Integrated Circuits, MOSFETs, OP-Amps and their Applications
Prof. Hardik J Pandya
Department of Electronic Systems Engineering
Indian Institute of Science, Bangalore

Lecture – 15
Introduction to Operational Amplifiers

Welcome to this particular module. And here actually this is our next class. So, next lecture in fact, and in this lecture we have we will have two modules; and both the modules will focus on op-amps all right. So, now, we have seen how you can design and integrated circuit right which is the example of a MOSFET and the same technology is used for designing the circuit as well. So, for once you know the process to fabricate the MOSFET, you will know the process for fabricating rest of the devices all right. So, we started with basics and introduction of monolithic is if you remember in the first class, then we moved on to how to make the op-amp, how to make the MOSFET, and then we have also seen some characteristics of a enhancement type, depletion type MOSFET right. We have solved a one or two problems for the MOSFET.

Now, let us see what are the operational amplifiers right. And I have prepared a set of experiments for you guys which I will show is a part of this particular course. So, you know how we can actually use this operational amplifier ok. So, today let us see how we can use the operational amplifier. First of all, we should understand how the operational amplifier works, and what are the characteristics of the operational amplifier. So, when you talk about operational amplifier like we have discussed earlier also, it is used to perform several operations right; it is used to perform summing there is summer, it can be used to perform integrator, it can be used to perform differentiator right it is also amplifier if you use proper feedback. It can be made oscillator if you use another kind of feedback. So, we will see several applications of op-amp as well ok. So, to start with let us see what is op-amp and what are its characteristics right.

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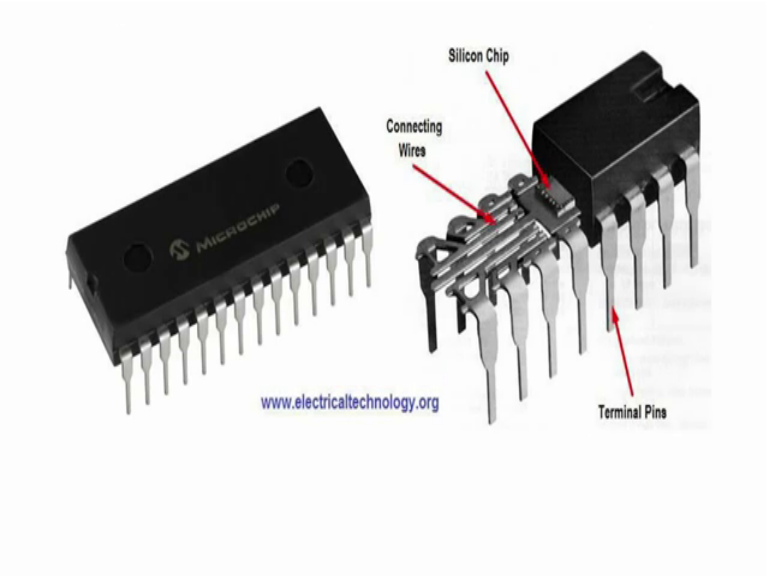

And if you remember we have seen this IC earlier also right. Now, you know that how this how this chip or what is there within the silicon chip. And if there are a lot of transistors at least you know how we can fabricate one transistor, one transistor that is your MOSFET. So, when you fabricate one transistor, you can propagate millions of transistor in the same process right. Whether you have everything one MOSFET or you are evaluating ten MOSFETs the process remains the same right process remains the same. Now, when you talk about operation amplifier you should know little bit history of operational amplifier how it was emerged, and how it was invented and now what we are using or what kind of op-amps we are using all right. So, we have already discussed this particular point. So, we I am not going into detail about this.

