a Darlington here for Q1 and Q4. This applies to Q2, Q3, Q5, Q 6 also. This, the chips will cost more, but it is a much better voltage amplifier, much better wideband voltage amplifier because if betas are less, you increase the beta.

(())(15:30

Does the FT increase, no, beta square…

(())(15:23). FH will increase?

FH will increase, FT will not increase, FT will not increase. Okay, any question on this? Now we go to the operational amplifier imperfections. These are the most popular IC chips, the Gilbert cell. Gilbert cells are used for many other purposes also.

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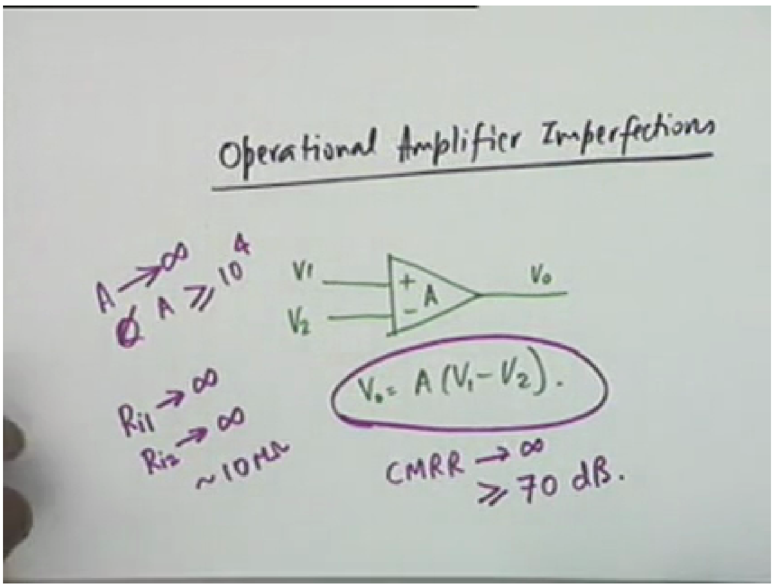

Operational amplifier imperfections. Are you having a control course now?

Next semester.

Okay. As you have learnt earlier an Op-Amp, it is very convenient to view it as an ideal device. There are 2 inputs, non-inverting input, inverting input, the gain is A and the usual thing you write is V0 equal to A V1 minus V2. Now there can be nothing more untrue than this relationship. This relationship also is very simple to write and simple to manipulate has many many imperfections. And these are the imperfections that one has to be careful about if uses an Op-Amp. The 1st imperfection is that capital A, we assume this to be infinity, hardly ever it is more than 10 to the 6.

A must be, the usual Op-Amp that you get in the market, if you get anything less than 10 to the 4, you reject it, it will be useless, okay. It must be much greater than 10 to the 4, in fact 10 to the 6 is an approximate figure. Number 2, you see that we assume that the Op-Amp does not take any current, that is the input impedance RI1 at V1, we assume this to be infinity. We also assume that RI2 tends to infinity but we know, we know that the input stage of an Op-Amp is a differential amplifier and a differential amplifier at the base, the impedance is not infinity, it always takes a base correct, okay. And the usual figures are of the order of 10 meg, practical figures.

The differential input impedance that is between V1 and V2 is also of the same order, of the same order 10 meg, that makes a good Op-Amp. The CMR, we have assumed that if V1 is equal to V2, then V 0 equal to 0, this relation says that if V1 is equal to V2, then it is 0. Now you know from the 1st stage the differential amplifier that CMRR is not infinity, our ideal value CMR R is infinity but in Op-Amp usually the CMRR is greater than 70 dB, not more than that. There is a common mode gain but the common mode gain is small enough in the ratio is approximately 70 dB.

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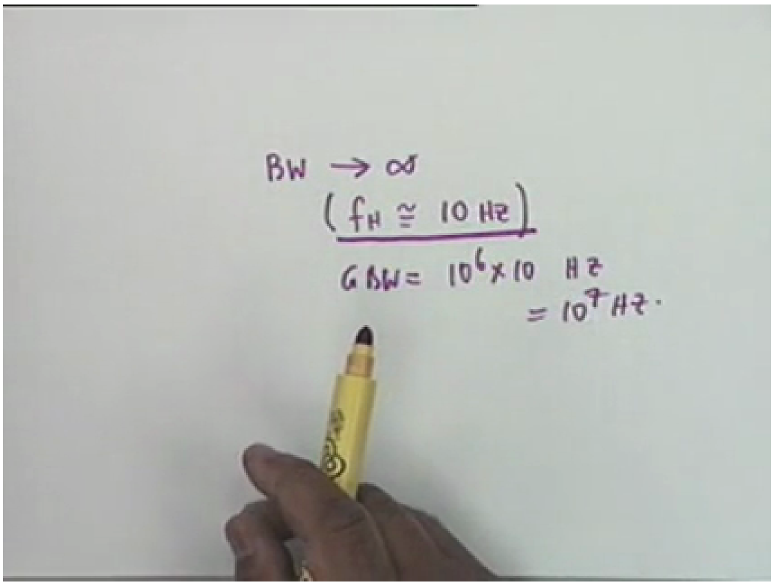

