Mechatronics
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Lecture - 16
Introduction to Signal Conditioning and Op-Amp

Good morning to you all. I welcome you to this lecture on Mechatronics. Today we are going to talk about Signal Conditioning and the use of Op-Amp as a signal conditioner.

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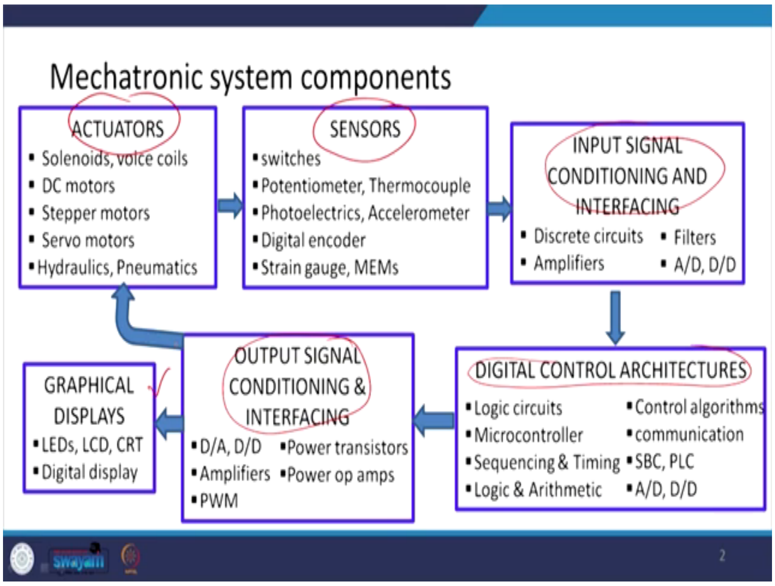

This block diagram essentially shows the important mechatronics components. Where you can see that usually, an actuator and there is a sensor and you have an input signal conditioning and interfacing. Then you have the digital control architecture and output signal conditioning and interfacing and then we have a display for viewing purposes.

Here as we have been discussing today out of these mechatronics components I am going to talk about the input signal conditioning and interfacing. So, how the sensor signals can be interfaced with your microcontroller? So, let us look at what are the basic requirement for signal conditioning.

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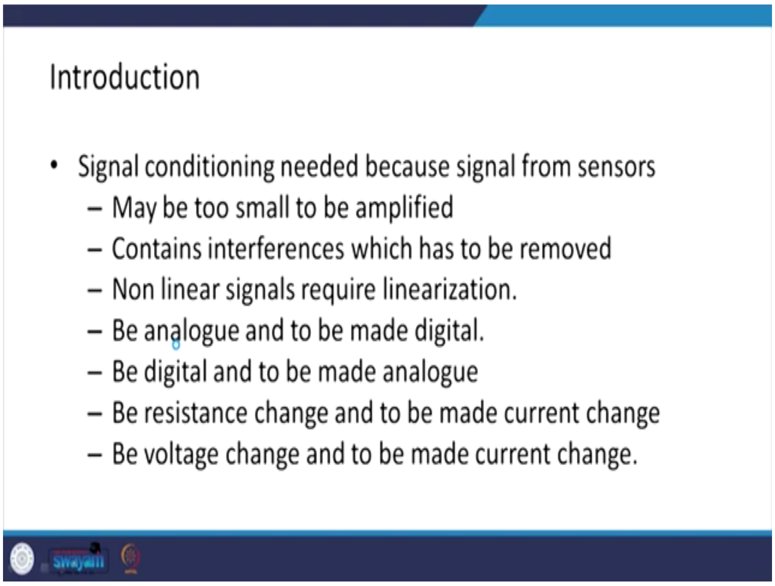

The signal conditioning is needed because whatever signal we get from the sensor, this signal may be too small to be amplified or they may have certain interferences which need to be removed. Many times this signal could be a non-linear signal and we may require a linearization process through linearization of the signal through some means or the signal could be an analog signal and we know that the microcontroller takes only digital signals.

So, we need to convert this analog signal and make it a digital signal or if your signal is digital you are getting from the microprocessor a digital signal, you may require it to be made to the analog signal so, that you can feed it to the actuator and sometimes the signal could be a resistance change and we want to convert it into a current change signal. Or your signal could be a voltage change signal and we want to make it a current change signal. So, these may be the varieties of requirements for which we need to have the signal conditioning. As I said the signals have to be sent to the microprocessor for processing purposes.

