Integrated Circuits, MOSFETs, OP-Amps and their Applications
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Lecture – 16
Operational Amplifier Characteristics

Welcome to this module. So, we are continuing our same lecture and we have divided like I said into few modules; 2 or 3 first module, we have seen the characteristics of op-amp in terms of power supply, in terms of the terminals, in terms of the ideal op-amp which has infinite input impedance, infinite gain, 0 output impedance, infinite band width right.

And then we have seen the balance versus unbalance output and, balance versus unbalanced power supply also how to apply balance power supply, how do I apply unbalance supply? And whether the output is taken from the 7 and 4 or between the terminal 6 and ground if it is between 7 and 4; it is floating in 6 and ground, then we already know how we are taking the output.

Now, in this particular module what we will see is feed back in op amps all right and then further applications also

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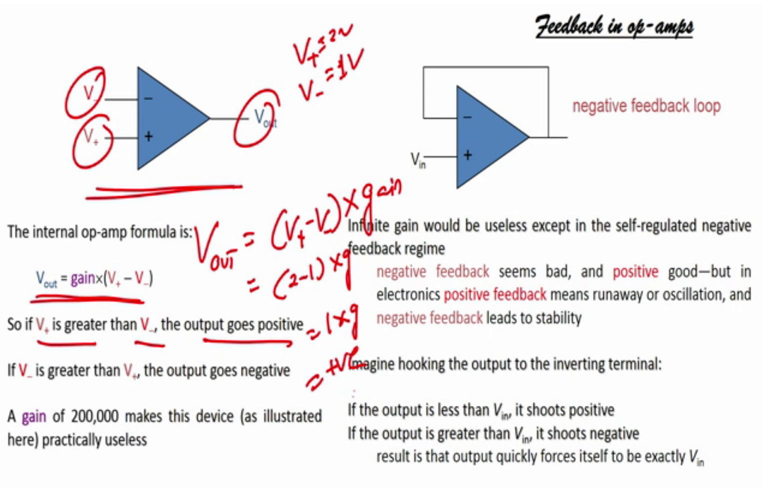

If you come on the screen what do you see is that If you have a op-amp and if it is a open loop op-amp like this, right, the internal formula of op-amp is V out equals to gain into difference of the input terminals; that means, that my V out is nothing, but difference of this; difference of this difference of what V inverting on non inverting minus V inverting into gain. So, if V plus is greater than V minus output goes positive it is correct right.

So, if I have V plus, let us say V plus equals to 2 volts V; V minus equals to 1 volt then what with my difference; difference will be 2 minus 1 into gain that will be 1 into gain. So, it will be positive correct, it will be positive, but if my; if V in; if V inverting is greater than V non inverting output goes to negative, right.

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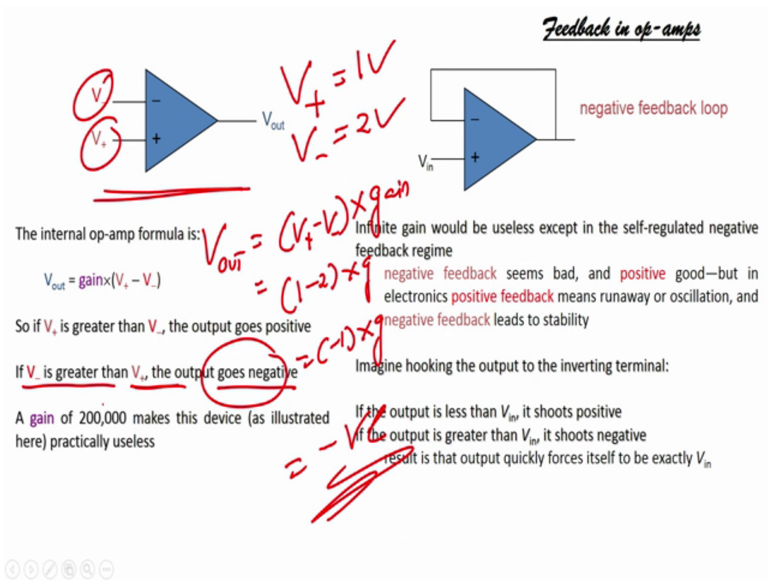

So, let us now consider that my V non inverting that is voltage in non inverting terminal is 1 volt voltage at inverting terminal is 2 volt. In this case, I have 1 minus 2 into gain that will be minus 1 into gain that will be minus whatever the output is. So, output is my negative. So, output goes to negative when my V in is greater than V positive easy very easy right.

Now, a gain of 200,000 or 250,000 makes this device practically useless right because if it is infinite gain, then how can I use this device. I cannot use this device that is why that is why the feedback is very important right because what will I do if I have gain of very high gain. What will I do if I have a extremely high gain, right, it becomes a useless for me. So, to make it useful we have to apply we have to apply feedback.

So, one of the feedback is negative feedback another feedback is positive feedback. So, let us see infinite gain would be useless except in self regulated negative feedback regime except in self regulated negative feedback regime; that means, if I apply negative feedback, then I can tweak my gain according to the registers or the components that I select and then I can use the operational amplifier in much better capability or capacity.

So, the infinite gain would be useless except in the self regulated negative feedback. So, negative feedback seems to be bad and positive feedback good right. So, if I give you a negative feedback you will be unhappy and if I give positive feedback, oh, your excellent student or somebody tells me, I am an excellent teacher, I am very happy, these are the human nature.

But in op-amp, it will not be happy if you tell op-amp, I give you positive feedback I give you positive feedback op-amp will start oscillating and we cannot control, but if I apply negative feedback op-amp works perfectly. So, it is kind of a the opposite to how we feel for us positive feedback is good negative feedback is not good negative feedback is not for op-amp negative feedback is good positive feedback is we will see the application on positive feedback as well, right, but negative feedback is very important because we can create lot of circuits using negative feedback right. So, let us see again come back to the slide.

Negative feedback seems bad positive good, but in electronics positive feedback means run away or oscillation and negative feedback means stability; stability, all right. So, immaterial or whatever feedback you get always learn something from that and try to improve right. So, for the op-amp when you talk about electronics a positive feedback will cause oscillation or generate oscillations and negative feedback will lead to stability ok.

So, imagine hooking the output to the inverting terminal like this right this is connected back to the inverting terminal and you can see here, if the output is less than V in right issues positive why because this is V in is here, right, output is let us say V in is 2 volts and output gets to 1 volt. So, 1 volt is feedback here.