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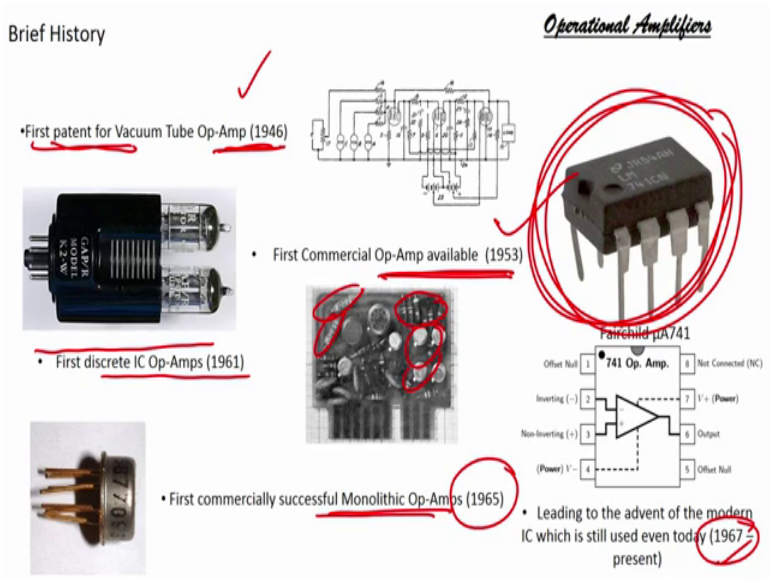

But if you see the brief history of operational amplifiers the first pattern of for vacuum tube op-amp was in 1946, 1946. In this, the op-amp was made out of vacuum tube ok, vacuum tube. Because all the functions earlier, if you see the transistors if you see the other electronic components earlier vacuum tube technology was used. And slowly with the advancement of technology, we came to the present technology which is our IC.

So, in the next one was first commercial op-amp which was available in 1953. So, the first patent was in 1946; the first commercial op-amp, it looked like this you see here and it was available in 1953, 1953. This was the first commercial op-amp how it looked like. Now, if we move to further then discrete IC discrete IC based op-amps in 1961, you say discrete IC we can see here some resistors, you can see other components, you can see here some transistors right. So, discreet IC based op-amps was first invented in 1961 ok. So, we started from 1946, we reached to 1961.

Now, first commercially monolithic op-amp, first commercially successful monolithic op-amp was found in 1965, 1965 ok. This was the first time when monolithic ICs or monolithic operation amplifier was available commercially, and it was successful. Then in 1967, 1967 we got the first op-amp which looked like this which currently also we are using the same operation amplifier mu A741 by Fairchild by Fairchild. So, leading to adventment or advancement of the technology which is integrated technology, we could have this particular IC ok. So, the point is that we started from 1946 we reached to 1967, but still we are using the same operational amplifier you see guys 1967 to present all right. So, this field is vast, you can first you should understand what is within the operational amplifier, once you understand you can make better operational amplifier as well. There is a lot of scope of performing research in the in the area of electronics in the area of semiconductor devices, in the area of biomedical devices.

And all this area more or less will require the knowledge of analog circuits, will require the knowledge of op-amps, will require the knowledge of ICs and that is why this course becomes kind of basic or the base that needs to be extremely strong to understand further several devices, to understand several other devices all right. So, that is why I have molded this particular course in the fashion that anyone and everyone who has a basic understanding of semiconductor electronics or just basic electronics can opt for this course, and can understand how the electronic things are particularly op-amps, particularly MOSFETs and ICs work.

Again you see that a lot of things I told you that I do not want to go into deep depth of this particular topic the reason is that we have to take all the students together and come toward come to a point there we can advance further there we can advance for that. So, there can be another course where it can be advancement of this particular course ok. So, anyway coming back to the screen what we see is that we have this IC.

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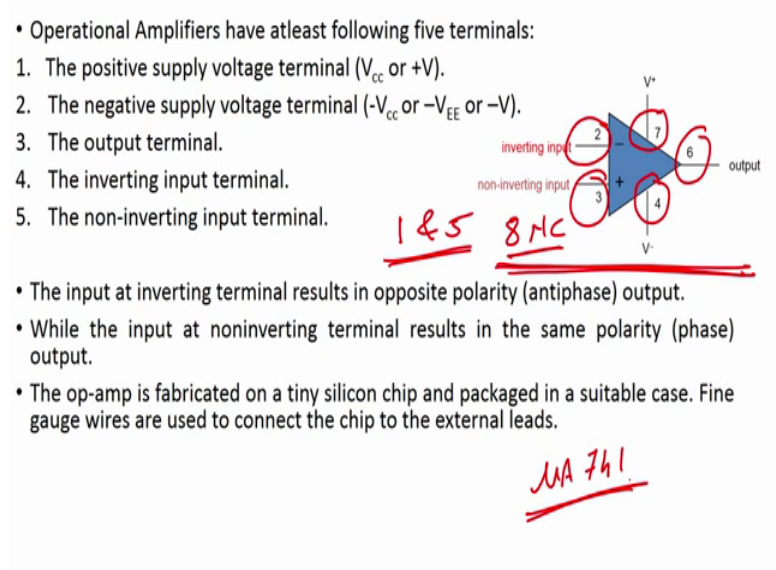