The most shocking thing is, the most shocking thing about Op-Amp imperfection is that you assumed a bandwidth, you assume that not only the gain is infinity but the gain is infinity at all frequencies. The bandwidth ideally is of the order of infinity. In practice the high-frequency 3 dB point is of the order of a few tens of hertz, 10 Hz is not an uncommon figure. This is the most shocking imperfection that an Op-Amp has and it is necessary to have this imperfection. The question is how do you use in Op-Amp then at 100 kilo hertz or 200 kilo hertz, what we do is we apply negative feedback to take is again and increase in bandwidth.

If you had a gain of 10 to the 6, then GBW is 10 to the 6 multiplied by 10 hertz, that this 10 to the 7 hertz. So if you want a gain of 10, then you can go right up to 1 megahertz, no problem, this is how it is done. But the high-frequency 3 dB point of necessity has to be reduced to a few tens of hertz. Even if you can design an Op-Amp with the differential amplifiers and other stages, we will come to the architecture a little later but of necessity it has to be reduced. We will see what the necessity is.

We also assumed, we also assumed that the input differential amplifier is the transistors are perfectly matched which never is the case. If they are not matched, then what will happen? Then VBE1 and VBE2 will be slightly different and therefore even if there is no signal between the 2 bases, you shall have a DC signal, all right. Which is called an offset voltage, input offset voltage. This occurs because the 2 VBEs are not identical so that even if there is no signal there appears the voltage between the 2 bases. It is usually denoted by the symbol VI0 and in practice it must be less than about 10 millivolts, the less the better. And you have seen, you have seen that in some of the differential amplifier, a small emitter the distance RE is attached. For example in the last Gilbert cell also, the voltage to current converter we had an RE.

This RE is usually used to balance the 2 transistors, even if they are slightly mismatched, a small resistance is used here and is the part of fabrication, it is adjusted like that. Even in that adjustment you might have an Op-Amp in which there is a voltage, input voltage offset. However in the Gilbert cell, nobody asked me this question, suppose we take away the RE, suppose the transistors are completely matched, we take away the RE, what is the harm? It is a voltage to current converter, that is the clue.

If it is a voltage to current converter, what kind of input impedance do we want? Hi input impedance. And if RE is not there, then what is the input impedance, twice R pi, that is all. So RE adds to the input impedance by them on beta Plus1. This is why RE is used in a voltage to current converter. Is a point clear?

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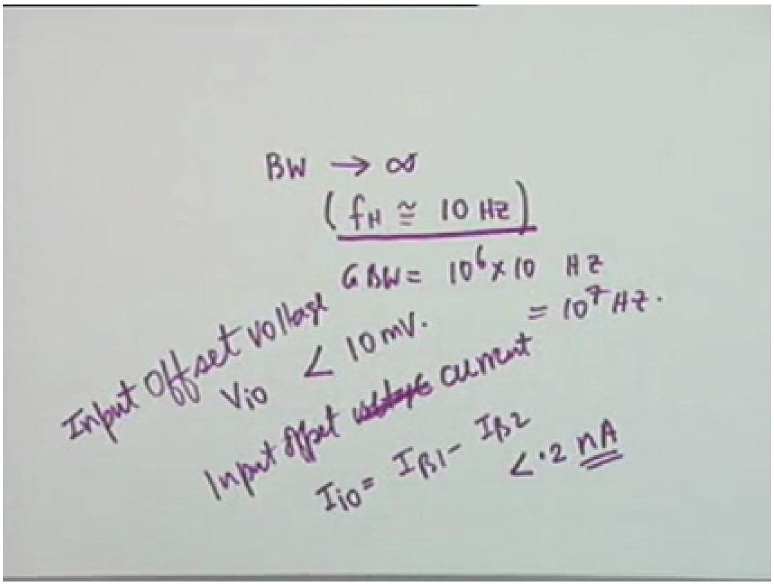

It will not be in the order of the homes, in a voltage to current converter you will increase, you will use a sufficiently, purpose is different, purpose is not to balance the offset, to balance the offset requires a small resistance. But there is no harm if we use too large resistances on 2 ends, they can be slightly different to balance the offset. Already, the purpose of RE in the Gilbert cell voltage to current converter is different, it is to increase the input impedance.