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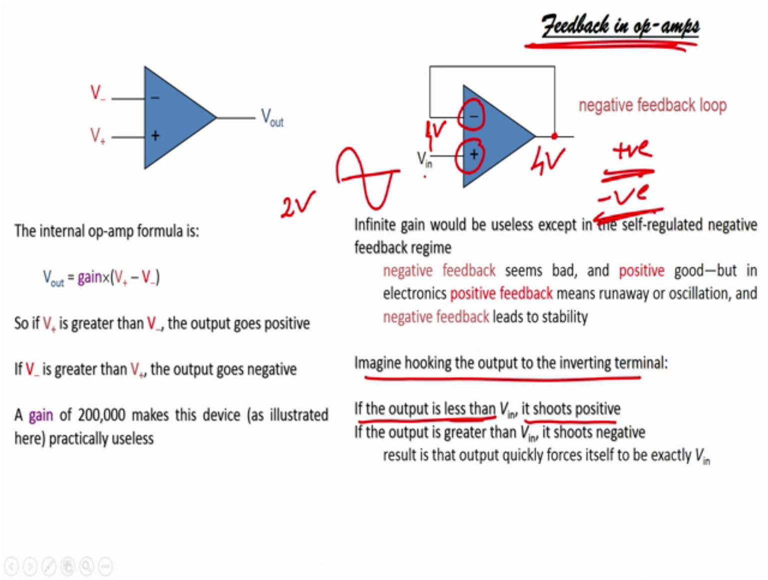

So, the inverting; this is plus V in is positive here this is non this is non inverting this is inverting; that means, at 2 minus 1 is 1. So, output will should to positive right if output is greater than the V in; that means, if I this voltage I can control right this output is there and if I apply voltage that is 2 volts, then my output will go to positive now. Now, this becomes; let us say because of my op-amp becomes 4 volts will come here, then inverting would be greater than non inverting right voltage at inverting will be more than voltage at invert non inverting. Let us try my output will go to negative, the output will go to negative right easy very easy, right, very easy.

So, if output is greater than V in it suits negative, it results in output result is that output quickly force is itself to be exactly V in result is that output quickly force is to be exactly V in very easy, right. So, now, the op-amp will do everything, it can within its current limitation to dry the output until inverting input resist V in correct a negative feedback makes itself correcting.

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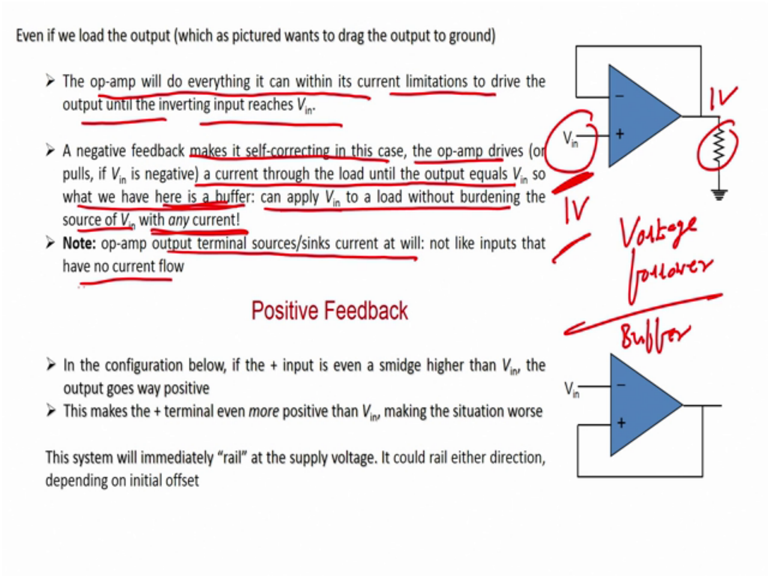

In this case, op-amp drives a current through the load until V in. So, V have here is nothing, but a buffer; that means, that what it says that the inverting this way negative feedback in this case the when we apply V in the output will try to match the input the output will try to match the input until it reaches the V in, right.

And the load current through the load the op-amp will drive the current through the load register right until the output resists its value which is input voltage V in; that means, it is nothing, but it is nothing, but a voltage follower is nothing, but a voltage follower right because whatever voltage, I apply the output will try to maintain the same voltage which is applied at the input. So, this becomes my voltage follower it follows the voltage at the input or it is also called buffer right it is also called buffer.

So, here we have is a buffer can apply V into the load without bordering V in with how with any current right op-amp output terminal sourcing at V will not like inputs at which will have no current; that means, that what we have seen in the golden rules what we have seen is that the input will draw no current right the input of the op-amp draws no current, but the output is not like this output in output terminal source and sinks current at will output can source or sink current at will right, it is not like input that it will not draw current, all right. So, you have to note this particular sentence. Now let us see positive feedback.

So, instead of negative feedback which is connecting into inverting terminal if I connect it to non inverting terminal in this configuration if positive input even is a smidge higher than V in output goes positive, it is correct right output goes positive this makes positive terminal even more positive and then V in making the situation worse; that means, there if the inverting input this one it goes slightly greater than slightly greater than V in, then the output goes positive ok.

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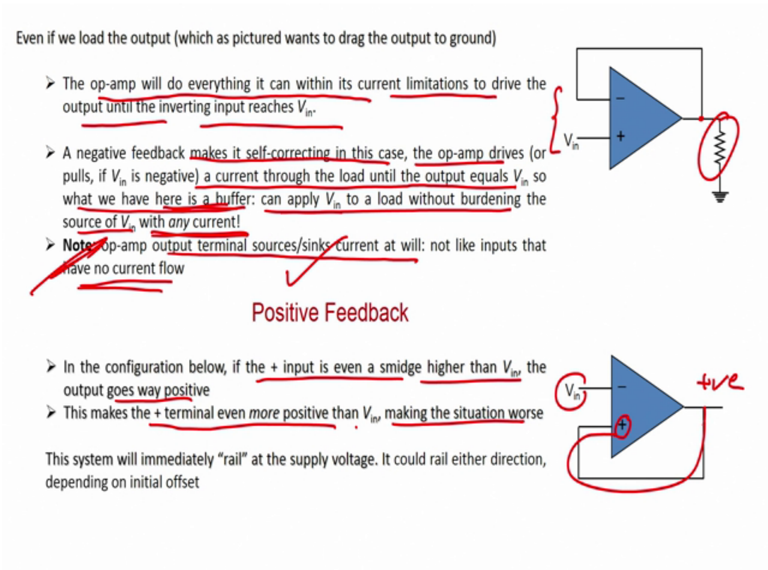

And this makes if this gives positive this makes even more positive at the input this makes even more positive at the input because now it is connected to the non inverting terminal right what, we say is that if my if my voltage at the non inverting terminal is slightly greater than the non inverting terminal my output will reach to positive.

