Integrated Circuits and Applications

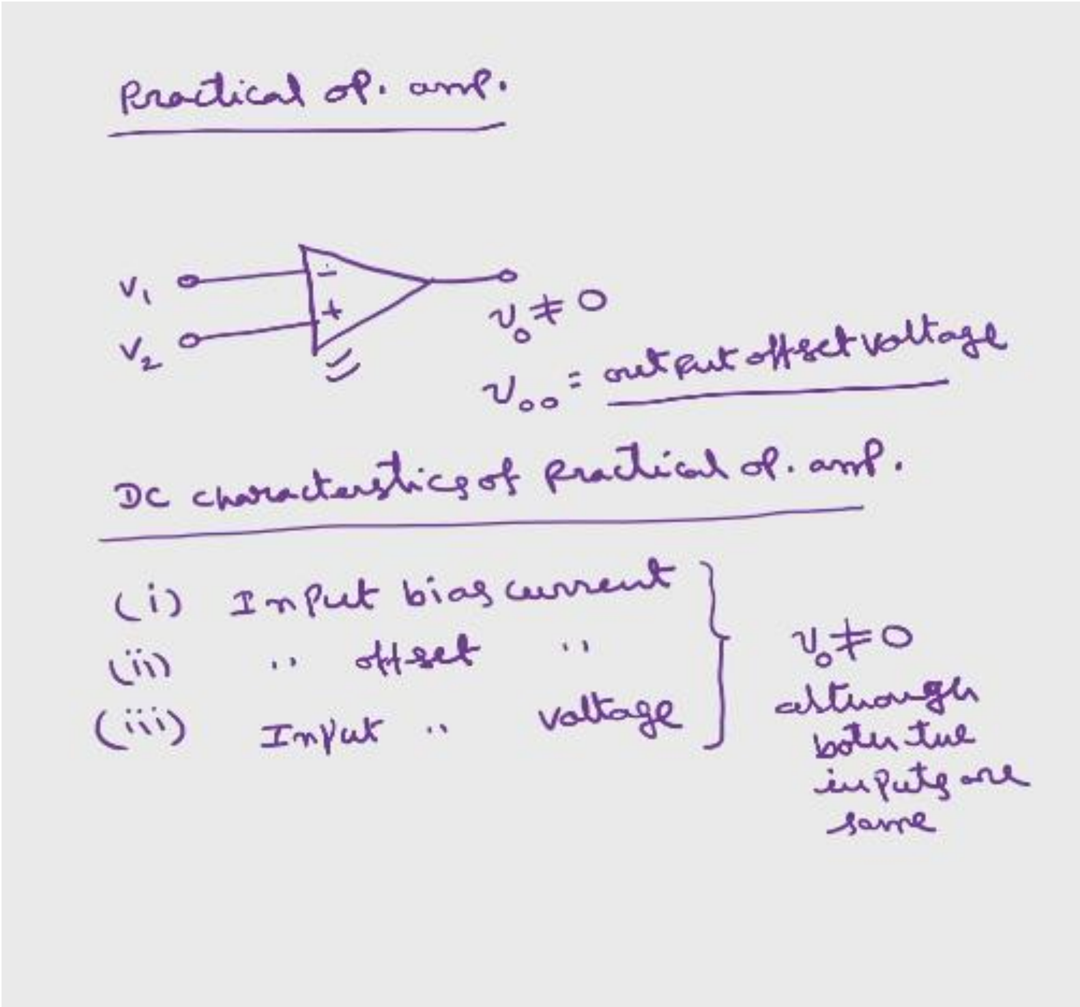
Prof. Shaik Rafi Ahamed
Department of Electronics and Electrical Engineering Indian Institute of Technology, Guwahati

Characteristics of Practical Operational Amplifier
Lecture – 08
DC Characteristics (Offset Currents and Voltages)

Ok. In the last lecture we have discussed about the ideal operational amplifiers. So, where we assume that the input bias currents are 0 and the voltage at input terminal that is voltage at inverting terminal is equal to voltage at non-inverting terminal. But in many of the applications, so there will be some small output voltage even if the input voltage is 0 that is what is called output offset voltage ok. So, in order to process the signals with lower amplitudes that will affect the overall output. So, if I consider the practical op-amp we need to consider some DC characteristics as well as AC characteristics ok. So, today we will discuss about the practical operational amplifier.

So, in case of practical operational amplifier even if this input voltage are same, output voltage will not be same there will be output voltage is called as V_{OO} this is called output offset voltage. This is due to the mismatch between the transistors which are present inside the differential amplifier. So, because of this output offset voltage, so there will be 3 DC characteristics of practical op-amp which we need to consider to find out the overall output, output due to the ideal op-amp and the output due to the practical op-amp. So, there is some DC characteristics of practical op-amp.

(Refer to the slide at 04:11)



So, one is called input bias current. Second one is input offset current, third one is input offset voltage. Because of these 3 characteristics output will be is not equal to 0 even if both the inputs are same that means, there will be some output offset voltage ok. So, what are the effects of this input bias current, input offset current and input offset voltage and how to compensate this we are going to discuss now. So, first I will consider input bias current.

So, I will consider the inverting amplifier with input is equal to 0. This is the standard inverting amplifier which we have discussed in the earlier lectures. This is the output voltage v_o, this is the input voltage v_i, this is input resistance R_1, this is feedback resistance R_F. But in the previous discussions we assumed that the bias currents are 0 here. But now I will consider some bias currents because in a practical op-amp there will be some bias currents which we are going to make this bias current to operate this the transistors which is present inside this operational amplifier into linear region.

So, there will be some bias currents I will call this bias current as this as I_B^- this is for inverting terminal this I will call as I_B^+. So, because of this if I make input voltage $v_i = 0$, then there will be some output voltage this output voltage is not equal to 0. What is this output voltage? I have to find out. So, this output voltage is because of this input bias current. So, now this voltage is because this terminal is grounded this is also 0V and the current here if I call this one as I_1.