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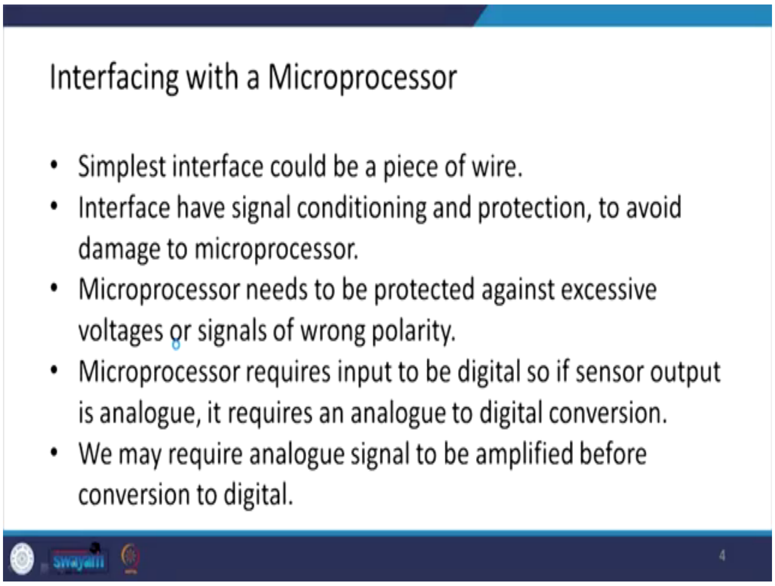

Now, we need to send these signals to the microprocessor from the sensor, we need to interface it, we required a certain type of interfacing of the sensor signal with the microprocessor. So, what could be the simplest interface? As all of you know it should be a piece of wire where we can just connect your signal output port to the microprocessor input port. So, the simplest interface could be a piece of wire, and these interfaces we are going to do for the signal conditioning and protection of signal conditioning purpose. Then there has to be certain protection such that your abnormal signals are not able to damage your microprocessor. For example, these microprocessors need to be protected against excessive voltage or signals of the wrong polarity if by mistake it comes.

So, there should be safety provisions in the interfacing to take care of this wrong polarity and the microprocessor requires as I said input to be a digital one. So, if your sensor output is analog; a potentiometer gives you an analog voltage then you require this analog signal to be converted into a digital signal and we may require an analog signal to be amplified before being converted into a digital signal, so all these types of tasks could be done in the unit what we call it as interfacing. In the interfacing unit, we can do all these tasks; there is certainly more requirement. Even many times digital signals need to be conditioned for better quality means, if we do not have a better quality digital signal, we may require it to be better conditioned it and the actuator might require an analog signal.

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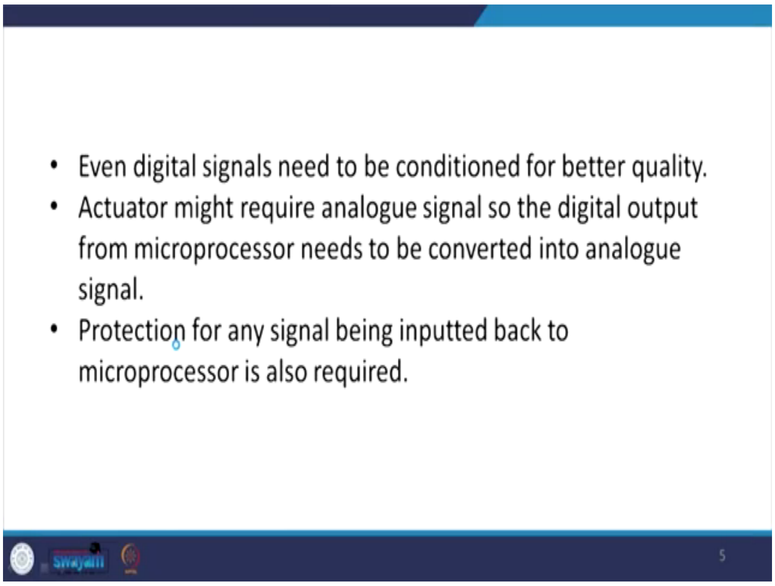

So, the digital output from the microprocessor needs to be converted into the analog signal, for example, if you take the case of a DC motor control. So, you need to give the DC motor an analog signal, and the signal coming out from the microprocessor they are digital in nature.