And this positive will again; we fed to the invert non inverting terminal making it more positive right. So, ma this will make the situation worse the system will immediately rail at the supply voltage, it could rail either direction depending on the initial offset, right.

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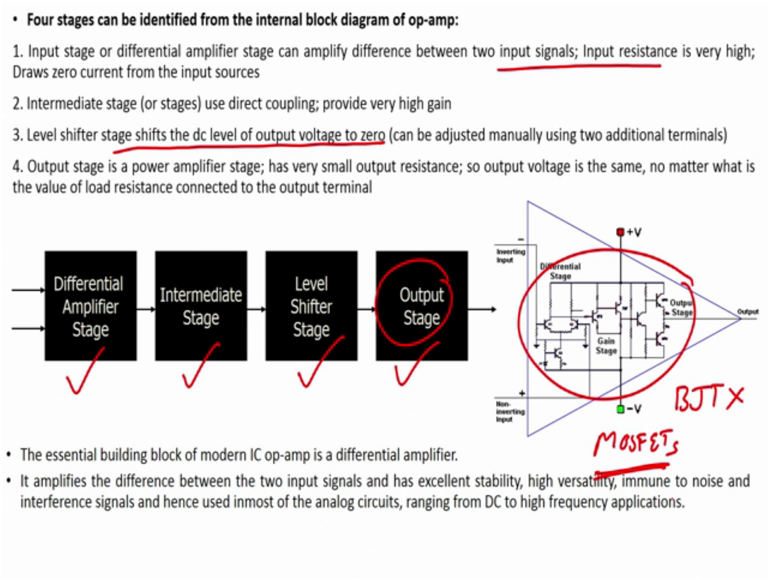

Go to the other direction depending on the initial stage now when we see the operation amplifier according the block diagram according to block diagram of the operation amplifier it has following blocks first is the differential amplifier stage, then it has intermediate stage it has a level substrates and it has a output stage 4 basic stages differential amplifier stage intermediate stage level shifter stage and output stage.

Now, when we see; what is the role of each stage, then we will understand further that how we can use the operation amplifier and what is the role of each stage of the operational amplifier when you talk about the block diagram.

So, again coming back on the screen, what we see is that we have 4 stages, we have 4 stages and the first stage input stage or the differential stage can amplify difference between 2 signals of course, because the differential stage input resistance is very high and draw 0 current from input sources correct this is what we have already discussed earlier also that this; this stage the input stage of the operation amplifier would be a stage in which we have high input impedance and it would draw no current from the input sources.

Intermediate stage used direct coupling or providing extremely high gain level shifter stage this level shifter stage will shift the DC level at the voltage to 0, right because we know do not require any output with any the DC level. So, DC level would be ca close to 0 level shifter will shift DC level to 0 and this can be adjusted by nearly by a distal 2 terminals bearing 2 terminals, we can adjust it manually we will see output stage in a power amplifier stage in a power amplifier stage has very small output resistance right. So, the output voltage is same no matter what is the load value it can be also a voltage follower it can be also a buffer and also a buffer.

So, if you see here if you see here a single op-amp will have internal circuit which is shown in the schematic; however, mind it that now most of the now op amps they use MOSFET and not BJTs; BJTs are seldomly used; BJTs are seldomly used most of the circuit, you will find use of MOSFETs.

So, that is the very important to understand very important to remember now the essential building block of border I c is a differential amplifier it amplifies the difference between 2 signals has excellent stability high versality high versatility immune to noise and interference signal and hence in most of the analog circuits ranging from DC to high frequency applications the it is used the differential amplifier is used differential amplifier is used in most of the most of the application when we talk about the operational amplifier, all right, easy; easy to understand very easy, right.

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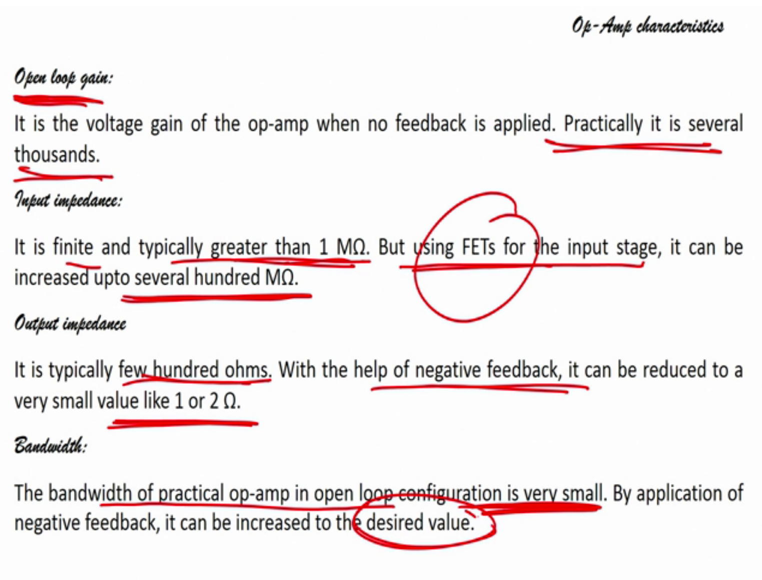

Now, let us come to the come to the characteristics of an operational amplifier op-amp characteristics we have seen this already that open loop gain it has voltage gain of op-amp when no feedback is applied why that is why it is open loop no feedback is applied and practically it is several 1000s, several 1000s we have seen right that in practical op-amp input impedance. Now input impedance is infinite and typically greater than one mega ohm, but using FETs for input stage it can be increased to several mega ohms you see when we use field effect transistor the input impedance will increase to several 100s of mega ohms.

Output impedance, it is typically under few hundred ohms with the help of negative feedback it can be reduced to one or 2 ohms very small way hmm band width band width of practical op-amp is an in open loop configuration is very small band width is extremely small by application of negative feedback, it can be increased to the desired value right band width is very small in case of op amp, but if I apply a proper negative feedback we can increase the fed. We can increase the band width we can increase the bandwidth.