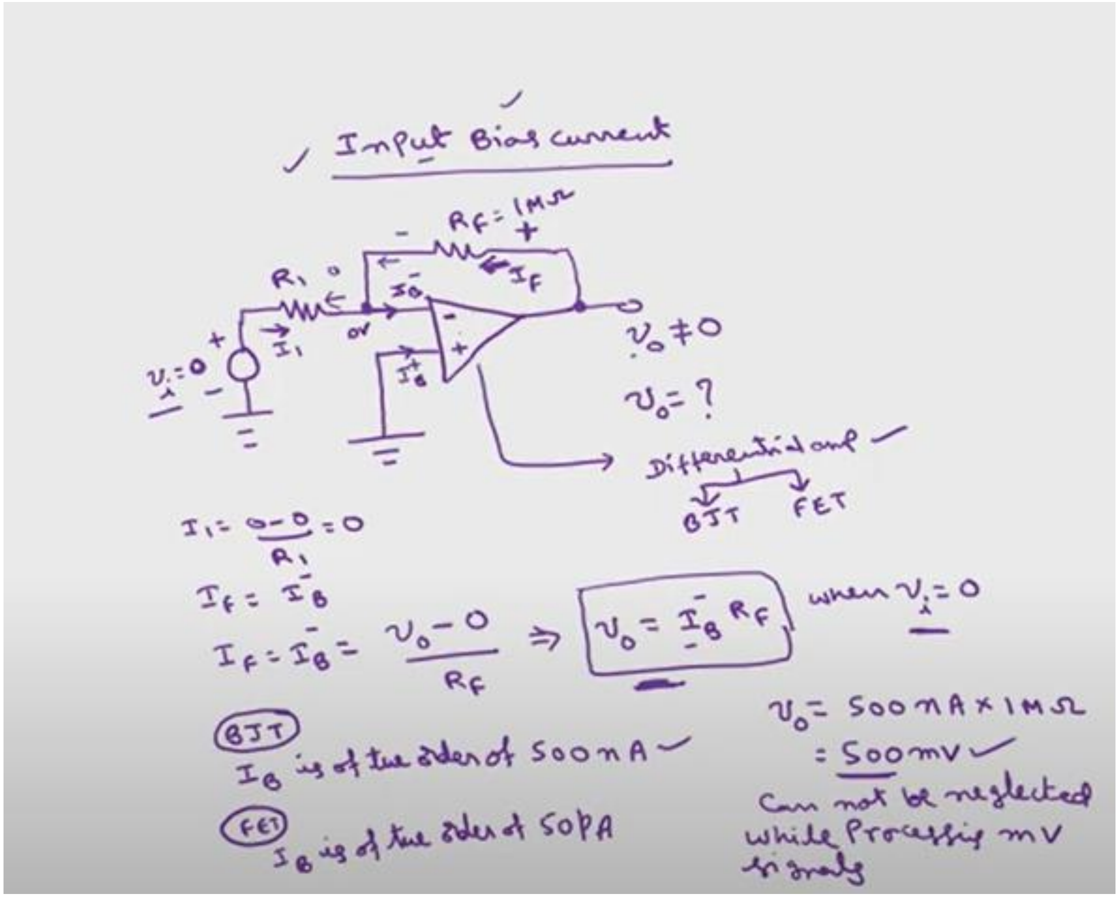
So, this is also 0, this is also 0. So, 0 minus 0 $I_1 = \frac{0-0}{R_1} = 0$, this current is 0. And if I assume that this is I_F or I_2 it is up to you I_F if I assume that this is I_F current, then this is 0 volts this is plus minus. So, what will be output voltage? This I_F will become I_F is flowing in this direction. So, here this current is 0.

So, this entire I_F will flows through I_B^- this I_B^-. So, therefore, what happens $I_F = I_B^-$. So, what will be output voltage? This is 0V this is $\frac{v_o}{R_F}$ or if I take the direction of the current from positive to negative. So, then this is v_0. So, I_F is equal to I_B^- is equal to this I_F is equal to this I_B^- this is equal to this voltage because this is a positive terminal $\frac{v_o-0}{R_F}$.

So, implies what is v_0? $v_o = I_B^- R_F$. So, you see the output voltage when input voltage $v_i = 0$, this input voltage you make as 0. So, still you are getting some output voltage, this output voltage is because of this input bias current. So, in ideal op-amp if input is 0 output also has to be 0, but in practical op-amp because of this input bias current this much output voltage will be 0.5. Now, if I take this op-amp with transistor differential amplifier BJT differential amplifier. Just how discussed in earlier lecture was inside this there will be a differential amplifier stage there are different stages series of differential amplifiers then level shifter and all. So, this differential amplifier can be implemented by using either BJT or FET. If this differential amplifier is implemented by using BJT then this I_B bias current is of the order of 500nA in case of BJT. In case of FET this is less 50pA and still there will be some current.

Now, if I assume that this 500nA is this I_B^- and if I choose this feedback resistance is equal to $1M\Omega$, then what is the output voltage v_0 due to this input bias current is given by I_B^- which is of the order of say 500na into R_F is of the order of $1M\Omega$. So, this nano mega becomes milli. So, this will be 500mV. So, for the applications where if you want to process the weak signals of the amplitude of milli volts this is reasonably a large value so, which we cannot neglect because of that there will be some accuracy effects. So, because of this there will be some error in the output.

(Refer to the slide at 10:50)



So, this we cannot neglect while processing the milli volt signals. So, this is undesired effect then how to compensate this input bias current effect? Input bias compensation. So, this input bias current can be compensated by connecting a compensated resistor at the non-inverting terminal of the op-amp. This is the overall circuit which compensates the output voltage due to input bias current. This is called R_{comp} by connecting R_{comp} resistor in the non-inverting terminal we can nullify or we can reduce the effect of input bias current.

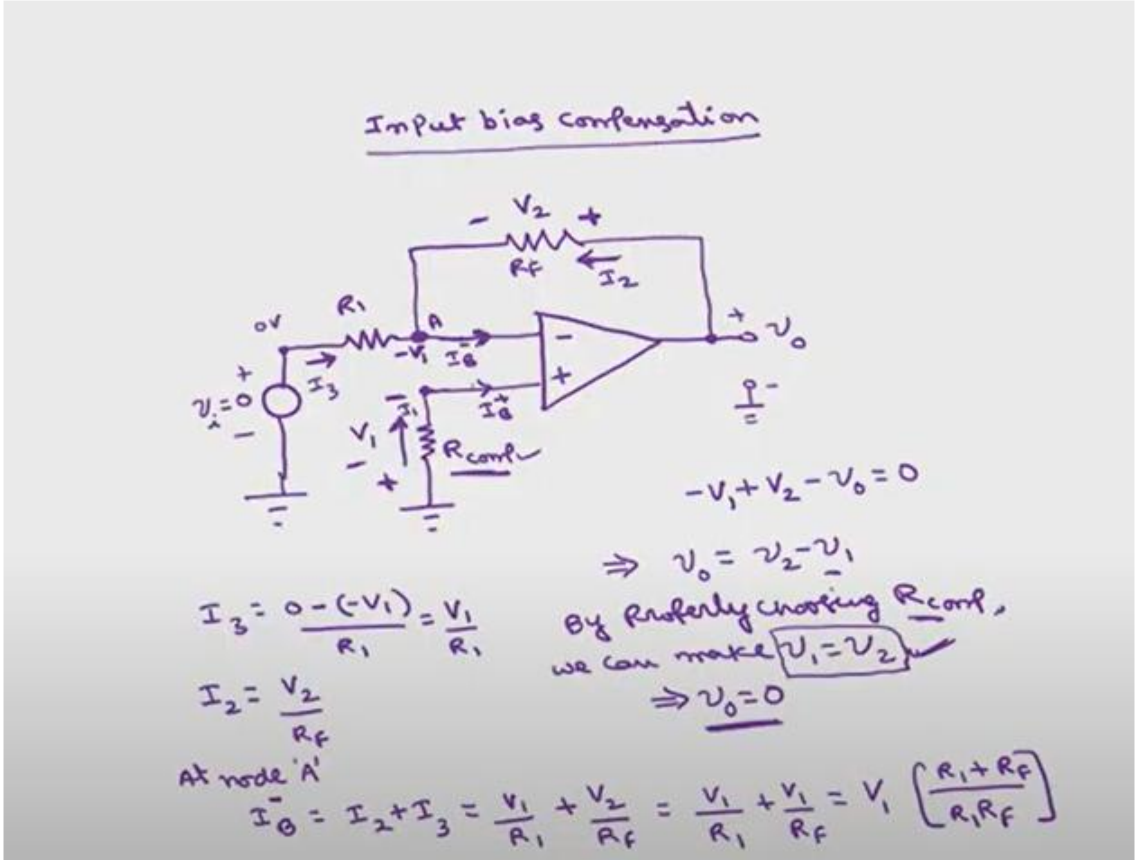
Again I will assume that this is a practical op-amp. So, this bias current is I_B^- and this bias current is I_B^+. This current you call as I_1 this is plus minus this current you call as I_1 this voltage drop you call as v_1 and this if this is the current direction of I_2 this is plus minus and this voltage is v_2 and we will make this $v_i = 0$. Now, what should be the value of this R_{comp} which nullifies the effect of input bias current? So, the voltage at this point is equal to voltage at this point. So, if I take this KVL between this point and this point this is v_2.