So, we need the conversion from digital to analog, and protection for any signal being inputted back to the microprocessor is also required. So, these are the things that are taken care of by the interfacing units.

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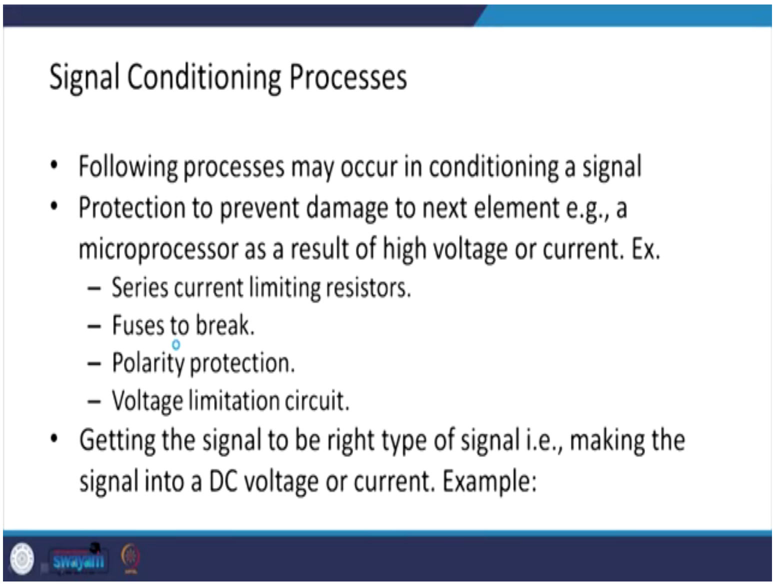

Now, the signal conditioning process may occur or the following process may occur during the signal conditioning. As I said protection to prevent the damage to the next element (microprocessor) as a result of high voltage or current. So, we need to have a protection unit and this could be a series current limiting resistor or normal fuses to break. So, that the fuse breaks and it protects your microprocessor or polarity protection could be there or the voltage limiting circuit. Further, getting the signal to be the right type of signal, making the signal into a DC voltage or current. So, all these are the provisions that could be there.

There could be various examples to get the right type of signal. If you look at a Wheatstone bridge, there what is happening? There we have had the change in the resistance changing resistance change in the strain gauge and that is converted into voltage change by the Wheatstone bridge and out of balance voltage.

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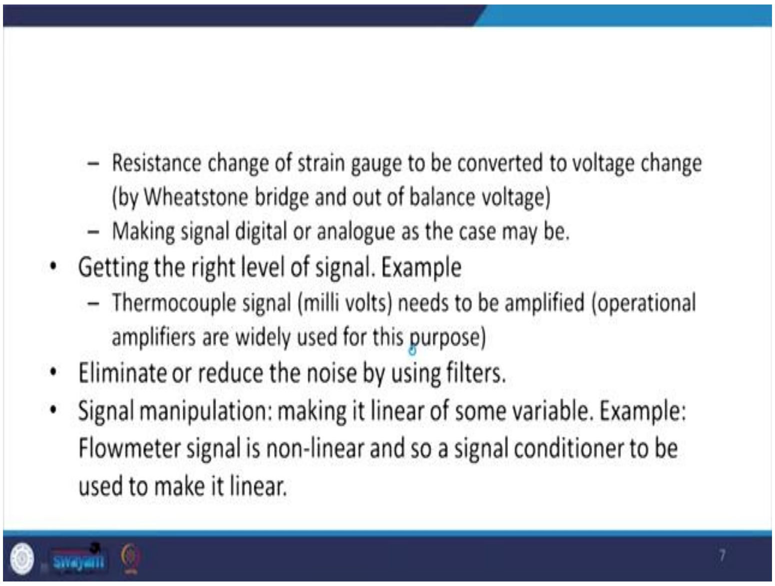

And making signal digital or analog as the case may be then getting the right level of the signal. As I said the thermocouple signals are very minute in the range of millivolt. So, we need this signal to be amplified, and as we are going to talk in the coming slides about the operational amplifiers. These operational amplifiers are widely used for the amplifying purpose of these signals.

And then we may need to eliminate or reduce the noise by using various filters. I will also be talking about filters maybe in the next lecture. Then as I said we may need to manipulate the signal that is making it linear of some variable, for example, the flow meter signal is non-linear and so, the signal conditioner is used to make it a linear signal.