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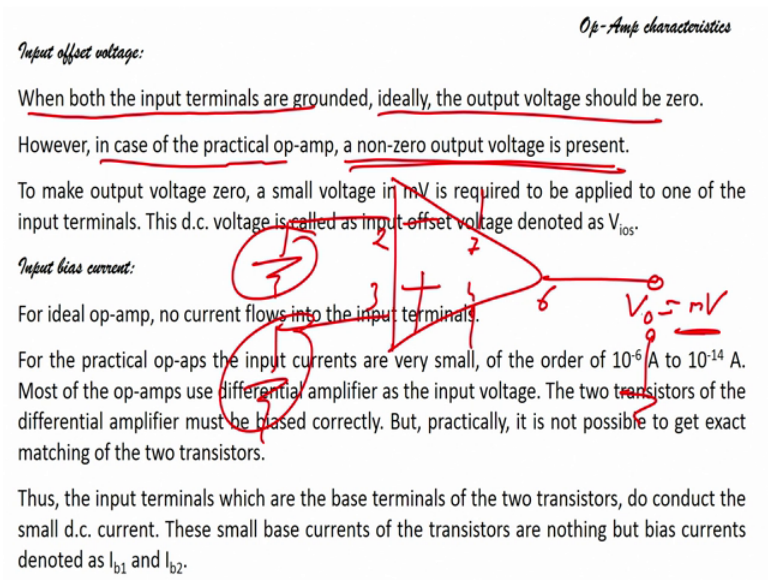

Now, let us talk about very important point which is the input offset voltage umm input offset voltage. So, what is input offset voltage? Let us see now when both the terminals both the input terminals are grounded both the input terminals of what both the input terminals of op-amp both the input terminals of op amps are grounded ideally the output voltage should be 0 that is correct right, if I take the operation amplifier and if I say that my inverting and non inverting terminals both I am grounding both I am grounding the output voltage should be V o should be 0 correct this is what I am assuming because I have grounded this I have grounded this no voltage at the input output should be 0.

However in case of practical op-amp a non-zero output voltage is present. So, if you do the similar experiment what you will see that some voltage which is in terms of millivolts, you will find that output terminal of the op-amp right if you write like this 2 3 6, 7, 4, right you will see output at the op-amp to be of few millivolts, but not 0, but not 0

So, right what we are saying let us see once again when both the input terminals are grounded ideally the output voltage should be 0; however, in case of practical op-amp a non-zero output voltage is present non-zero output voltage is present to make the output voltage non-zero small voltage in millivolts is required to apply to one of the input terminal this DC voltage is called the input offset voltage denoted by V ios very important very important.

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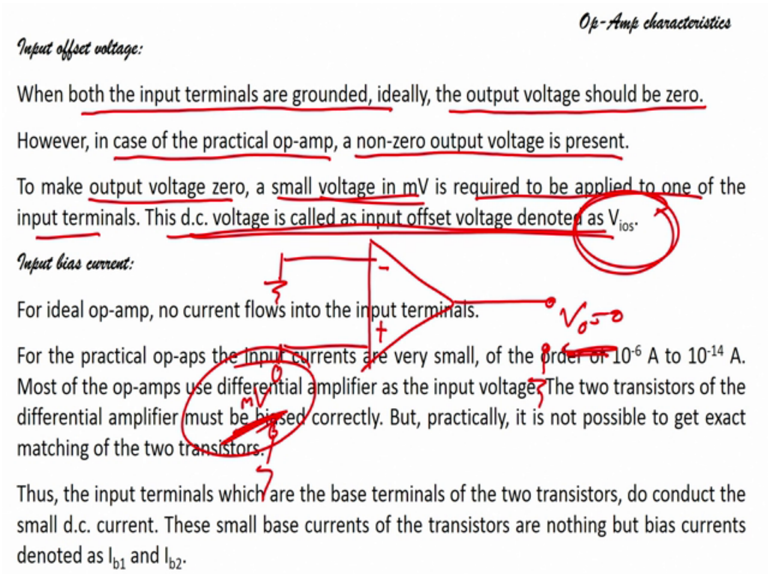

So, what we are saying that because the output when we ground the inverting and non inverting terminal because there is some output of millivolts, we have to apply we have to apply a small voltage at either inverting or non inverting terminal at either inverting or non inverting terminal to make the output voltage 0, you got it.

So, this small voltage that we are applying this small DC voltage is our input offset voltage is called input offset voltage is denoted by V ios, V ios, all right, good.

So, what is the next point next is input bias current now what does this mean we have seen input offset voltage now it comes input bias current what is input bias current. So, for an ideal op-amp for an ideal op-amp no current flows into input terminals we have seen right golden rule no current can flow into the input terminals for an ideal op-amp for practical op amps for practical op amps the input ca currents are very small are very small it is like not no current you see here it is very small of order of 10 raise to minus 6 or 10 raise to minus 14; 10 raise to 10 raise to minus 6 to 10 raise to minus 14 ampere, right.

Most of the op amps use differential amplifier as a input voltage the 2 transistors of the differential amplifier must be biased correctly, but practically it is not possible to get exact matching of those transistors. So, if I use the differential amplifier you will see that there is a transistor one and there is a transistor 2. Now this transistor should be biased properly biased correctly, right.

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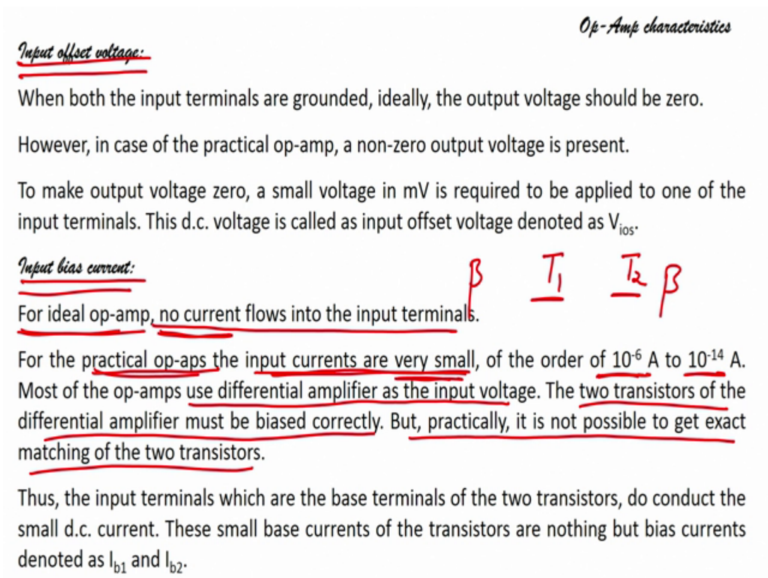

So, but because of the manufacturing there will be a small change in your beta the small change in beta between T 1 and T 2 and due to that you cannot bias the transistor T 1 and 2 correctly and because of which there is a small input current that can flow into the op-amp does the input terminals which are base of the terminals of the 2 transistors do not current small DC do not conduct small DC current. This small base currents of transistors are nothing, but the bias currents denoted as I b 1 and I b 2 whereas, repeat I think, I made as wrong statement actually the input terminals which are the base terminals of the 2 transistors do conduct do conduct.