Now, once we have this I see what is there within this IC, what is there within the operation amplifier. So, when you take our integrated circuit, when you take an operational amplifier, what you see do you see that there are five terminals, five main terminals what you will be using, we say inverting terminal, we say non inverting terminal, we say positive supply, we say negative supply, we say output. Now, there is two more terminal, terminal 1 and 5 that is used for offset that is used for offset. And then that there is terminal 8 which is not connected which is not connected right. So, we have 8 terminal IC we have a terminal IC when we talk about single op-amp when we talk about 741, 741 u A, 741 right.

So, when we talk about the op-amp, and we talked about the terminals then first and first thing that we had to understand is you see we had to apply we have to apply 7 and 4 plus V, minus V this are called these are called bias voltages these are called bias voltages all right. And there is an advantage of this voltage that we will see at some point or I can give you an example that this operation amplifier has a several characteristic like infinite input gain. And how this infinite input gain what is the maximum output voltage that you can obtain even if the op-amp has infinite input gain. Even if op-amp has infinite input gain what is the maximum output you get at the output of the operational amplifier, we will see we will see ok. Right now just understand that it has five terminals it has five terminals positive supply, it has negative supply, it has output terminal inverting and non inverting terminal, easy very easy right.

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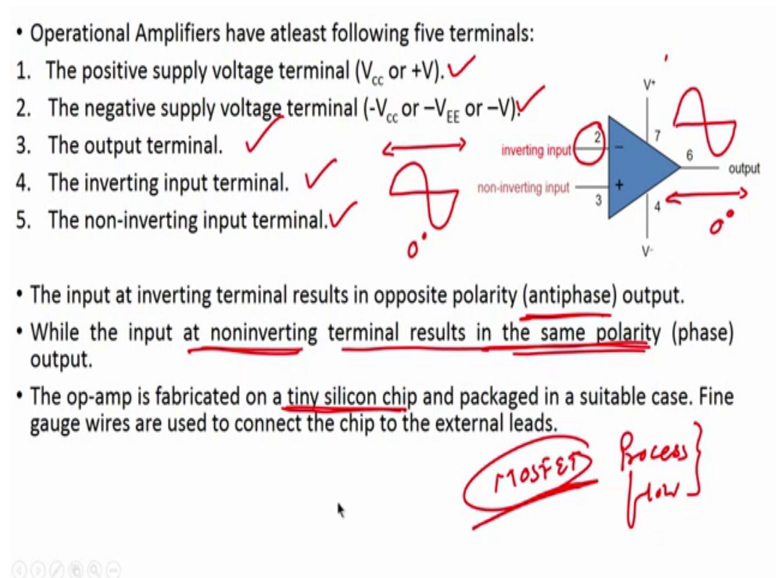

Now, input at the inverting terminal is in opposite polarity that means if I apply a input in this particular fashion right, my output my output here will be opposite polarity, polarity is opposite right. If this is 0 degree, this you can see is 180 degree 180 degree out of phase. So, this is 0 degree, this is 180 degree out of phase right. So, this is the antiphase output antiphase output. When, when we apply input to terminal number two. When the input and non-inverting terminal, if I apply input at non-inverting terminal, so now, what I will do ill apply input here then my output my output will be will be in phase, you see same polarity same polarity all right, then the opera op-amp is fabricated.

So, now, we understand right that if I apply input at inverting, output will be out of phase; if I apply signal at non-inverting, output will be in phase. Then what is another thing, the op-amp is fabricated on tiny silicon chip we have seen that right. And this op-amp has millions of MOSFETs billions of transistors all right. And how to fabricate the transistor, we have seen how to fabricate a MOSFET is not it? We have seen how to fabricate a MOSFET actually the process flow not actual fabrication. But at least we know now how if somebody asks you can you understand what is this process flow, you can say yes, I can and because I know how MOSFET is fabricated I know how we can have millions of MOSFET on one silicon chip on a tiny piece of silicon chip right. So, now we see this op-amp is fabricated on a tiny silicon chip and packaged in a suitable case, fine gauge wires have you use used to connect the chip to the external leads, we have seen this in the previous slide.