Now, after all, let us look at the operational amplifier which is a very popular device and is widely used for many signal conditioning operations. So, first, we will be looking at the basic model of the operational amplifiers and in the next lecture, I will be talking about the use of operational amplifiers as the signal conditioner.

So, these operational amplifiers, in short, are called op-amps it is high gain DC voltage amplifiers and they have got a differential input and usually a single-ended output.

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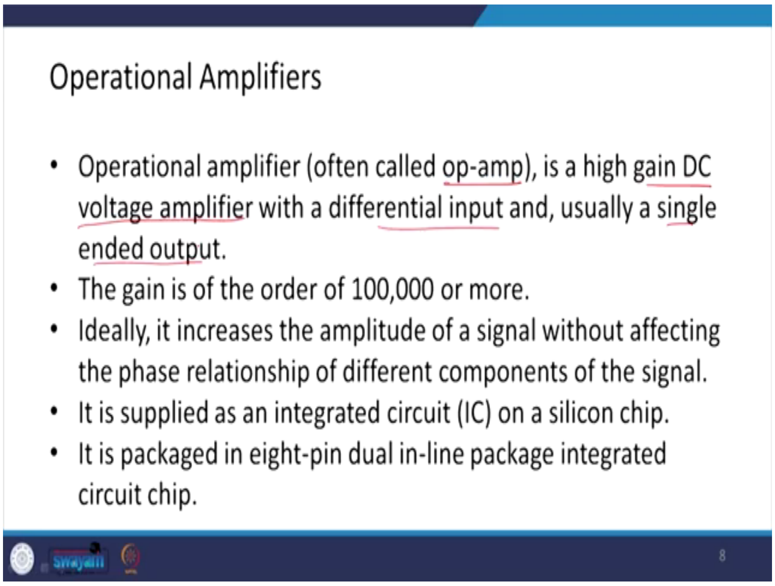

The gain of these amplifiers is of the order of 100,000 very high gain and ideally, it increases the amplitude of a signal without affecting the phase relationship of different components of the signal, so that is another beauty of it. And how it is available in the market? It is supplied as an IC or integrated circuit on a silicon chip and it is packaged in an eight-pin dual in-line package integrated circuit chip. The op-amp is available in the packaging as I said 741 op-amp is a very widely used operational amplifier. And, then you may ask what does it consist of ?

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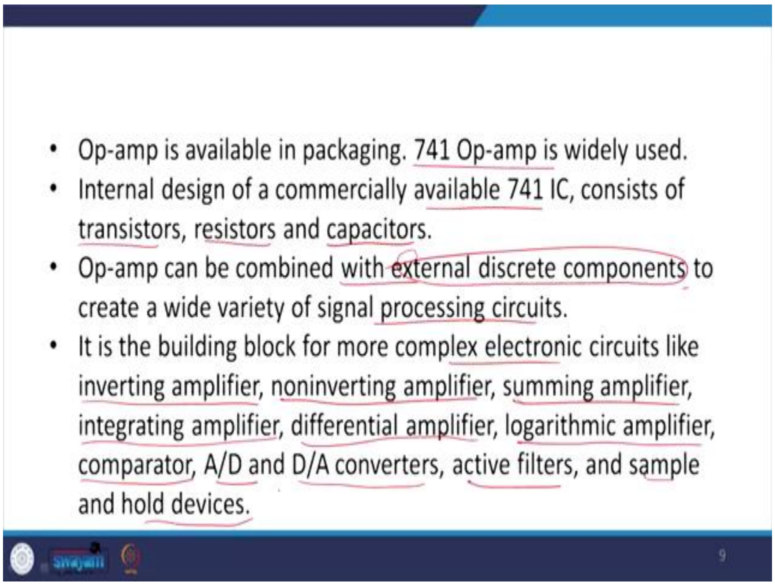

The internal design of the commercially available 741 IC consists of transistors, resistors, and capacitors. These three components put in a combination constitute the 741 op-amps. These op-amps can be combined with external discrete circuit components to create a wide variety of signal processing circuits. These are the external discrete components, the one which I am talking about. Here are you could have the resistances, you could have the capacitors which are external to the op-amp circuit, and by putting them in the different combinations you can get the different types of signal conditioning. It is a building block for a more complex electronic circuit like inverting amplifier the one which is used to in voltage signal as well as amplify it, the non-inverting amplifier that is just amplifying the signal, summing amplifier that is summing of the two signals then integrating amplifier that is the signal being integrated, a differential amplifier that is the signal being differentiated, logarithmic amplifier, then comparator analog to digital and digital to analog converter active filters.