Okay, similarly if the 2 bias currents are slightly different, I B1 and IB2, if the 2 bias currents are slightly different, then there exists a differential input offset current, okay.

There can be an input offset voltage. And if it is the current amplifier or voltage amplifier, this will produce a signal at the output. Even if there is, this will produce an output even if there is no signal input. And therefore you have an input offset current which is the difference between the 2 bias currents. That is denoted by I I offset, input difference between the 2 bias currents. These are very small, of the order of 0.2 nanoamp but it can cause a great harm to the operation of the operational amplifier. It can reduce the signal to noise ratio because of the existence of a DC input offset voltage, okay. One has to be careful about these imperfections.

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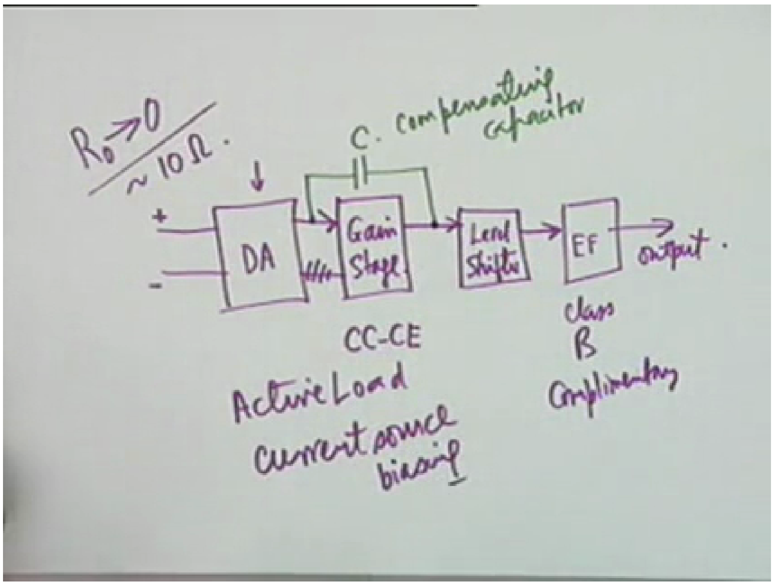

Now we shall look into each of these imperfections and see how they can be, how they can be annulled in a practical circuit and how their effects can be minimised. At this point it would be good to see what the usual architecture often Op-Amp is. What one does is, you know the input stage in a differential amplifier, showed by block, input change in a differential amplifier, there is a inverting, noninverting input and there is an inverting input. Okay, differential amplifier, you may have a couple of them. The differential amplifier is direct coupled and the 2 collector outputs can be taken to the next stage of the differential amplifiers to increase the gain.

But what is the property of a differential amplifier, what about the output impedance? Input impedance can be made high if you use those 2 Res, output impedance is usually large and therefore it is a voltage to current. In other words these are transconductance amplifiers, is that correct? There is a high input impedance and therefore what one does is after 1 or 2 of the differential amplifiers, the 741 for example has 2, there are some others which also has 2. The output is then , usually you take a single ended output from a differential amplifier, you do not take, you do not take this difference unless you want to apply to another differential amplifiers, okay.

So a single ended output and then another gain stage is attached, another gain stage is attached. Now this gain stage usually is a common connection, we have already, 741 for example has a CC CE combination, collector, common emitter. This is, this also aids broadbanding but it also supplies the gain, the input stage is CC in order to match the current amplifier to a voltage amplifier, okay. So that the input impedance is high and then the output is a common emitter stage.

Now usually a capacitor is attached from the input to the output, a capacitor C, this capacitor is called for reasons to be discussed a little later a compensating capacitor. Sometimes called Frequency compensating capacitor and it is this capacitor which brings down the 3 dB points to 10 hertz, several tens of hertz. Because you see differential amplifier gain stage, we can design them for several megahertz but usually a capacitor is attached from the input to output to bring down, to bring down the 3 dB points to several tens of hertz. How does it do it? You see it happens because of the Miller effect. There is a large gain and therefore this capacitance reflects at the input at a large capacitor and the time constant determines the actual 3 dB point, okay. Pardon me?

Why do we do it?