Do conduct small DC current. So, when I apply the; when I see that in case of ideal operation amplifier.

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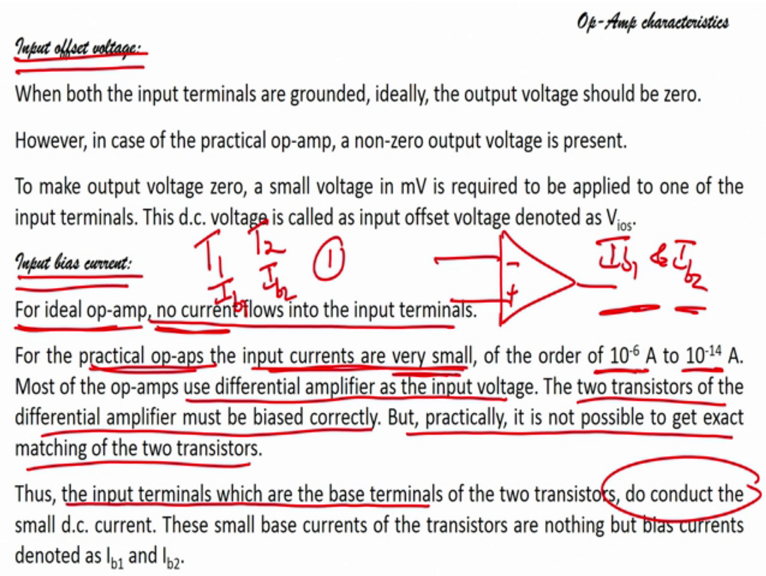

The input draws no current right the input draws no current, we have seen that, but in case of practical op amps you will see that the input draws some amount of current that the small current is because we cannot bias the 2 transistor in the differential stage which is my first stage of the operational amplifier there are 2 transistor in differential stage the 2 transistors, I cannot bias currently because I cannot bias correctly, what I see is that the base terminal of the 2 transistors will conduct some amount of DC current and this small DC current that it conducts the transistor one is conducting small amount of DC current and 2 is conducting some small amount of DC current this current is denoted by I b 1 and I b 2, I b 1 and I b 2, all right, I b 1 and I b 2.

This is my this is my bias current this is my these are these are small these are nothing, but my bias currents I b 1 and I b 2 you got it you got it easy right let me repeat once again let me repeat once again because this is very important input bias current input offset voltage very important. So, now, let us see for ideal op-amp, no current flows into input terminals right no current flows input terminals, but when you see that in actual op-amp, in practical op-amp, the current would be small- small in the sense that there is no current is or correct it will be 10 raise to minus 6 to 10 raise to minus 14 ampere.

Now, why this current flows is because at the first stage of the operation amplifier we are using differential amplifier whereas, the differential amplifier; that means, you are using 2 transistors when you are using 2 transistors, then we have to bias these 2 transistor correctly, but practically it is not possible to bias perfectly.

Due to this the base of this transistor will allow or will conduct small DC currents and this base current we are saying I b 1 for transistor one I b 2 for transistor 2 and this I b 1 and I b 2 will be your input bias current this will be your input bias current. Now you understood it is easy right it is easy.

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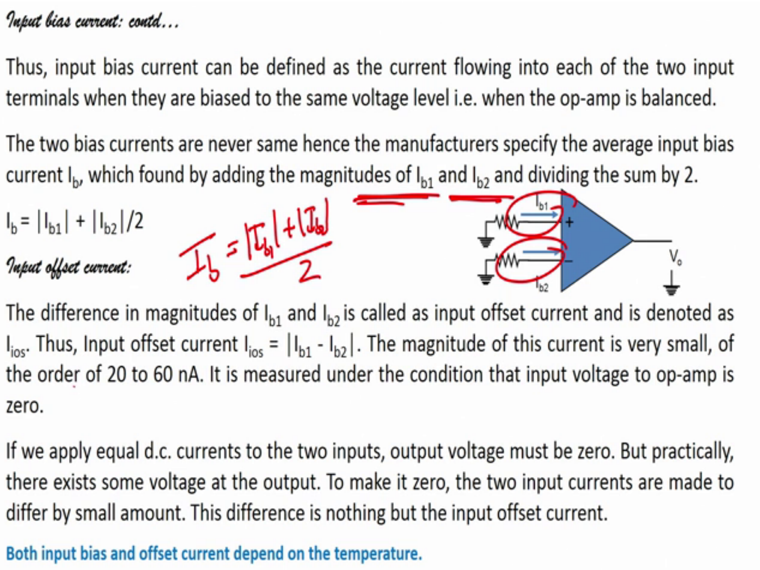

Now, 3 thus the input bias current can be defined as the current flowing into each of the 2 input terminals, thus the input bias current can be defined as the current flowing into each of the 2 input terminals when they are biased at the same level when they are biased at the same level that is when the op-amp is balanced, all right.

So, if I have you can see here you can see here right if my if I do this kind of connection if I correct my circuit as shown in schematic then my op-amp is balanced, but still there is small amount of current flowing into the non inverting and inverting terminal that is generated by I b 1 and I b 2, right and this 2 bias currents are never same hence average input bias current I b which can be found by this particular formula we can find the input bias current.

So, what does that mean what does that mean that if I have I b 1, if I have I b 2 which is small amount of current present right small amount of current present this is because the bias currents can never be same, right.

Hence, what how can we find what is the input bias current? We can find input bias current by taking mode of I b 1 plus mode of I b 2 divided by 2 divided by two. So, this is how I can find my average input bias current; that is how can I find my average input bias current, all right.

Now, let us see one more term; what we have seen until now, input offset voltage, then we have seen input bias current. Now, let us see input offset current input offset current alright.

So, what is it input offset current the difference in magnitudes of I b 1 and I b 2 is called input offset current; so, easy right.