I will be talking about all this and the sample and hold devices. So, all these are the possible use of the op-amp.

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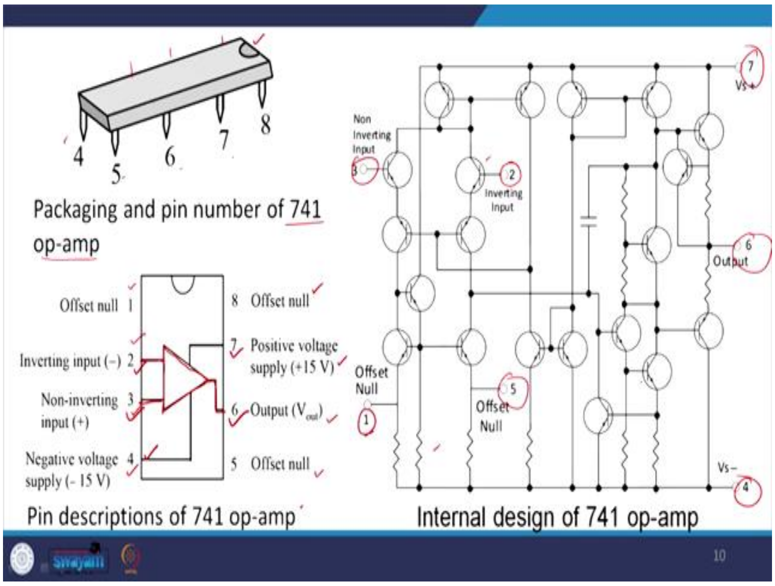

This is how it looks like as I said dual pins are there. You have the two lines of the pins, here 1 2 3 and this is 4, 5, 6, 7, 8. So, there are eight pins in it and this is packaging and pin numbering of 741 op-amp amplifier and there is a mark here just to identify that from the left-hand side of that you have to start counting the pins.

This is how the packaging consists of and the pin description of these eight pins is one is offset null, the second is inverting input now that is there, third is the non-inverting input, then you have the 4 is the negative voltage supply usually minus 15 volts. Then the fifth is the offset null, 6 is the output voltage from where the output is taken and 7 is the positive voltage supply that is 15 volts and 8 is the offset null. This is how these op-amps are described. So, the terminals which are usually shown here for the op-amp are the inverting input non-inverting input and output. That is why you can see these connections over here and many times we also show the voltage supplies terminals. So, here you can see that the negative voltage supply and the positive voltage supply. As I said, you may be eager to see how does the op-amp internal design looks like. So, you can see here there are various transistors or their resistors are there and you can see the various ports that are offset null that is ‘1’ here.

Then we have the second is inverting input. This is inverting input third is non-inverting input, then fourth is the power supply you can see this is the fourth is the power supply fifth is the offset null. So, you have the offset null, six is the output and so, on 7 is the again positive power supply. So, this way it is there, and inside you have the transistors registers being connected.

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If you go to the market to buy this op-amp this is how these are available. So, you will find out this 741 is imprinted over there and this is how the 741 you will be seeing. So, this is how these are commercially available forms of the 741 op-amp.

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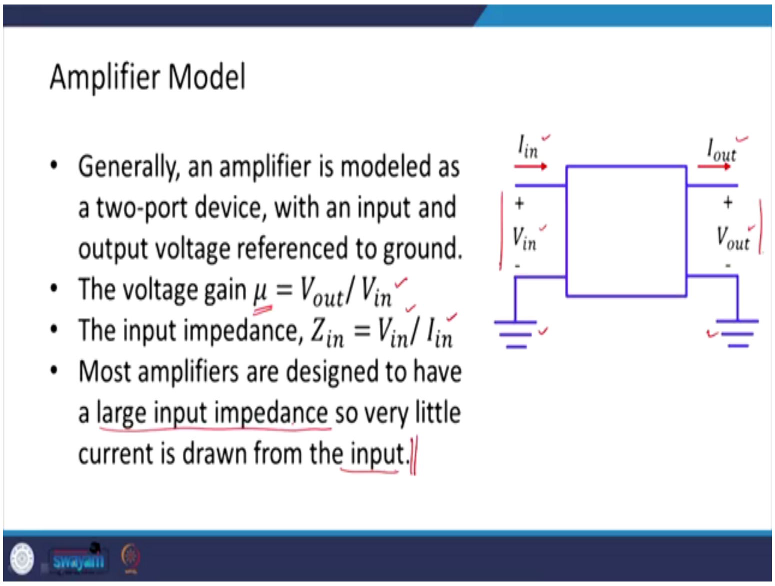