Why do we do it, we will come to this a little later. The next stage is the gain stage, the output of this, there is no capacitor inside, there is no coupling capacitor, well this capacitor is usually supplied by the manufacturer or sometimes 2 terminals are brought out in an Op-Amp and called compensating terminals where you have to connect a capacitor externally depending on, depending on where you want your 3 dB cut-off. We will come to this but at the output you see in that DA, neither in the DA, nor in the gain stage there any coupling capacitor. And therefore the output may have a DC level which cannot be applied to the next stage.

What should be the next stage? The last stage, the last stage should be common collector and usually if the Op-Amp is to deliver power, then this is a class B common collector amplifier. You remember the class B complementary-symmetry transformer less amplifier, usually that is the last stage. Almost all Op-Amp have that kind of… But the point is, suppose this is at 5 volts, you cannot apply 5 volts to a base, you remember the class B, there are 2 transistors, PNP, NPN and the bases are connected together, you cannot apply that voltage.

So what is needed, this we have not discussed so far, what is needed is a level shifter, we shall discuss this in detail, level shifter. The DC level has to be shifted such that the overall output of the Op-Amp is equal to 0 when the signal is 0, all right. And is such that it does not affect the operation of the next stage which is usually an emitter follower but connected in class B Complementary connection and that is the output, the output goes to the load. This is the general architecture of an Op-Amp. The 1st stage, the 1st block is a transconductance amplifier, the 2nd block is a voltage gain stage, usually CC CE combination and then out of necessity you have to have a level shifter.

Finally an emitter follower which has to deliver the power to the load. Even if power is not important, emitter follower is necessary to reduce the output impedance to a negligible level, several tens of ohms. This is one of the imperfections which we did not mention. The output impedance we usually assume this to be 0 but in an actual Op-Amp it is of the order of several tens of ohms, 100 ohms is not very uncommon. Alright, now let us look at the DC level, this level shifter. But before the level shifter let us recall that in the DA, as well as in the gain stage we do not use any external resistance for biasing. For biasing we use a current source and we do not use any external resistance for the load resistance, you use an active load.

So both of them use active load and current source biasing, those current mirrors.

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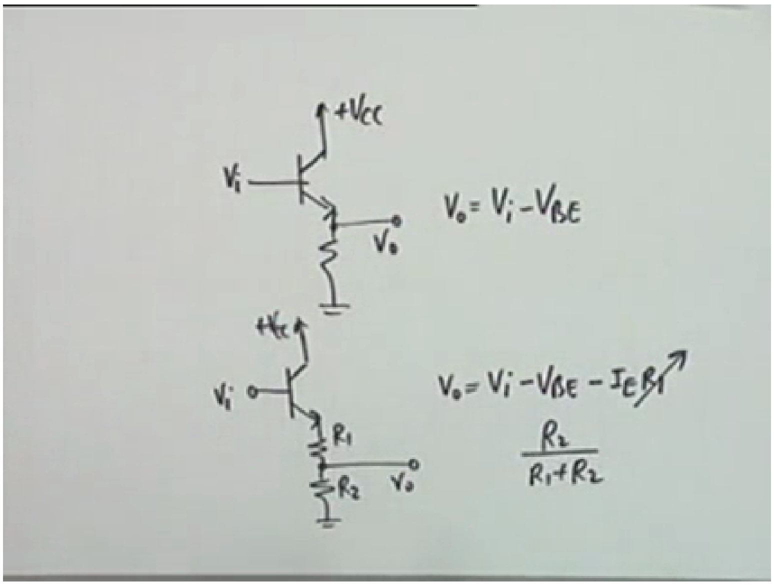

Let us look at level shifting. There are various possibilities of circuits and some of the simple ones which are used in Op-Amp, I shall describe. Suppose you have a simple emitter follower plus VCC and then a resistance, this is your VI and this is V0. You should see that the level shifter does not change the gain, you took great pains in cascading DA and CC CE stage to make up, to make up again of the order of 10 to the 6, level shifter should not change the gain. And it should also change the DC level, you see that here the DC level of V0 is VI minus VBE, agreed.

This is a simple level shifter, you shift it by the amount 0.7 volts, VBE. If you want more than 0.7, then what you do is you use a circuit like this. The same emitter follower plus VCC but you use 2 resistances, V I and V0, let us say R1 and R2, okay. Here V0 would be equal to V I minus VBE minus IE times R1, agreed. But the disadvantage is, obviously by changing R1 you can shifted to by any, any amount. But obviously the disadvantage is that the signal itself gets attenuated by the amount R2 by R1 plus R2. We do not want this and therefore we have to do something about it.