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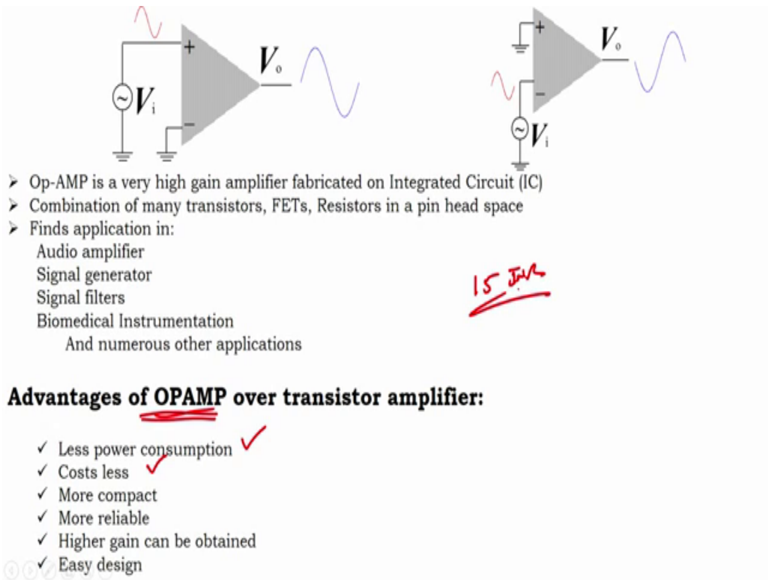

Now, let us see some interesting advantage of op-amp over transistors. First is op-amp is a very high gain amplifier fabricated on a integrated circuit; this is a high gain amplifier ok. It has combination of transistors if it is registered in a pin head size, so that means, that when you take a small [sink/silicon] silicon chip, it has lot of circuits that can include transistors, resistors, FETs right and so on and so forth. And it is it has extremely high gain, high gain ok. So, two things we understood about op-amp, it has extremely high gain and it has lot of components.

Then what are the applications of op-amps, what are the application of operational amplifier, it can be used as an audio amplifier, it can be used as a signal generator, it can be used as a signal filter, it can be used as a biomedical instrumentation and numerous other applications, numerous other applications ok. We will see how it can be used as signal generator, filters we can design using op-amp and we will take an example also, we take example also.

So, having said that what are the advantages of op-amp, why we have to use op-amp over transistor amplifier right, we have seen transistor base amplifier C E amplifier, CC amplifier, CB amplifier right. Why I have had to use op-amp, why I have use op-amp right, these are just few examples there are lot transistor amplifiers. So, the advantage of op-amp is first is low power consumption, then cost is less. So, when you buy a IC, it will be like 15 rupees, 15 Indian rupees right. So, it is really cheap very cheap low cost right. Then the IC is so small IC. So, small right if you have IC then what you will see is it is very small tiny and that is why it is more compact, more compact, reliable it is more reliable right.

Finally, higher gain can be obtained and design is extremely simple, design is extremely simple why because if I have op-amp if I may want to make inverting amplifier I have to just put two resistors and that is it. If I want to make two non-inverting amplifier again two resistors and that is it. Integrator, differentiator, one capacitor, one resistor and that will that will be it right; oscillators LC or R in a particular formation particular combination I can get oscillators. So, designing of analog circuit becomes extremely easy when we use op-amp over transistor based amplifiers all right, easy, very easy right. So, now let us see. So, now, you got it right said that we have very high gain, we have lot of components, there are a lot of application of operational amplifier, and there are several advantages of operational amplifier over transistor amplifiers, over transistor amplifier correct.