So, this is minus v_1. So, this is plus to minus I am taking as minus v_1 minus to plus I will take as plus v_2 and this is again with respect to ground this is plus to minus. So, this is plus to minus. So, this $-v_1 + v_2 - v_0 = 0$ implies what is v_0? $v_0 = v_2 - v_1$. So, you can easily see that if I make this v_1 v_1 depends upon this R_{comp}.

If I properly choose this R_{comp} such that if I make this $v_1 = v_2$ then $v_0 = 0$. By properly choosing R_{comp} we can make $v_1 = v_2 \Rightarrow v_0 = 0$, this is the offset voltage due to input bias current. So, in order to make this offset voltage 0 what is the condition v_1 should be equal to v_2. So, what value of R_{comp} will make this $v_1 = v_2$ that we have to derive now. So, for that so, we can choose this. So, this current if I assume that this is I_2 this I will call I_3 say. So, what is I_3 is given by this is 0 volts this is 0 volts and this is $-\frac{v_1}{R_1}$. So, $\frac{0-(-v_1)}{R_1} = I_3$ this is nothing, but $\frac{v_1}{R_1}$. And what is I_2? I_2 is basically between this this is v_2 is between plus and minus and this direction is I_2. So, simply $I_2 = \frac{v_2}{R_F}$.

What is I_B^- at this point if I apply KCL. So, what are the currents entering this point if you assume that this is point A, at node A what are the currents entering is I_3 is entering and here I_2 is entering what are the currents leaving I_B^-. So, $I_B^- = I_2 + I_3 = \frac{v_1}{R_1} + \frac{v_2}{R_F} = \frac{v_1}{R_1} + \frac{v_1}{R_F} = v_1\left(\frac{1}{R_1} + \frac{1}{R_F}\right) = v_1\left(\frac{R_1+R_F}{R_1R_F}\right)$, this is the expression for I_B^-.

(Refer to the slide at 17:21)

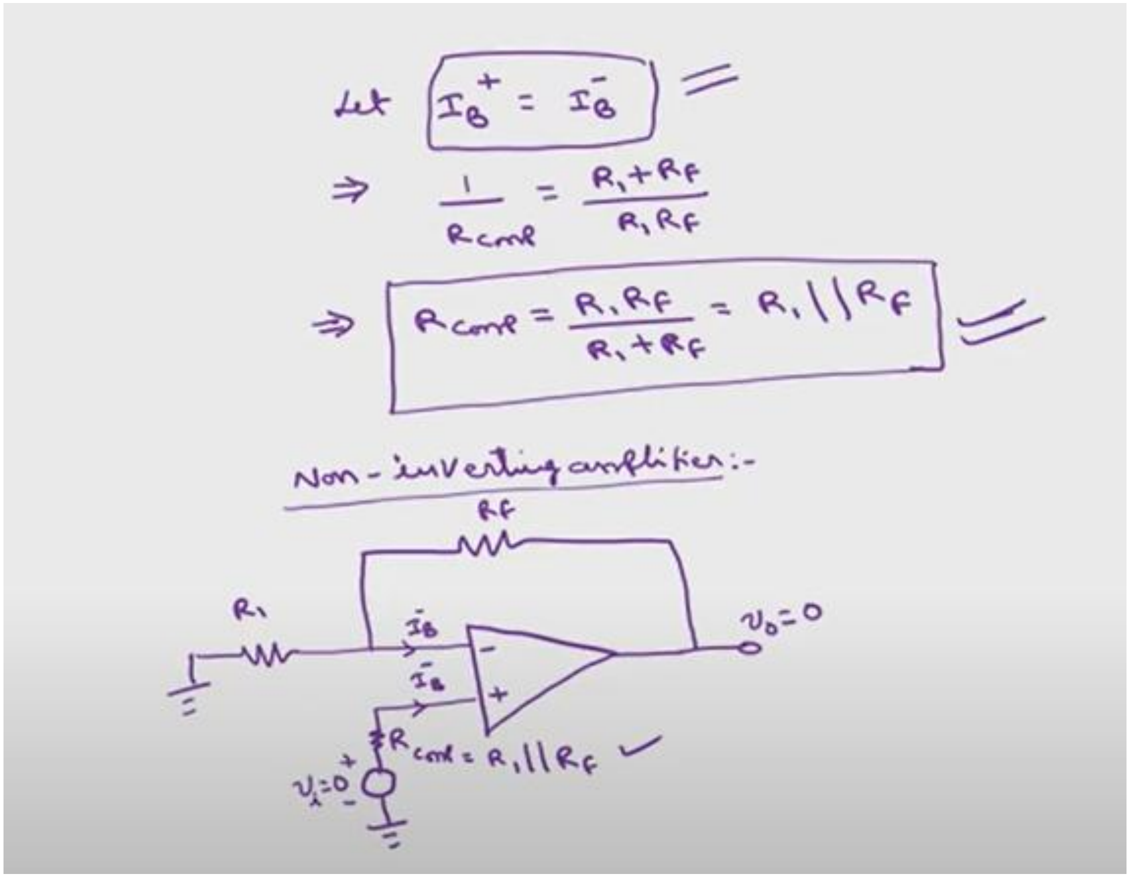


Let us assume that $I_B^- = I_B^+$, later I am going to consider the case where this $I_B^- \neq I_B^+$, but now for the sake of simplicity I will assume that this I_B^- and this I_B^+ are same. So, what is this I_B^+ is nothing, but I_1 is I_1 will flows to this one I_1 or I_B^+ is nothing, but I_B^+ or I_1 is equal to the voltage across this R_{comp} is $\frac{v_1}{R_{comp}}$. So, this I_B^- is this one this is equal to I_B^+, but what is this $I_B^+ = \frac{v_1}{R_{comp}}$. So, this v_1 v_1 at cancelled. So, what is $\frac{1}{R_{comp}}$? $\frac{1}{R_{comp}} = \left(\frac{R_1+R_F}{R_1 R_F}\right) \Rightarrow R_{comp} = \frac{R_1 R_F}{R_1+R_F} = R_1||R_F$. Here by choosing this R_{comp} is equal to parallel combination of this R_1 and R_F we can nullify the effect of input bias current provided I_B^+ should be equal to I_B^-. So, this is the case of this inverting amplifier this is inverting amplifier. Similarly, you can prove for the non-inverting amplifier also the same R_{comp}. So, the so, the compensatory circuitry for non-inverting amplifier is as follows.