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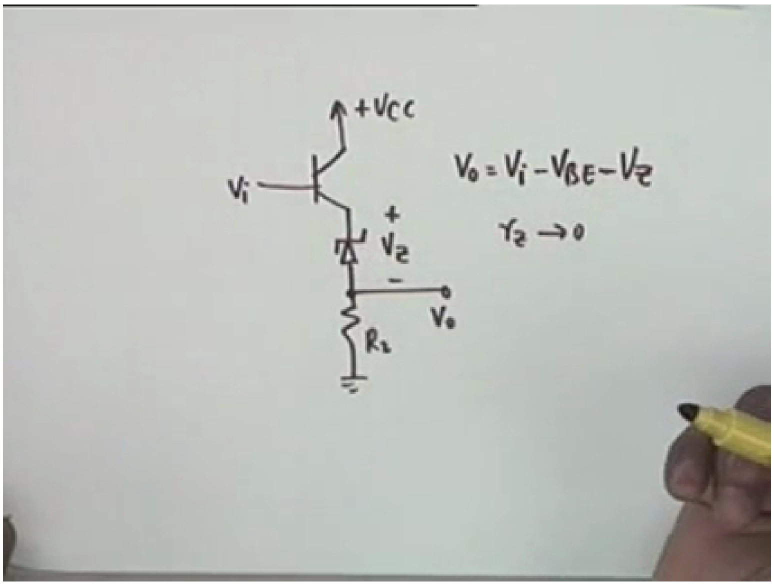

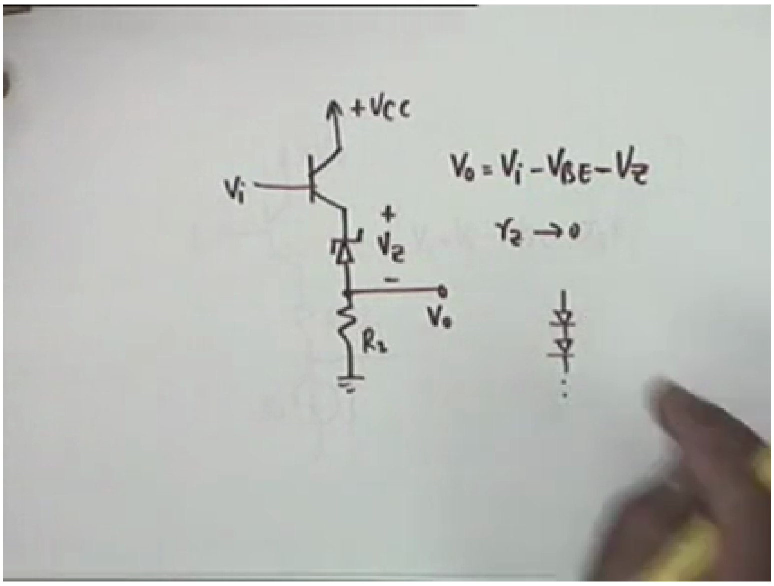

What can be done is, one of the simple ways that can be done is to replace R1 by a zener diode, a reverse biased Zener diode, let us see how that looks like. Plus VCC, this is VI and then you use a Zener diode here, a reverse biased Zener diode and then and R2, the voltage you take, output voltage is here. The Zener diodes voltage is VZ this polarity, it is the reverse biased. Obviously now V0 would be equal to VI minus VBE minus VZ, you choose the Zener diode properly so that the amount of shift is adequate.

Does it affect the gain, signal gain? Does it affect the gain? No because the Zener diode dynamic resistance is a very small quantity, okay. RZ tends to 0 and therefore V0 signal component is approximately the same as VI. The other thing that can be done is instead of, instead of changing R1 to VZ, let us keep R1 the same, there are various techniques that have been used in Op-Amps. The Op-Amp design is as good as 30 years old now. 1964 or 65, this is 96, 30 years, various techniques have been used.

One of the things that has been used is you keep R1 the same but instead of R2 you use a current source I 0. In any case you will have to use a current source for biasing, okay, so we are going to use the emitter follower also and we keep the output here, V 0. Then once again V0 is equal to VI minus VBE minus I0 R1, agreed. What about the signal attenuation? Nothing. Why not? Because the effective impedance of this is infinity and therefore there is no signal, this is also very popular technique. Another technique that is used…

But if you use a current source for this, active load (())(36:43).

Finite but if that is large compared to R1, okay, the minimum that you expect is R0 and R0 is of the order of 100 K, this is 500 ohms. We want that is most sophisticated of this, you can also, one can also argue here, let us go back a couple of slides. Instead of a reverse bias PN junction, that is a Zener, one could also use a number of forward biased diodes. Okay, for example instead of Zener you could use like this to make up for the, for the voltage, you could also use that. This is also used in some of the chips, particularly Motorola chip is available in which several forward biased diodes have been used.