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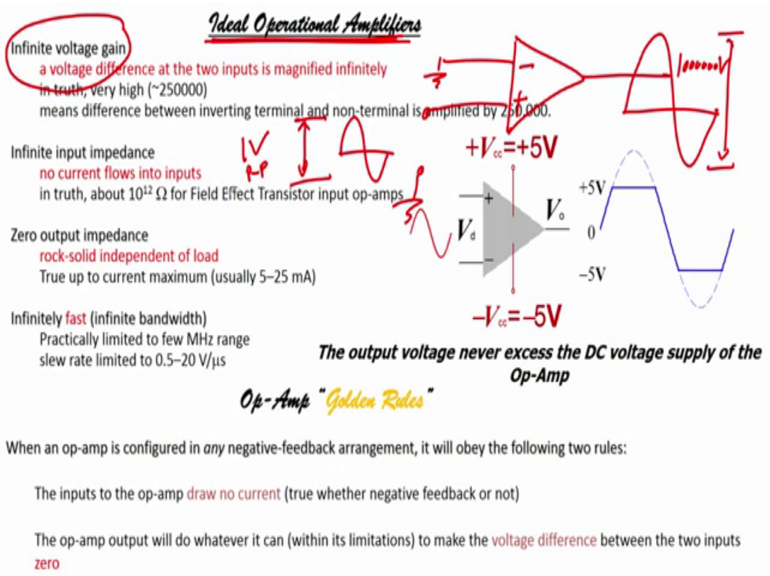

Let us go to the next characteristics next characteristics. What is that sorry, ok. Ideal operational amplifiers we are talking about now ideal situation ok. And then we will see that in truth or practically what is the case. So, these are very important points. If you remember these points it has these are repeated in several paths when we talk about the operational amplifier ok. First point is it has infinite voltage gain; it has infinite voltage gain. And the voltage difference the input is magnified infinitely that means, that if I apply if I apply. So, that mean that what does it mean infinite voltage gain means suppose I have a op-amp suppose I have op-amp and I have inverting terminal non inverting terminal right.

Suppose inverting terminal I am grounding, non-inverting terminal I am applying a signal which is that say 1 volt, 1 volt peak to peak, 1 volt peak to peak ok. And it has how much in finite voltage gain that means, at the output can I generate, can I generate a voltage which is 100 volts peak to peak because it has infinite right. So, in finite voltage gain that means, that I can have infinite amount of voltage I can get 1, 1 million times output, one can I have this much voltage right.

So, what we will see, what we will see is that the output this output even it is in finite voltage gain, even it is in finite voltage gain, the output cannot exceed, output cannot exceed more than more than the supply voltage more than the supply voltage. So, what is supply voltage your plus V cc your minus V cc. So, even your output input is small, let us say 1 volt, the maximum output that I can get is you see 5 volts, minus 5 volts. And a little bit less than that, little bit less than that. You will see in the experiments also that means, you can use op-amp as an amplifier and it has an infinite voltage gain, but that will again also is governed by the supply voltage or the bias voltage that we apply across the op-amp then we apply across the operational amplifier. This is very important to understand in finite voltage gain ok. But in truth in true that is in experimental op-amps in practical op-amps, you will see that the gain is gain is very high is about this much value, around this much value ok. ok.

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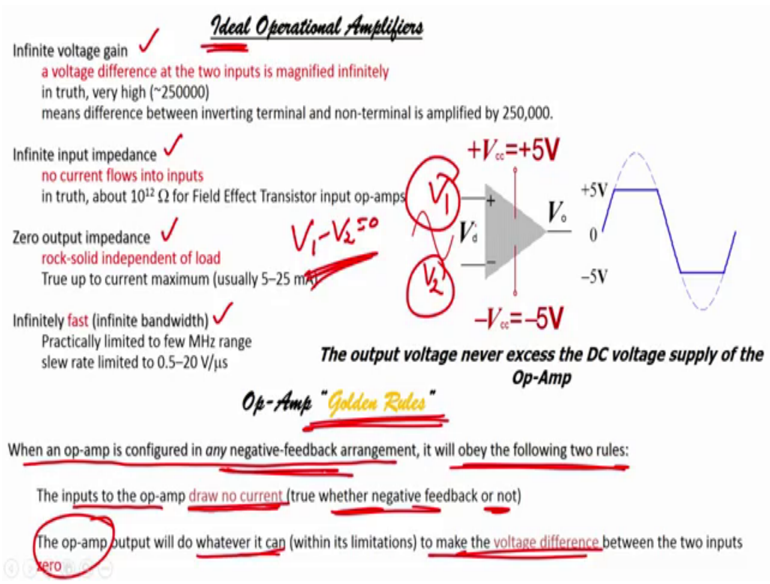

Next one is in finite input impedance in finite input impedance. So, no current flows in two op-amps right because if the impedance is very high then the current cannot flow right. Suppose, I talk about resistance the resistance is extremely high can current flow it will not flow right; same way if the excuse me. If the impedance is extremely high can current flow current cannot flow into the inputs current cannot flow into the input of the operational amplifier. Now, in experimental op-amps or in practical op-amps, what we will see that the input impedance, input impedance is about 10 to the power 12 ohms right for FET based op-amps, for FET based op-amps.