So, for non-inverting the input is applied here. So, instead of simply applying the input you have to apply the input through this R_{comp} and in a similar manner you can prove that this is equal to this $R_1||R_F$. So, if this $v_A = 0$, we can say that $v_o = 0$ if $R_{comp} = R_1||R_F$ for practical op amp. So, you see about the input bias current and the corresponding effect on the output and then the compensation of the output due to the input bias current.

This we have derived based on the assumption that $I_B^+ = I_B^-$, but for a practical operational amplifier this is not possible to make this $I_B^+ = I_B^-$, because of the mismatch between the transistors.

(Refer to the slide at 21:20)



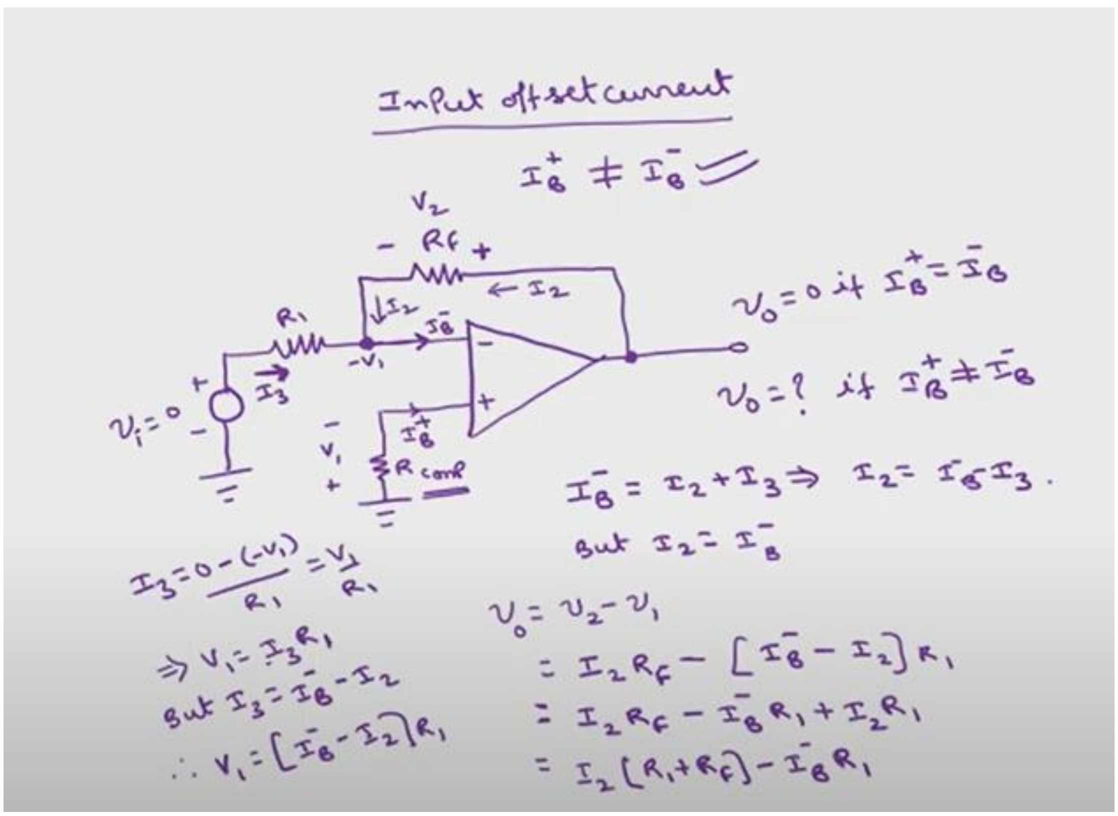
Even if you fabricate the transistor by the same manufacturer then I_B^+ and I_B^- will be different. So, if this $I_B^+ \neq I_B^-$ then what will be the effect? That effect is called as input offset current. So, the second DC characteristics of a practical op amp is input offset current. This is the second DC characteristics. So, here we will make the assumption that $I_B^+ \neq I_B^-$.

So, if you take the again the same circuit with R_{comp}, you have compensated the effect of input bias current. Now, what will be effect of input offset current? Again, I will consider the inverting amplifier the same treatment you can apply for the non-inverting amplifier also. So, this is $Z - v_1$ volts, this is R_1 this will make as $V - 0$. So, if I assume that $I_B^+ \neq I_B^-$, what is v_o even you apply R_{comp}. This $v_o = 0$, if $I_B^+ = I_B^-$, that we have derived in the previous slide. Now, what will be the output? If $I_B^+ \neq I_B^-$, this is the more practical case. So, in order to derive this v_o this is R_F, this is I_3, I_B^- KCL at this point is equal to $I_2 + I_3$. So, what is I_2? $I_2 = I_B^-$ and if you take the KVL which you have applied in the previous slide also. So, this is minus v_1, this is minus 2 plus plus v_2, this is V naught is plus 2 minus. So, $v_o = v_2 - v_1$, this you have already derived.

This is equal to what is v_2? v_2 is this value, $v_2 = I_2 R_F$ and $v_1 = I_3 R_1 v_1$ is this v_1 is from this I_3 is equal to from this $I_3 = \frac{0-(-v_1)}{R_1} = \frac{v_1}{R_1} \Rightarrow v_1 = I_3 R_1$. But what is I_3? Yes, I_3 is entering here, this current is leaving this I_2 is also entering. So, $I_2 + I_3 = I_B^-$ or $I_3 = I_B^- - I_2$. Therefore, what is v_1? IB minus this I_3 minus I_2 times R_1. We substitute that here, this $v_1 = (I_B^- - I_2)R_1$.