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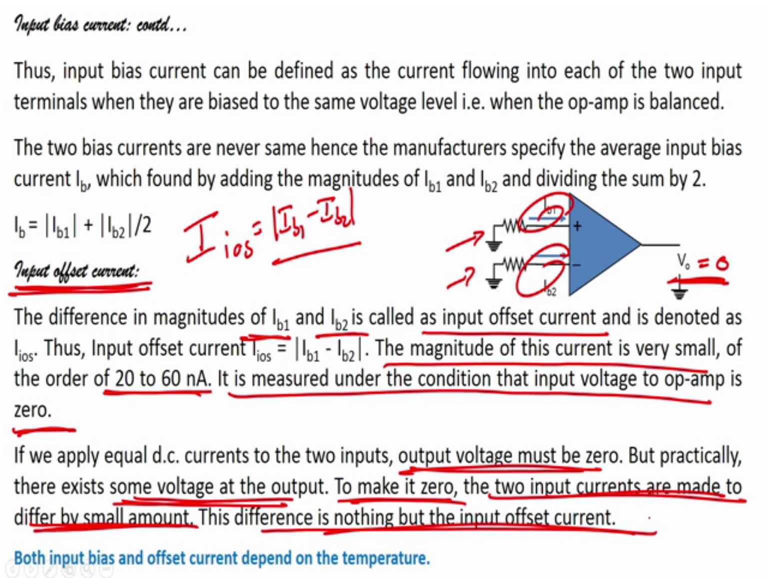

So, in this case, I b or input offset current. So, I am denoting input offset current by I i o s is nothing, but I b 1 minus I b 2 mode of I b 1 minus I b 2 the magnitude of the current is very small of order of 20 to 16 ampere. It is measured in the condition, a input voltage of the op-amp is 0, right. So, input offset current we can measure when we to consider the condition that input op voltage the op-amp is 0.

So, what do we see input bias current if we want to find out the formula is I b equals to mode of I b 1 plus I b 2 divided by 2, if we want to find input offset current the formula would be I b equals to I b 1 minus I b 2 absolutely a more of I b 1 minus I b 2. Now let us come back to the screen if we apply equal DC currents if we apply equal DC currents to that 2 inputs output voltage must be 0, right; that is correct, but practically there exist some voltage at the output to make this to make it 0 the 2 input currents are made to differ by small amount this difference is nothing, but your input offset current, all right.

What does it say that if I apply equal DC currents to the 2 inputs my output should be 0 right this is correct, but practically there is some voltage at the output, there is always some voltage at the output you see ground; ground an output will have some voltage. So, make this voltage 0 to make this voltage output voltage equal to 0 right the 2 input currents are made to differ by small amount this current and this current are made to different by small amount that difference is nothing, but my input offset current difference is nothing, but input offset.

Both input bias and input offset current depends on the temperature input offset current and input bias current both depends on what temperature all right that is another thing we have to remember is that input bias current input offset current also depends on the temperature also depends on the temperature.

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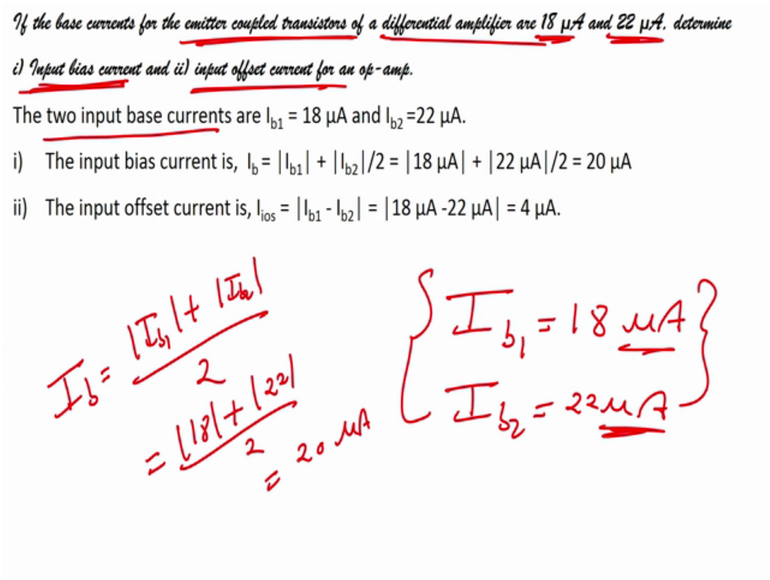

Now, let us see further let us see further an example an example. So, what is the example? So, if the base currents of the emitter couple transistors of a differential amplifier are 18 microampere and 22 microampere; that means, it is given by I b 1 equals to 18 microampere it is given that I b 2 equals to 22 microampere right and what we are asked determined first input bias current.

Second input offset current if I am asked to find this how can I find this the 2 input base currents are given like this right now I know input bias current what is the formula? Formula is very simple I b equals to I b 1 plus I b 2 mode of I b 1 plus I b 2 divided by 2 this is equals to 18 plus 22 by 2 is nothing, but twenty microampere why because everything is micro easy; so easy, right.

But if I want to measure input offset current then it becomes even easier because formula becomes even easier just subtraction of I b 1 and I b 2, I b 1 and I b 2, right. So, what we write this is I b 1, I b 1 is 22 microampere.

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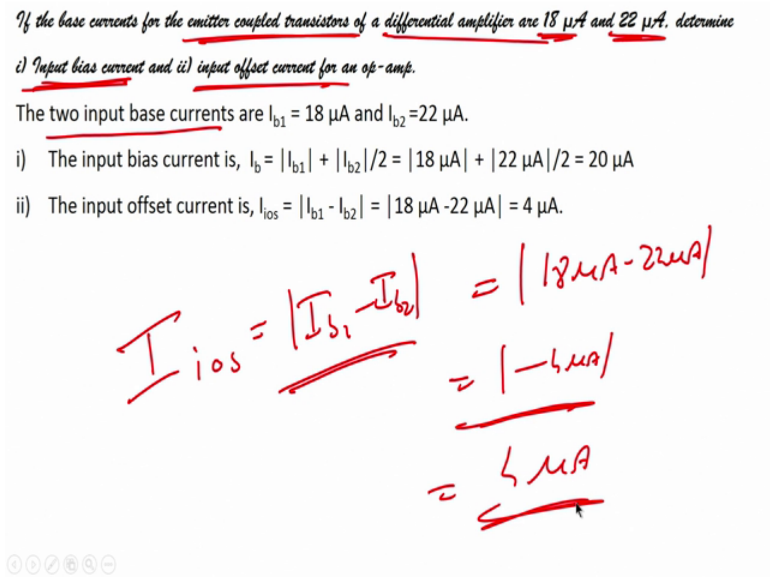

Sorry, I b 1 is 18 microampere, I write I o s equals to I b 1 minus I b 2, you can see mode right, this is 18 microampere minus 22 microampere, this will be minus 4 ampere, it is mode. So, answer is 4 microampere answer is 4 microampere, right.