Now, the point is it has infinite input impedance, but why it has infinite input impedance because the input of the operational amplifier, the input of operational amplifier, we are using the FETs MOSFETs right MOSFETs, it is has extremely high input impedance extremely high input impedance that we know right. So, also you have to see that what is the first stage of the op-amp and what is the last stage of the op-amp.

So, when we understand what is there in the first stage of op-amp, you will also see that the amplifier that is design the first stage of op-amp has extremely high input impedance. And amplifier which has which is at the last stage of the op-amp has extremely low input impedance all right, so that is why when we see about input impedance of the op-amp it is infinite or it is extremely high. When we talk about output impedance it is 0 or it is low, it is low ok.

Last is infinitely fast it is very fast it has infinite bandwidth this is way when we talk about ideal operation amplifier, but practically it is limited to few megahertz practically it limited to few megahertz. And it can also be determined by understanding the slew rate by understanding the slew rate ; that means, if I apply this signal at the input can I also see the corresponding change in the output simultaneously right it has some lack. So, what is that lack, how fast my op-amp output can track the input right, so that will be by slew rate as I will show you the slew rate also later on. So, the point is that we have slew rate which is 0.5 to 20 micro 20 volts per microsecond, we have limited few megahertz range that is your bandwidth, that is your bandwidth. However, the ideal operational amplifier it is infinitely fast, ideal operation is infinitely fast.

So, what we understand from here, what we understand from here that we understood four main characteristics of an ideal operation amplifier in finite voltage gain, in finite input impedance, zero output impedance, infinitely fast right. But in case of actual op-amp, in case of practical op-amp, what we understand is the voltage difference is very high the input is magnified at a very high range, but not infinite input impedance is extremely high, but not infinite output impedance is close to zero, but not zero, the it is not infinitely fast, but it is extremely fast, and it has it is limited to few megahertz range right.

This these are the cases of practical op-amps right. The top one are the first one this the one that I am taking here these are all the characteristics of a ideal operational amplifier ideal operational amplifier easy very easy right. Now, whenever you use operational amplifier, whenever you use operational amplifier, you had to understand golden rules. What are these golden rules there are two golden rules ok, golden rules two golden rules when op-amp is configured in any negative-feedback arrangement it will obey the following two rules. So, now, you see the sentence very clearly what is written, when op-amp is configured in any negative-feedback arrangement. So, this golden rules tends to when you have negative-feedback, when you have negative-feedback.

So, what are these following rules. So, first rule is that the inputs to the op-amp draw no current draw or source or no current right, draw drain no current ; that means, the input to the operational amplifier here the current is 0 is 0. And it is true whether feedback is there or not does not matter. This is true even the feedback is not there ok. First golden rule inputs the op-amp would draw no current.

Second the op-amp will do whatever it can whatever it can to make the voltage difference to make the voltage difference between this two. So, voltage difference between the two inverting and non-inverting terminal or between the input terminals to be 0, to be 0 ok. So, op-amp will do whatever it can to make the voltage difference that is V 1 minus V 2 V 1 minus V 2 to be 0. Two golden rules understood. First is the current input current inside the op-amp is there is no current, because it cannot draw any current input to the op-amp draws no current. Second is second is that the voltage difference right. So, the voltage difference between the two inputs would be zero, would be zero. This op-amp will do what it can to make the input voltage difference or voltage difference between the input terminals to be zero these are two golden rules that we had to remember when we understand the operational amplifier when we understand the operational amplifier. So, if I if I go to the next slide what I will see ill see that I had to compare the ideal op-amp versus real op-amp.