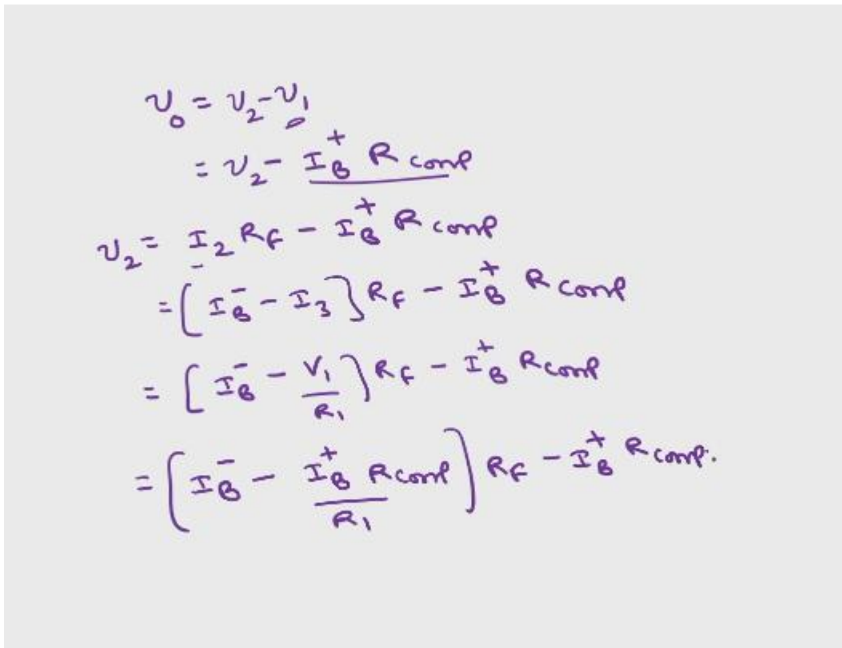
And what is I_2? So, this is equal to from here $I_2 = I_B^- - I_3$. So, if you substitute this $I_2 R_F - (I_B^- - I_2)R_1 = I_2 R_F - I_B^- R_1 + I_2 R_1 = I_2(R_1 + R_F) - I_B^- R_1$. But what is v_0 from here? Is v_2-v_1. So, this v_0 is equal to v_2 minus v_1, this $v_o = v_2 - v_1$.

(Refer to the slide at 27:36)



This is equal to what is v_1? v_1 is nothing, but $I_B^+ R_{comp}$ from here $v_2 - I_B^+ R_{comp}$. And what is v_2? v_2 is equal to $I_2 R_F$, $I_2 R_F - I_B^+ R_{comp}$ But what is I_2? I want this everything in terms of I_B^+ and I_B^-. So, I have to express this I_2 also in terms of I_B^-. So, from this KCL what is I_2? $I_2 = [I_B^- - I_3]R_F - I_B^+ R_{comp}$. This is equal to IB minus what is I_3? This I_3 is nothing, but v_1 by R_1. R_F minus $I_B^+ R_{comp}$. This is equal to I_B^- what is v_1? Is $[I_B^- - \frac{I_B^+ R_{comp}}{R_1}]R_F - I_B^+ R_{comp}$.

(Refer to the slide at 30:01)



Now here how to compensate this input offset current? So, for that I will do the analysis in the next slide. This is the R_F and this current is I_2, this is plus minus and this is v_2, this current you have called as I_1, this is I_B^+ of course, the same I_B^+ will flows through this one also.

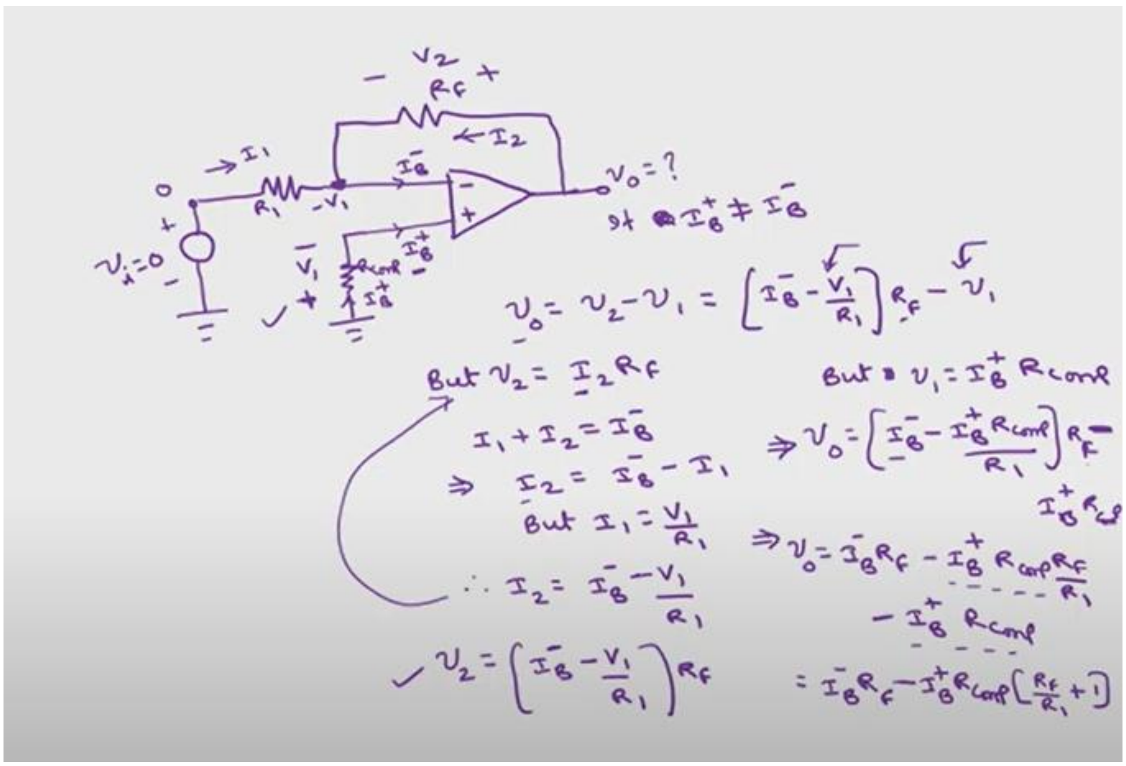
This is plus minus and this is v_1, this is R_{comp}, this is R_1, this voltage I have shown that this is minus v_1, this is v_0. So, I have to find out this v_0 if $I_B^+ \neq I_B^-$. So, for that v_0 is equal to which I have already derived. So, this is minus v_1, this is plus v_2 minus v_0. So, this is $v_2 - v_1$, but what is v_2? v_2 is equal to I will write here separately $v_2 = I_2 R_F$.

So, our intention is I have to express this v_0 as a function of this I_B^+ and this I_B^-. So, I have to express everything in terms of I_B^+ and I_B^-. So, what is this I_2 in terms of I_B^+ and I_B^+? If you apply the KCL at this point, so the current I_1 is entering and I_2 is also entering I_B^- is leaving. So, implies $I_2 = I_B^- - I_1$, but what is this I_1? This is 0 volts minus of minus v_1. So, but $I_1 = \frac{v_1}{R_1}$. So, if you substitute here I_2 is equal to $I_B^- - \frac{v_1}{R_1} = I_2$. And if you substitute this I_2 here, $v_2 = (I_B^- - \frac{v_1}{R_1})R_F$. But what is v_0? v_2 this v_2 that is $(I_B^- - \frac{v_1}{R_1})R_F - v_1$. So, this v_1 also I have to eliminate and I have to express this v_1 in terms of I_B^+ or I_B^-. So, this is clear from here that what is the relation between this v_1, but v_1 is equal to from here $V = IR$ current is I_B^+ and resistance is R_{comp}.

So, this $v_1 = I_B^+ R_{comp}$. If you substitute this v_1 here and here, you will get $v_o = [I_B^- - \frac{I_B^+ R_{comp}}{R_1}] R_F - I_B^+ R_{comp}$. If I take this v_0 is equal to I_B into R_F, I_B^- into R_F, the second term $-\frac{I_B^+ R_{comp}}{R_1}$, then minus the third term is $I_B^+ R_{comp}$. So, this $I_B^+ R_{comp}$ is common here and here. So, if you take this one, this one is equal to $I_B^- R_F$ of $I_B^+ R_{comp}$. If you take as common here this is R_F by R_1 and this is 1 and minus already have taken.