This is how we can calculate this is how you can calculate what is the input offset Vo current and what is the input bias current given that you know the values of input off, you know the values of current flowing to the base of the transistor to the base of the transistors, all right, this is one example what we have discussed.

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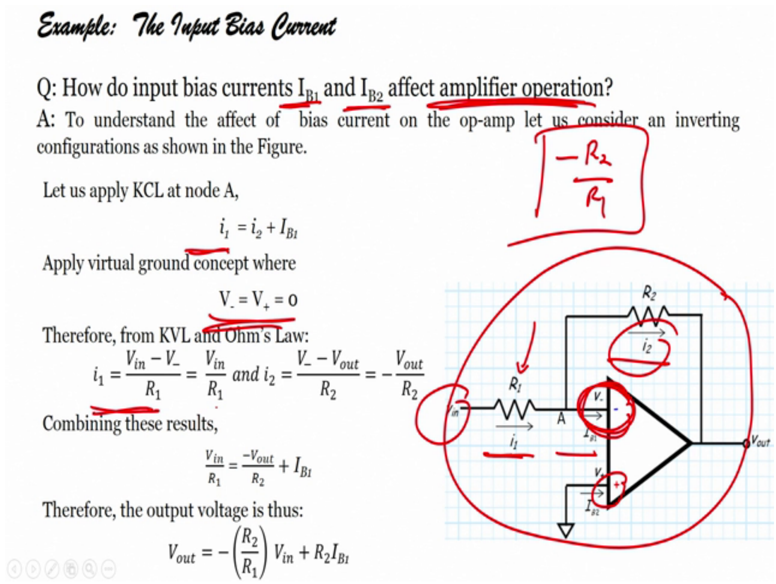

Let us see one more example, let us see one more example and the example is how do input bias currents I b 1 and I b 2 affect the amplifier operation if this is the question right to understand, to understand the effect of bias current and op-amp, let us consider a inverting configuration.

So, this is inverting amplifier, we will discuss this inverting amplifier in the subsequent lectures, right. Now you just see that this is an inverting amplifier. Now if I apply a Kirchhoff's voltage law I have i 1, I have resistor R 1, R 2, right and the formula for gain for inverting amplifier is R 2 by R 1 a gain of inverting amplifier is minus R 2 by R 1 the current flowing into the from R 1 is i 1 from R 2 is i 2, this is I b 1, this is I b 2 inverting and non inverting terminals of the operation amplifier.

Now, if I apply Kirchhoff's voltage law, what will I have i 1 equal to i 1 equal to. So, I have to go in this particular way this one this one and this one; i 1 equals to i 2 right i 2 plus I b 1, right applying virtual ground if I there is another concept called virtual ground we will see; we will have virtual ground means whatever the whatever my non inverting terminal if it is grounded my inverting terminal is also considered as the ground it is virtually ground now we will see about this concept right now V minus equals to V plus equals to 0 therefore, from k V l Kirchhoff's voltage law and ohms law we know that i 1 equals to nothing, but i 1 equals to V in minus V minus right divided by R 1 this is nothing, but V in by R 1 V now because here V minus you see the because of the co concept of virtual ground this terminal will be considered as ground, right.

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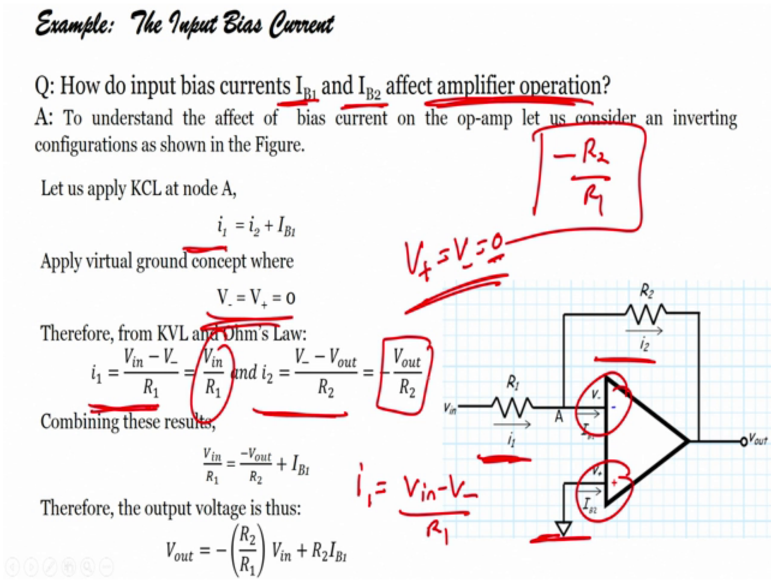

So, V plus equals to V minus equals to 0 right because V plus is 0 here. So, V minus is also 0. So, if I want to write i 1; this particular formula then how can I find i 1 equals to V in minus V inverting by R 1 what is V inverting V inverting is 0. So, I will have V in by R 1 same way i 2 equals to i 2 this one, right, V inverting minus V out by R 2 is nothing, but V out by R 2 right now combining these results if I combine these results where V in by R 1 equals to minus V out by R 2 plus I b 1 right because we as of substituting value of i 1 and i 2 that we have found here right therefore, the output voltage is V out equals to minus R 2 by R 1 into V in plus R 2 I b 1 you see the output voltage is minus R 2 by R 1.

Now, what I say initially in this starting of this particular problem that the gain of the amplifier gain of the inverting amplifier is given by minus R 2 by R 1.