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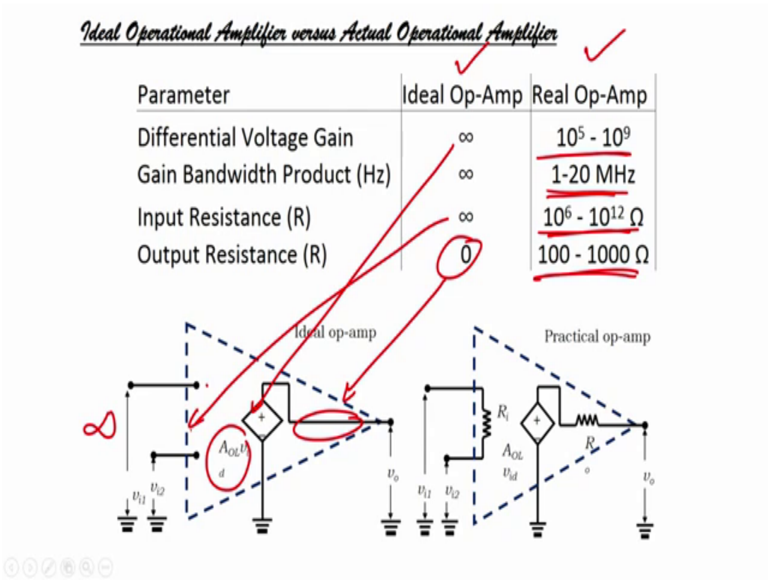

So, if you can say focus back on the slide what we see we see that the parameters are written for idea op-amp is there and real op-amp is there or practical op-amp is there you see here that is what we were discussing right. Differential voltage gain or voltage gain in finite, second bandwidth product bandwidth products in finite, input resistance in finite, output resistance zero right, this is what we have seen. But when we talk about real op-amp or we talk about practical op-amp, then we see that it is not infinite, it is extremely high, it is not infinite it is extremely high, it is not infinite it is extremely high. It is not 0, it is low or close to 0; it is low or close to 0 right. So, this is the ideal versus real op-amp.

Now, if you see the equivalence circuit, equivalence circuit, very easy to draw equivalent circuit. You see this is A OL into v i d d came here. So, forget about that. This is your open loop gain input the differential input voltage v i 1 minus v i 2. Now, you see there is no connection, there is no connection because in finite input impedance in finite input impedance right. So, the if you apply voltage v i 1, v i 2, we can write like this, then you have a gain in finite gain A OL open loop gain, v i d right and the output you see output is connected directly. So, there is a zero resistance right.

You have to we have to see this ideal op-amp; it has zero zero resistance, you can see here. It has in differential voltage gain in finite right, you have to see here input resistance infinite, you can see here right. But in case of actual op-amp, in case of actual op-amp, what it will be same circuit, but here we can put a resistance because now we have some value of resistor it is very high, but still it is there. So, we have used a register at the at the between the input terminals.

Then we have very high gain, very high gain. You see the resistor is about 10 raise to 6 to 10 raised to 12 ohms. It has very high gain 10 raised to 5 to 10 raised to 9 right very high gain that is fine. Then it has low resistance low output resistance. So, still there is a resistance, it is not 0 right. So, you cannot connect like what we have seen in the ideal op-amp. We had to we have to put a register. We have to insert a resistor right that is what we have done we have inserted a resistor and this resistor value is low ok. Finally, we are showing the output voltage. Here also we have shown the output voltage. This is how we can draw the equivalent circuit of the operational amplifier, this is how you can draw the equivalent circuit of ideal versus actual or real or practical op-amp right, ideal or real or practical op-amp easy, easy right.

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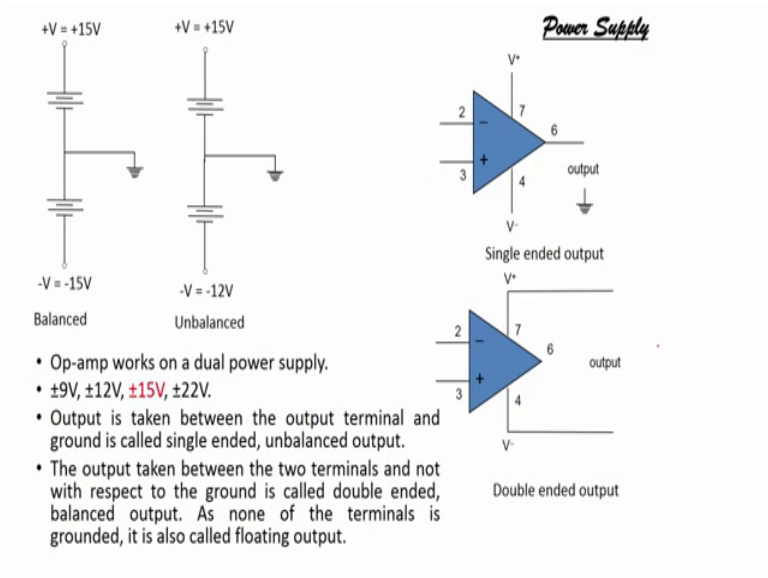