So, this is equal to $\frac{R_F}{R_1} + 1$ right. So, what will be v_0? Therefore, $v_o = I_B^- R_F - I_B^+ R_{comp} [\frac{R_F}{R_1} + 1$. So, this is equal to $I_B^- R_F$, $-I_B^+ R_{comp}$, and this will be $\frac{R_F}{R_1} + 1$.

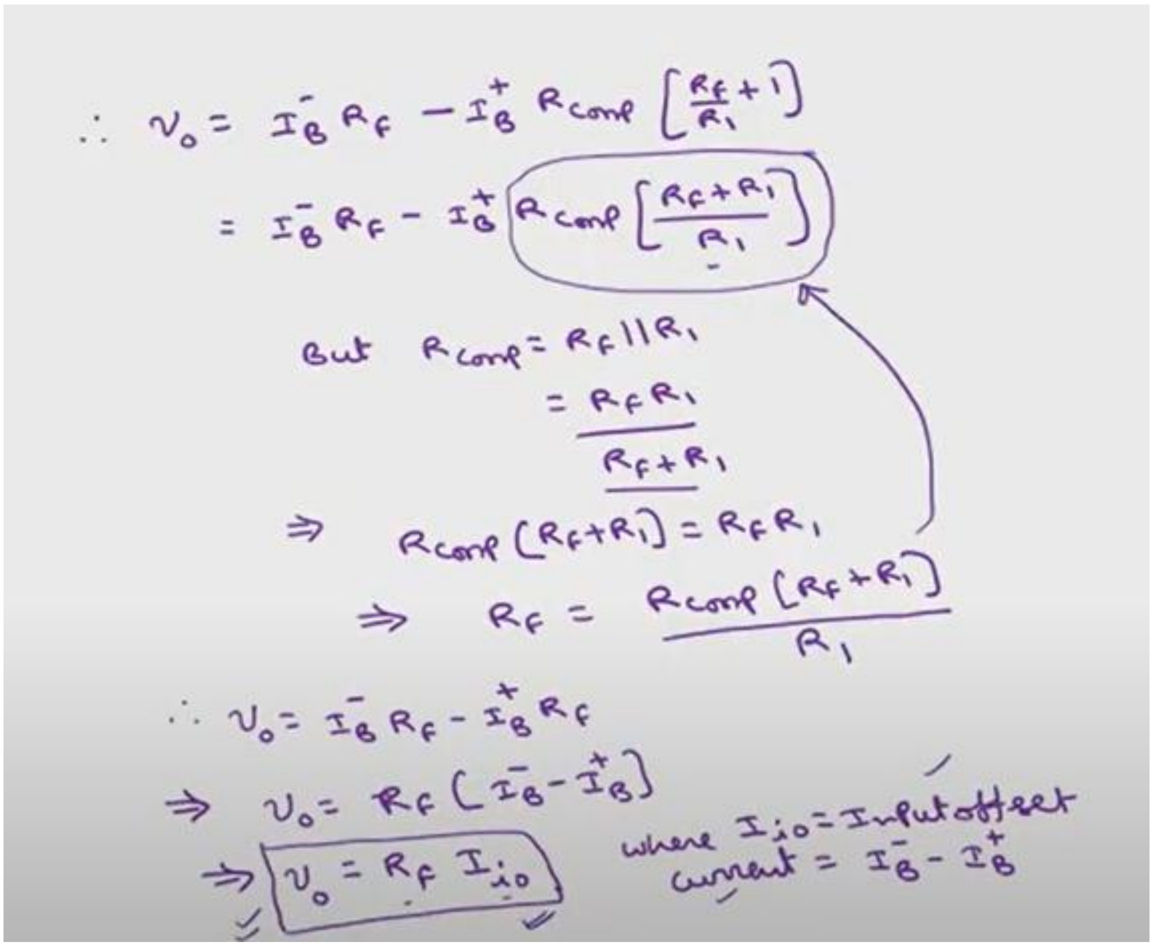
(Refer to the slide at 35:51)



But we know that R_{comp} which we have derived in the input bias current compensation R_F you have derived as R_F in parallel with R_1 that is equal to $\frac{R_1 R_F}{R_1 + R_F}$. So, implies what will be this value? Implies $R_{comp}(R_1 + R_F) = R_1 R_F$, you take this two other side $R_{comp}(R_1 + R_F) = R_1 R_F$, also implies $R_F = \frac{R_{comp}(R_1 + R_F)}{R_1}$.

This is same as this. So, this entire this thing is R_F. So, therefore, $v_o = I_B^- R_F - I_B^+ R_F$. R_F is common. So, this is equal to $v_o = R_F(I_B^- - I_B^+)$. So, this difference is called as input offset current I_{io} where I_{io} is input offset current given by I_B^+ or I_B^- minus the other value. So, you see the effect of even if you use this R$_{comp}$ resistance there will be output voltage because of this input offset current that output voltage is this.

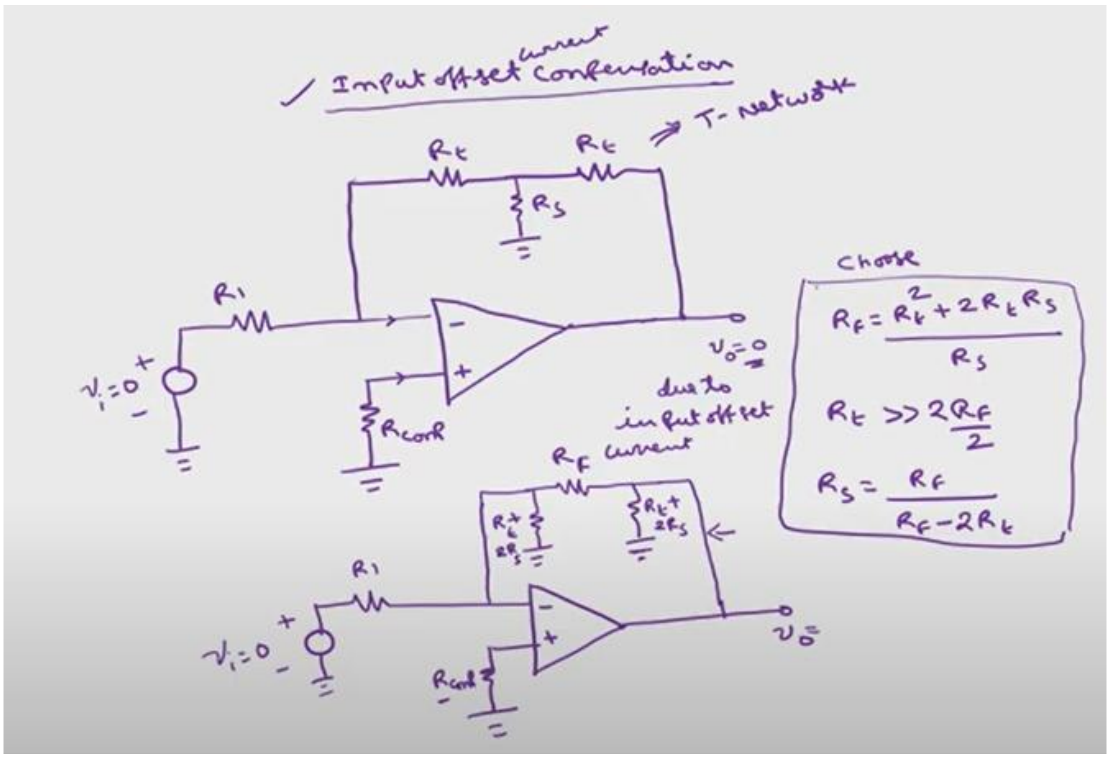
(Refer to the slide at 39:41)