Now, let us look at and try to understand the model of the amplifier. So, generally, an amplifier is modeled as a two-port device with the input and the output voltage reference to the ground. This is how the amplifier is modeled. So, you have an input side here and you have the output side, and input and output voltages are references to the ground over here this is the input current, output current, input voltage, and output voltage and as you know these are the amplifier. There are there is going to be a gain in the voltage and this gain is represented by,

$$\mu = \frac{V_{out}}{V_{in}}$$

The input impedance is defined as,

$$Z_{in} = \frac{V_{in}}{I_{in}}$$

Most of these amplifiers are designed to have very large input impedance so, that very little current is drawn from the input. So, as I will be talking about this is one of the very important assumptions which we also take in the modeling of these operational amplifiers.

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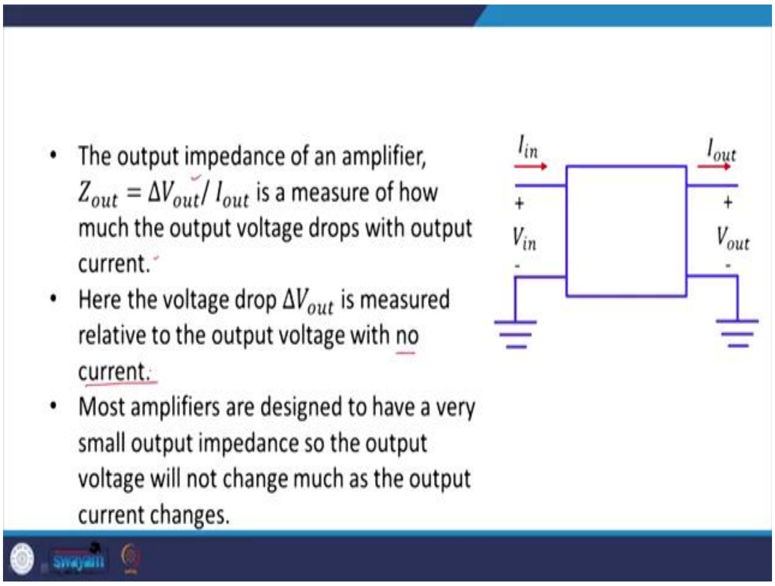

So, the output impedance of the amplifier,

$$Z_{out} = \frac{\Delta V_{out}}{I_{out}}$$

It is a measure of how much the output voltage drops with the output current. Here the output drop or voltage drop is measured relative to the output voltage with no current. So, this is how it is done and most amplifiers are designed to have very small output impedance so, that the output voltage will not change much as the output current changes.

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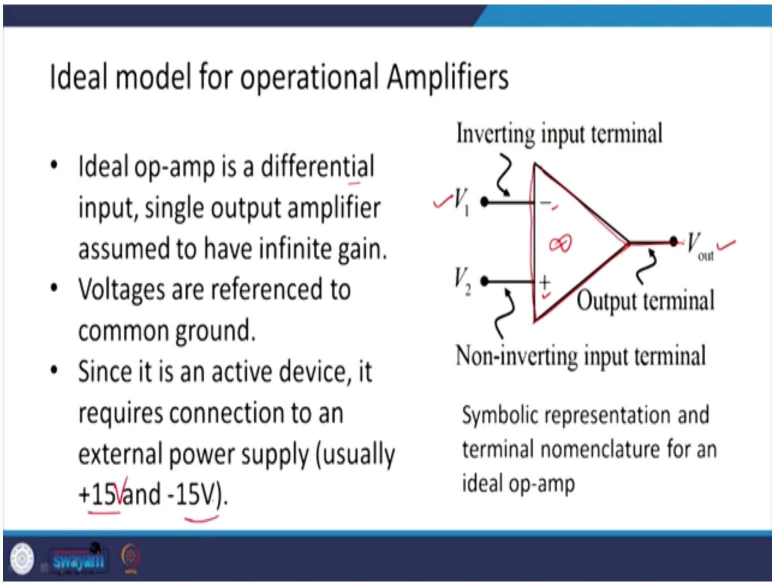

Now, let us look at the ideal model of the operational amplifier. In this way, it is represented. You have the inverting input terminal here and you have the non-inverting input terminal and you have the output terminal over here. So, this is how symbolically the op-amp is represented and an ideal op-amp is a differential input and single output amplifier. As you can see that there is a differential input and single output is their amplifier and this has got an infinite gain and voltages are referred to as the common ground and as I said it is an active device, its required connection to an external power supply as I have talked about. It is usually +15 volts and -15 volts.