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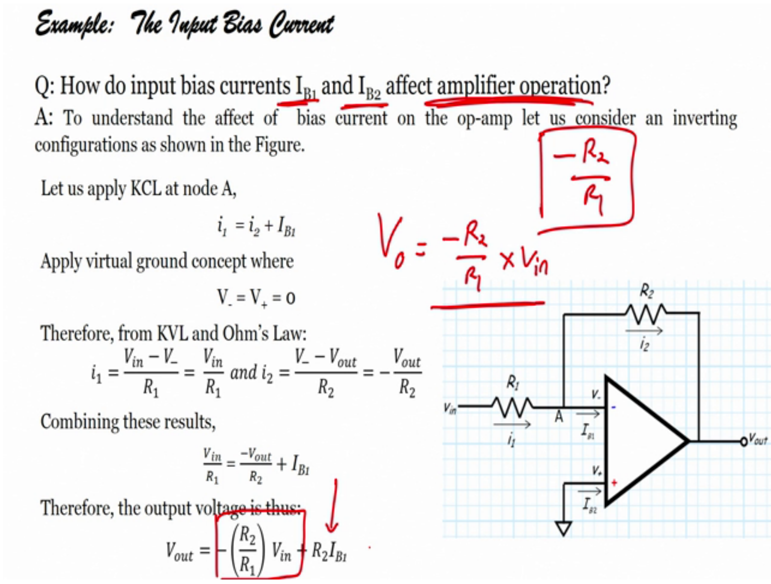

So, V out if I write V out is nothing, but minus R 2 by R 1 into V in into V in. So, this we can see here also minus R 2 by R 1 into V in.

But, then there is one more term R 2 I B 1 you see 3 is one more term R 2 I B 1 and if I B 1 is 0, then the results reduces to expanded inv expected inverting amplifier, right.

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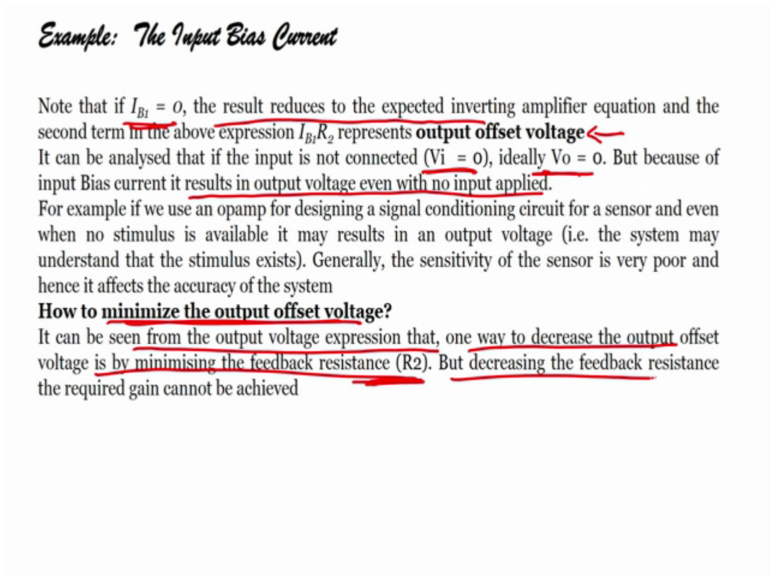

If I have I b 1 equals to 0, then I get this formula which makes sense, but if it is not then there is a change or there is the output voltage output voltage has to rely on my I b 1 because the I b 1, it will change the output voltage rather than it will be minus R 2 by R 1 into V in, it will be minus R 2 by R 1 into V in plus R 2 I b 1. So, this I b 1 into R 2 represents here input offset voltage it represent here input offset voltage, right.

It can be analyzed that if the input is not connected right V I equals to 0 ideally V equals to 0, but because of input bias current if the results in proved voltage even when there is no applied no input is applied, right. So, the point is; how can I minimize this output offset voltage how can I minimize this output also right. So, what we see is that we are going to see from the output voltage expression that one way to decrease output voltage is by minimizing the feedback resistance R 2, but decreasing the feedback resistance the required gain cannot be achieved, but decreasing resistance the feedback resistance the required gain cannot be achieved, right. So, we have to understand that we have to consider the effect of I b 1 only when I b 1 is close to 0 then we can have value which is our desired value all right.

So, what we will do is we will stop at this particular point, if it is a input bias current and in the next module, we will see further applications or further characteristics of operation amplifier till then you all take care read again, once what whatever we have seen in this particular module and in the next module.

We will see; how can we understand the other characteristics of operation amplifier which are the 0 input current virtual ground, we have just discussed virtual ground concept right over here, right.

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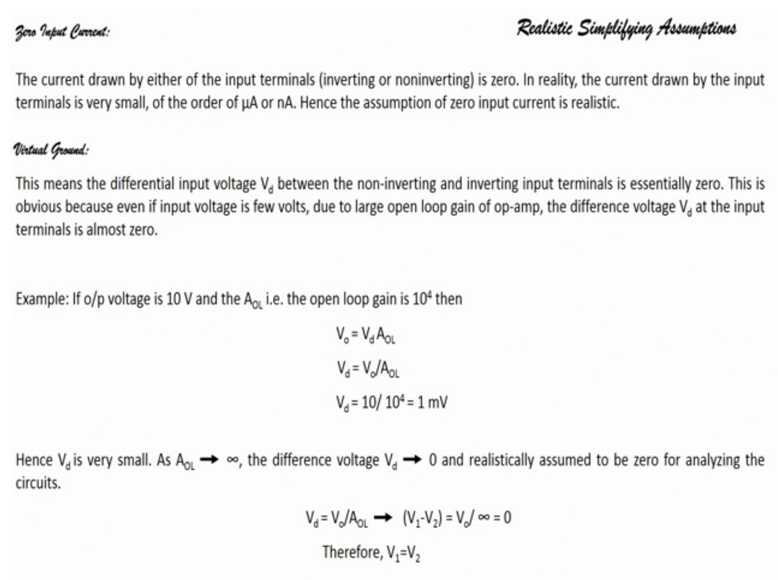

So, we will see this concept in the next module. So, that you can understand further of what is this inverting amplifier how the virtual ground come into picture I took an example which is little bit tricky suddenly in middle of this because you may or may not have idea of how exactly operational amplifier works or how the inverting amplifier works or how the virtual grounds comes into picture.

So, we will see these concepts we will see these concepts is just to tell you that input bias current is very important input offset current is very important input offset voltage is very important because these all things we have to use and we have to make the output voltage balance that is output voltage should be 0 when we our inverting and non inverting terminals are grounded then only our op-amp is balanced then we should use it for further application, right.

So, in when you design the circuit you make sure that you are you are output voltage is 0 when your input terminals are grounded. So, we will see in the next module, the further parameters of the op-amp, till then, you take care, I will see you in the next module, bye.