This is also if I take this I_{io} is of the order of nano amps and this is of mega ohms still there will be a millivolts output voltage due to input offset current. Input bias current you can nullify by using the R$_{comp}$, but because of this input offset current there will be some output voltage which is of the order of this $R_F I_{io}$. Then how to compensate this input offset current? For this you have to use a T network in the feedback. Here of course, R$_{comp}$ will be there to compensate the input bias current when $v = 0$. So, in feedback path what we are going to do is here is there will be a T network this is R_t, this is R_t, this is R_S.

If I use this circuit then you can nullify the output voltage due to input offset current. You can make the output voltage 0 due to input offset current. Then how to choose these values of R_t and R_S? So, this is T connection we can convert this T into pi. If you convert this T into pi the resultant circuit will be this is T network. You might have studied in your circuit theory you can convert T network into pi network by using star delta conversions. This I will make as now pi network. Now this will be R_F and this will be $R_t + 2R_s$ this is also $R_t + 2R_s$. Now how to choose these values of R_t and R_S? For what values of R_t and R_S? v_O is equal to 0 due to the input offset current. So, for that first we have to go choose $R_F = \frac{R_t^2+2R_tR_s}{R_s}$. Then we will make $R_t \gg \frac{2R_F}{2}R_t$. Then we choose $R_s = \frac{R_F}{R_F-2R_t}$.

(Refer to the slide at 44:31)



So, these are the formula that we have not derived by using these relations we can design this feedback network this feedback network so that the output will be 0 due to input offset current. This is how we can compensate the input offset current and input bias current can be compensated by using R_{comp}. So, with this the output voltage becomes 0 even if this input voltage input currents are nonzero and not equal. But there is another DC characteristics which is called as input offset voltage this is input offset current and input offset voltage also there. So, what is input offset voltage and how to compensate the input offset voltage? Then third DC characteristics is input offset voltage.

This can be defined as the input difference voltage that is required to make the output 0 ok. That is even this input terminals are at this if you ground this also if you ground ideally output should be 0, but output is not equal to 0 this is the practical op-amp I have told that this output voltage is V_{OO} that is called output offset voltage. Now, we can define the input offset voltage as I have to make this input voltage nonzero value this input difference a nonzero value which will make or which will force the output offset voltage is 0. That is this you have grounded here we are going to apply v_{io} so, that V_{OO} is equal to 0 and this is called as input offset voltage. Now, clearly observe here if this input difference is 0 still there will be output voltage which is called output offset voltage.

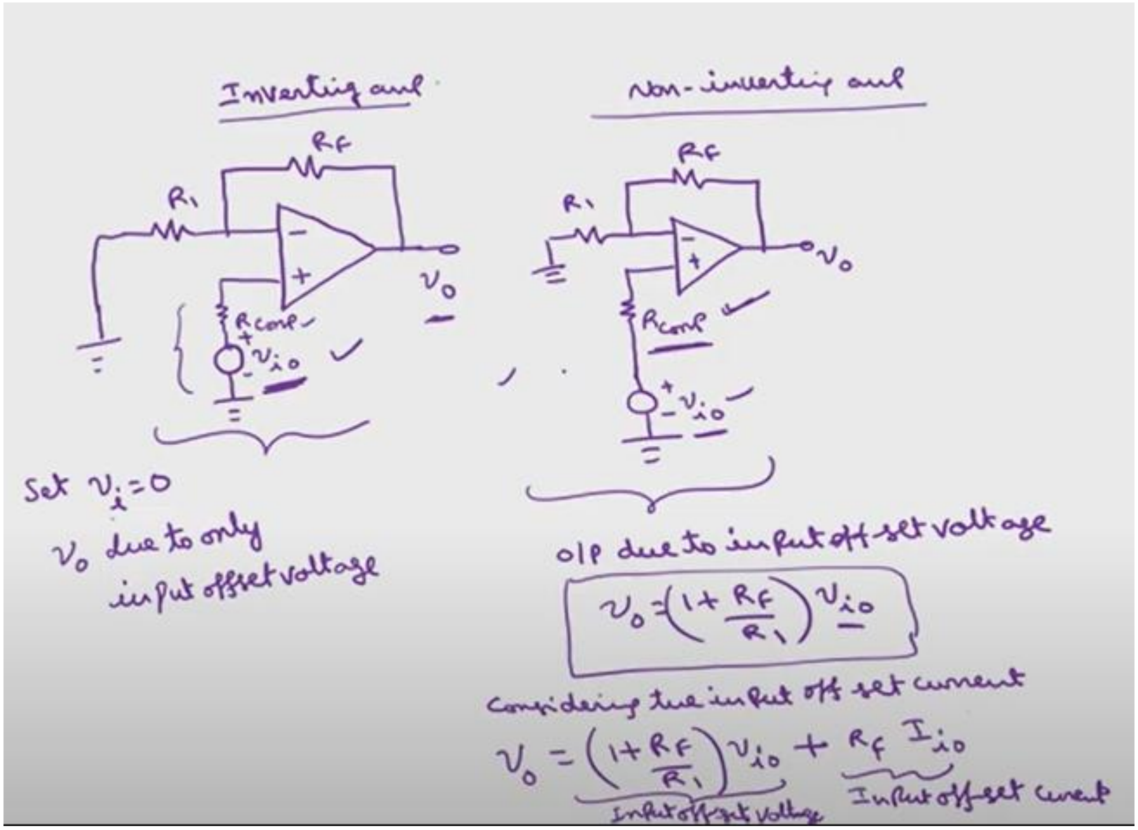
Now, if I apply a voltage of v of I_0 at the input side this will make the output offset voltage as 0 that voltage is called input offset voltage. This can be defined as the amount of input voltage required to force the output offset voltage to 0. Now, what is the effect of this input offset voltage on the output of inverting and non-inverting amplifiers? This is the inverting amplifier, here the input is applied. Here in fact, this will be grounded if you want to compensate this input bias current this will be R_{comp} and this has to be grounded, but here I am considering the input offset voltage. This is original input voltage, this is the configuration of inverting amplifier and what about non-inverting amplifier? Considering the input offset voltage without this, this is the standard inverting amplifier which you have discussed in the earlier lectures.