Why forward biased, why not a Zener?

This is negative, so we can make many diodes.

We can make diodes, we can also make a Zener. A Zener is a costlier diode as compared to an ordinary diode, why? Because it requires a heavy doping, it is to be such element. On the other hand a diode simply be made out of all the transistors, you need 3 more transistors to make a connection, that becomes a diode, okay, right. The most sophisticated of this is what is called a VBE multiplier.

A level shifter using VBE multiplier.

(())(13:26).

Which circuit?

Any of the circuits.

Well in this for example you vary this.

(())(38:38).

As far as…?

Dissipation is concerned?

As far as dissipation is concerned, dissipation needs to be checked within the limits, of course. I 0 Square R1 will be the dissipation here, this has to be kept within the limit. But please remember these are not variable from outside, it is part of a chip, this is taken care of during the design. You know precisely how much shift is required and we adjust to that. And once you are just you leave it at that. As I said the most sophisticated one is to replace R1 why what is called a VBE multiplier. A VBE multiplier is a chip by itself, it is available as a chip also, and the circuit is this, please write with me.

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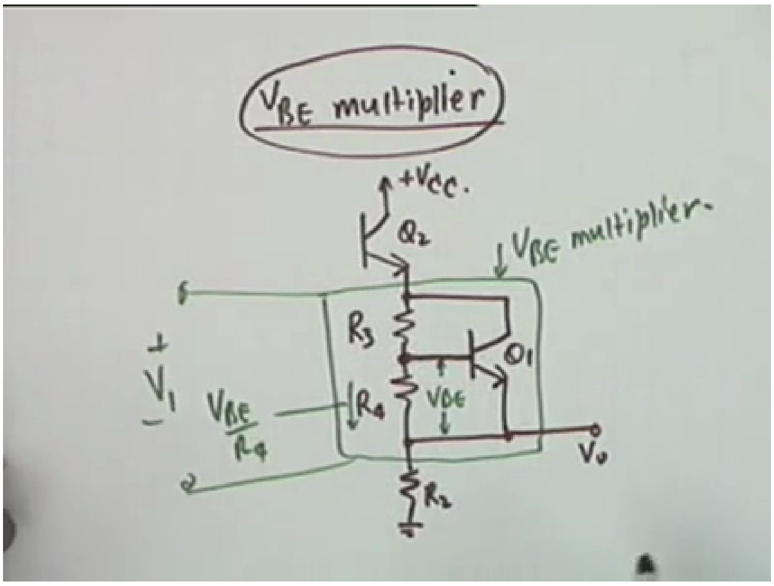

Not very complicated, VCC, same emitter follower, instead of R1 you have, you have a VBE multiplier and VBE multiplier the circuit is like this R 3, R4 and then you have a transistor like this base is supplied from here, this is Q2, and this is Q1 and the emitter is connected here. Then we have the R2, usual R2. R1, the place of R1 has been taken by this. The output is taken from here, V 0, this is called the VBE multiplier, so an interesting circuit and has many uses, many uses in regulated power supply chips, in multiplier chips, many other situations this particular circuit is used, it is a very simple circuit.

And it can be analysed very simply. You see this voltage, this voltage would VBE, agreed between the base and emitter, this is VBE, and therefore the current through R 4 would be

VBE divided by R4. And if you know the base current, if the beta is large, then the same current flows through R3, agreed, the same current flows through R3. And therefore the voltage between these 2 points, if you call this V1, V1 would be equal to, V1 would be equal to VBE plus VBE divided by R 4 multiplied by R3.

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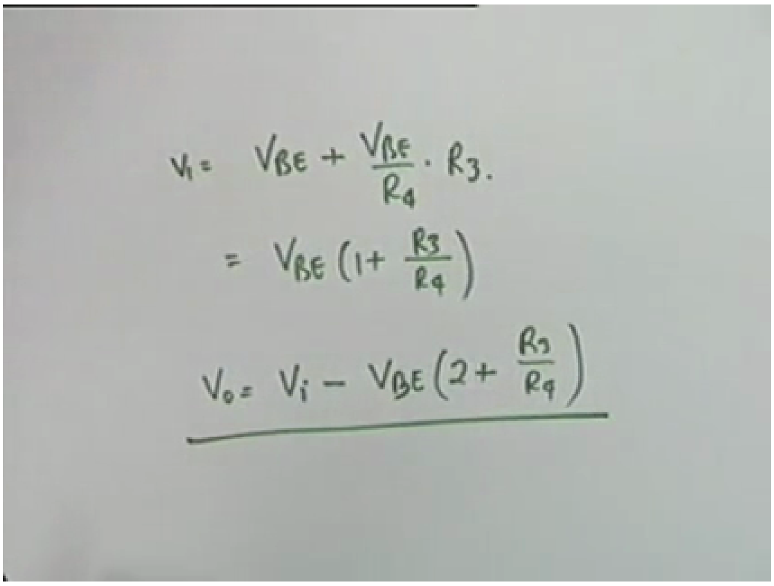