Now, let us see power supply. So, you have seen right that if I apply plus 15 volts and minus 15 volts to the op-amp to the op-amp at 7 and 4 right, then it will be by balanced power supply balanced, because both are same plus 15 minus 15. But in some cases we will we also apply plus 15 volts and minus 12 volts, plus 15 volts and minus 12 volts that will be my unbalanced power supply, there will be my unbalanced power supply ok. So, op-amp works, op-amp works on a dual power supply, but sometimes we will also see that one terminal can be grounded like this; and only one terminal we are applying some voltage. But anyway point is in general op-amp works on dual power supply, the dual power supply is plus minus 9, plus minus 12, plus minus 15 plus, minus 22 two ok, these are the dual power supply. And I have kept it read deliberately, so that you can understand that most of the time the most of the time you will see that we are applying plus minus 15 volts, we are applying plus minus 15 volts ok.

Now, the output is taken between the output terminal and ground is called single ended output. So, if the output is taken like this which we already know like this right, then it is your single ended output, output between the output terminal and the ground and the ground, then is single internal. But sometimes we take the output from 7 and from 4, from 7 and 4 that is called double ended output that is called double ended output. So, what is that? The output taken between two terminals and not with respect to the ground is called double ended output or balanced output as none of the terminals is grounded it is also called floating output.

You see here in this particular case single ended output. One terminal is ground with respect to the second terminal right. So, it is also called it is not floating, it is not floating, but in this particular case you are you are taking the output from here and see here that is between 7 and 4, but none of the pin is grounded and that is why this is also called floating output, ok. It is also called double ended output ok. So, this is the what we are understanding about the op-amps power supply and op-amp outputs how they are taken either they are taken single ended or they are taken double ended either we are applying balanced power supply or we are applying unbalanced power supply ok.

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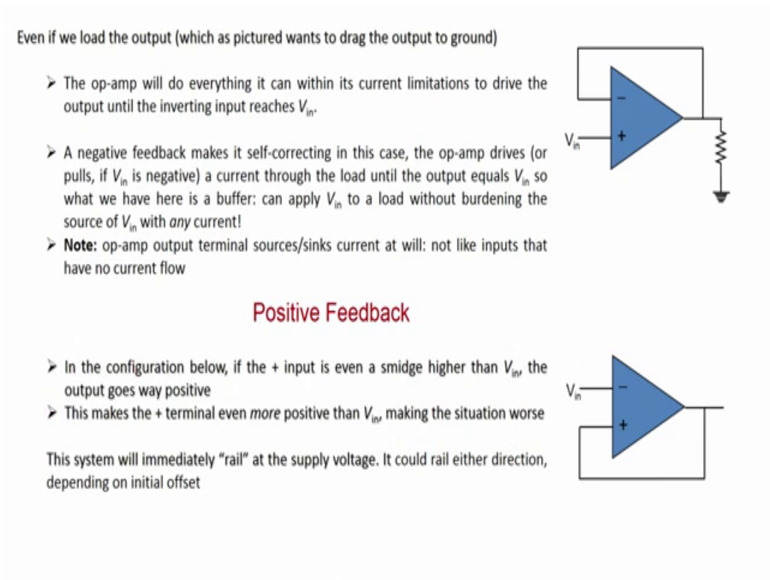

So, if I go to the next section, if I go to the next section that will be the feedback in op-amps. So, what I will do is let us finish this particular module at this particular slide which we understood now that what is op-amp right, what are the golden rules of the op-amp, and what are the characteristics of open, and what are the power supply whether it is unbalanced or balanced power supply right. Same way single ended or double ended output.

Now, in the next module, what we will see is the further under[stand] will further understand the operation amplifier. Till then what you do is you again see this slides these are very easy, very, very basic slides. And I will see you I will see you in the next module, I will see you in the next module, where we will understand the op-amps further that what they what they consist of and what are the parameters of the operational amplifier all right.

Till then you take care, I will see you next module, bye.