Now, I have included this compensation resistance to compensate the input bias input bias current and then I am considering the input offset voltage which is required to make output offset voltage of practical op-amp to 0. Now, here the actual voltage will be applied at input terminal in case of non-inverting amplifier this v_i and in addition to this there will be some offset voltage. So, these are the circuit diagrams of inverting and non-inverting amplifier considering the input as well as the input offset voltage which is required to make the output offset voltage 0. Now, if I want to find out the output voltage only due to this v_{io}, then we have to make $v_i = 0$ set $v_i = 0$ to find out the output voltage due to only input offset voltage.

Then what happens to equivalent circuit this v_i if I make as 0. So, this will be just grounded this is the equivalent circuit and if you make this $v_i = 0$, this is the equivalent circuit. Interestingly these two circuits are same this is same as this regardless of the inverting or inverting amplifier if I make $v_i - 0$ these two are same. And what will be the output due to this input offset voltage? This is nothing, but non-inverting amplifier this is also non-inverting amplifier with the gain of $1 + \frac{R_F}{R_1}$ and the input is v_{i0}. So, therefore, $v_o = (1 + \frac{R_F}{R_1})v_{i0}$. So, this is the amount of the output voltage at the output of both inverting and non-inverting amplifier due to the input offset voltage.

Now, considering the input offset voltage also input offset current also because input offset input bias current is going to be compensated by in this R_{camp}. So, this we have derived this. So, this v_o is equal to $(1 + \frac{R_F}{R_1})$ this is the contribution due to v_{i0} this is contribution due to input offset voltage. And for input offset current so, we have derived that this is the compensation this is the effect of input offset current which is $R_F i_i$ this is due to input offset current. So, this is about the output of this inverting and non-inverting amplifier subjected to two effects input offset voltage and input offset current.

(Refer to the slide at 52:31)



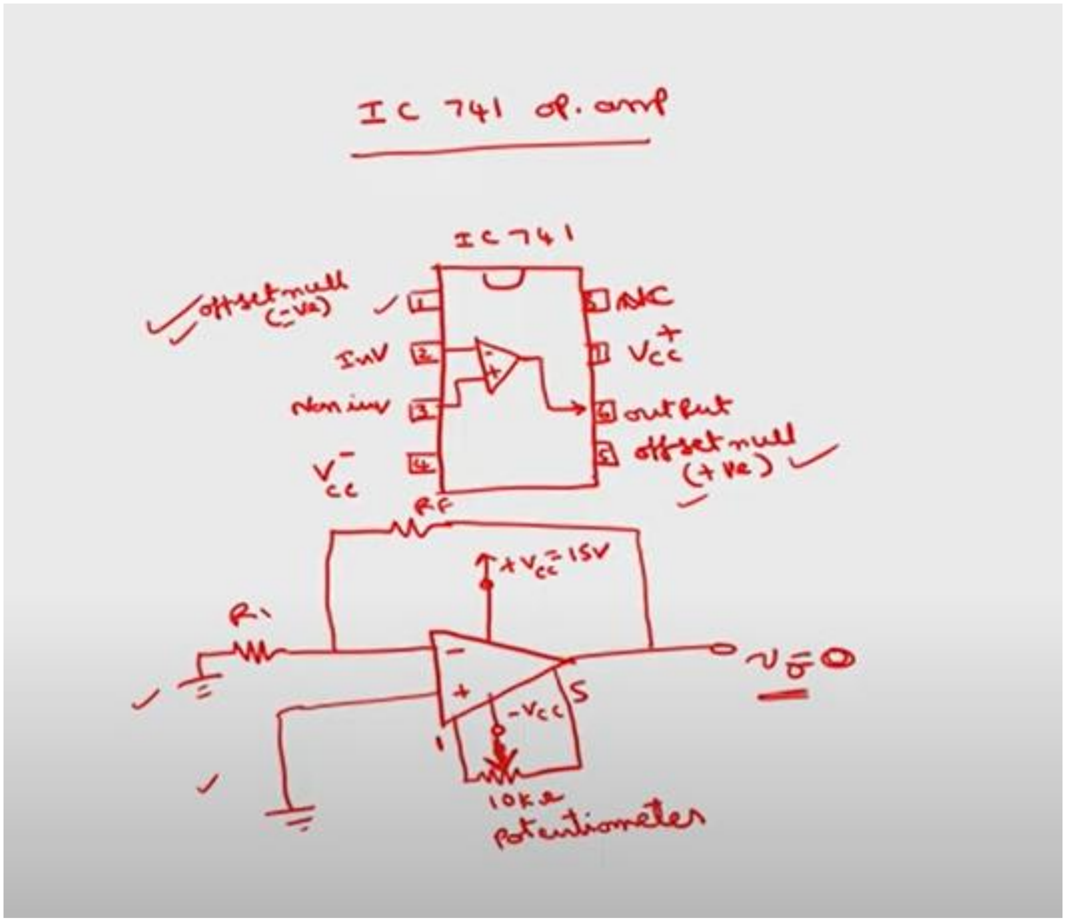
But input bias current we are going to compensate by using R_{camp} otherwise there will be a contribution of this input bias current also. So, this is about this 3 DC characteristics. So, now, how to compensate the three effects? So, for that in case of the operational amplifier say IC 741 there are two pins called offset null pins. If I take this operational amplifier 741 this is 8 pin IC you might have used in your laboratory course this is dual inlet package this is 741 IC 4 pins on one side 4 pins on other side.

This is pin number 1, pin number 2, pin 3, pin 4, pin 5, 6, 7, 8. So, this first pin is called offset null this is negative and the second one is the inverting input of op amp and third one is non-inverting this is minus this is plus and fourth one is $-V_{cc}$. So, any IC requires power supply and 5 is offset null positive this is negative this is positive this is output of op amp this is inverting input this is non-inverting input and this 7 is $+V_{cc}$ and this is no connection to make this half of the pins one side half of the pin other side. So, we require total 8 pins. So, this for the sake of uniformity this 7th 8th pin is fabricated, but this have no connection. Now, in order to compensate this all the three voltages all the three effects such as input bias current, input offset current, output input offset voltage.

What we have to do is you can take this operational amplifier either in inverting or non-inverting configuration this is $+V_{cc}$ normally of the order of 15 volts this is $-V_{cc}$ there will be potentiometer of $10k\Omega$ this is pin number 1 pin number 5 this is offset null minus offset null plus 1 5 pins. So, this is also 0. Without any input signal output should be 0, but because of the three effect that we have discussed it is input bias current, input offset current, input offset voltage output is not equal to 0 even the inputs are 0 this input are 0.

So, for that what you have to do is so, you have to connect this $-V_{cc}$ term this is potentiometer $10k\Omega$ potentiometer So, you adjust this potentiometer this wiper such that output is equal to 0. This is how we can compensate this offset voltage that is why these two points 1 and 5 are called offset null points.

(Refer to the slide at 57:41)



We can nullify the offset of this operational amplifier by just connecting a potentiometer to $10k\Omega$ potentiometer and you can vary this wiper until output is equal to 0. This is one of the technique to nullify this offset voltages. So, this is about this DC characteristics similarly a practical op-amp will be on some AC characteristics also such as slew rate and all that we will discuss in the next lecture. Thank you.