That is equal to VBE 1 + R3 by R4 and that is why it is called the VBE multiplier. You can multiply this 0.7 by any quantity that you require more than one, okay. By choosing R3 and R4 properly you can adjust to any level shift that you like. Incidentally, the level shifter here is V0 VI minus V1, now, minus VBE minus V1, so it is VBE multiplied by 2+ R3 by R4, is a point clear, okay. Now this is a sophisticated circuit and it is very popular, very popular. However I must point out that the 741, the most commonly used Op-Amp is a simple emitter follower, sometimes with a diode and sometimes not, it is a simple emitter follower.

Excuse me sir.

Yes?

(())(42:28).

Previous slide, yes.

Why do you use Q2?

This is a level shifter, this is VI.

Here also you have shown VI.

This is V1, this is a shift, this is the input. Now the million-dollar question, I thought Ankur was asking that question. Million-dollar question, what will be the signal attenuation between VI and V0? Is not there, does not this act as a resistance? Well, there will be signal attenuation, so it is important to calculate the signal gain of the stage by taking the hybrid pi equivalent circuit.

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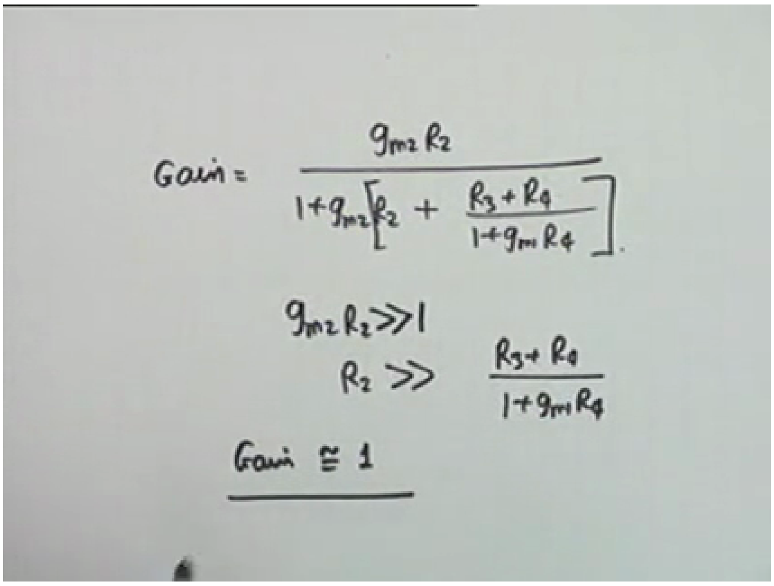

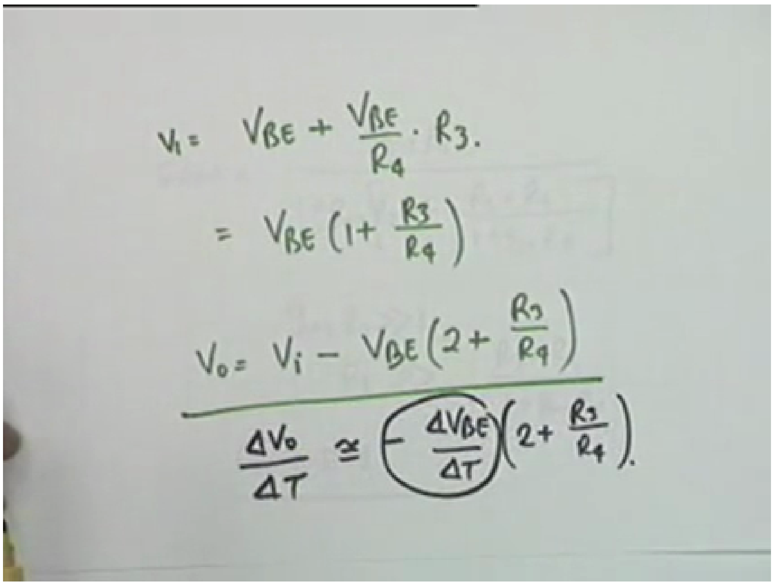

And if you do that the signal gain AV is given by, what do you think, can it be greater than 1? Can it be greater than 1? No because after all it is an emitter follower. It should be less than 1, if that VBE multiplier was like a lumped resistance. The gain if you calculate is given by 1+ GM2 R2 plus R3 Plus R 4 divided by 1 plus GM1 R4, this is the overall gain. Does it fit the bill? Suppose, is there any obvious defect in this expression? Or is there a way to check validity of the expression? Suppose R3 and R4 are 0, then the gain is, if R3 and R4 are 0, it will be simply emitter follower, GM2 R2 divided by 1+ GM2 R2, okay, so this correct. Now if GM2 R2 is much greater than 1 and R2 is much greater than R3 Plus R 4 divided by 1 plus GM1 R4, which can be very easily designed, you see that the gain, signal gain is approximately equal to1, all right.

So this is taken care of, VBE multiplier is very often used in an Op-Amp level shifting. The advantage of this circuit, the advantage is that the shift can be adjusted, you can get any amount of shift. There is the disadvantage also, what is the disadvantage? Disadvantage is temperature dependency. So Delta V0 by Delta T would be approximately equal to minus Delta VBE by Delta T multiplied by du plus R3 by R4. So if at all the temperature dependence of Delta V0 the output is amplified, what is this value, Delta VBE by Delta T? What is the value? 2.2, negative or positive?

Negative.

Negative and therefore this is 2.2 millivolts per degree C and the temperature changes, which it will, if it is in Delhi for example, very large change, the whole circuit will behave differently. Is there a way to compensate for temperature?

Yes.

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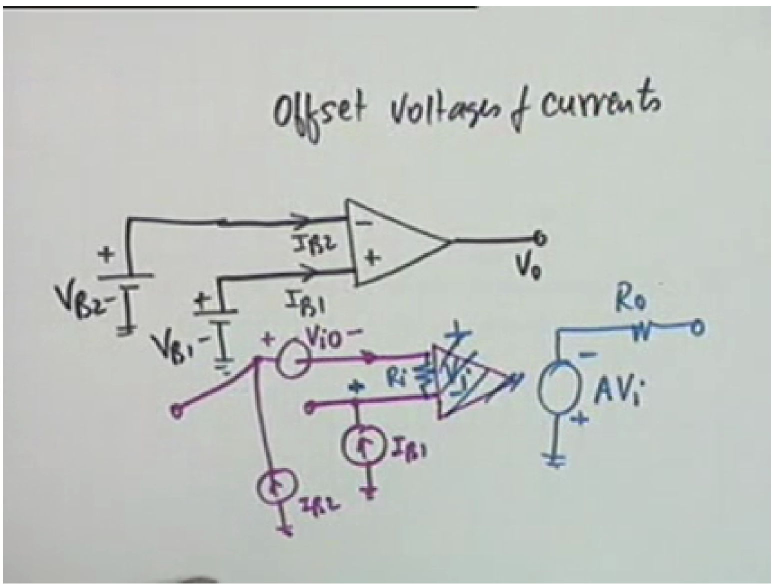

Yes, okay, you know this to compensate for temperature. All right. We next consider the question of offset voltages and currents. As I told you the offset occurs because of the mismatch in the input transistors, the 2 input transistors in the differential amplifier. And we can represent the offsets like this, we can model the offsets like this. There are 2 current, bias currents, let us call them I B1 and IB2, there are 2 bias currents and in addition the 2 base voltages are different, so let us include this by means of the battery VB1 and VB2.

The problem arises when V B1 and V B2 are not identical and I B1 and IB2 are not identical. If they are identical then there is no offset and this is V0. This can be further modelled like this, we take this term effects of these 2 offsets separately. That is, no, no more current, what we do is we assume that there is a current source I B1 and there is a current source IB2 here. And the difference between the 2 voltages VB2 and VB 1 we modelled by a single voltage source, because it V I offset which is the difference between 2 voltages with this polarity, okay.

Then as far as the Op-Amp is concerned, we can replace this by means of a single resistance, input resistance R I, forget about this triangle. If this voltage is V I plus minus, then the output is, I have done this intentionally, what would be the output? AVI with what polarity? Which is plus, down or up? Down, okay. You must remember this because I have said plus minus here would be inverting, this is the inverting and this is the noninverting R 0, okay. On Monday we shall analyse this circuit to find the effects of VI0 and the difference between I B1 and IB2 and take some examples to illustrate this.

Offset is one of the most irritating features in using an Op-Amp, particularly small signal, particularly small signal. Because the signals are comparable to offset, then you will confuse the output as due to the signal when it is actually due to an offset. Offset also can saturate the whole device and therefore one must be very careful.