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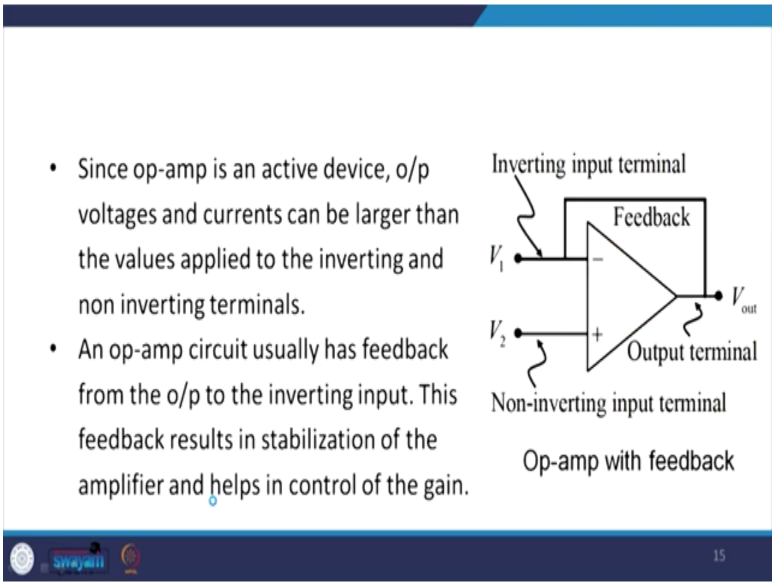

Since op-amp is an active device output voltages and currents can be larger than the value applied to inverting and non-inverting terminal because it is an active device we are supplying power to it and an op-amp circuit usually have feedback. From the output side, you have a connection towards the input side which is what we call feedback. So, the op-amp circuit usually has feedback from the output to the inverting input, and this feedback results in stabilization of the amplifier and helps in the control of the gain as we will be looking in the subsequent slides as well as in the lecture.

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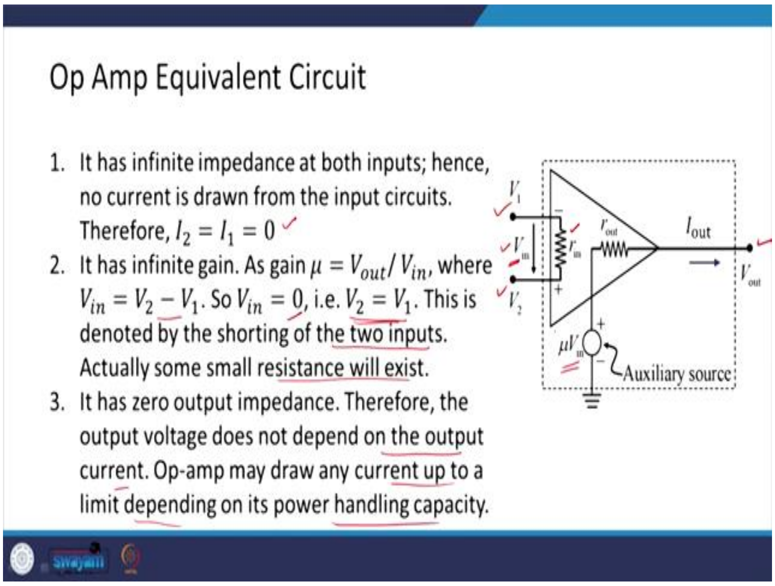

Now, let us look at the equivalent circuit of the op-amp. With the assumptions we have taken, here we can draw the equivalent circuit. So, in the equivalent circuit you can see here we have the two voltage sources source V_1 and V_2 over here. This is the input voltage and you have the output voltage over here, this V_{in} is the input voltage, although we have assumed that the input side is going to have high input impedance. It has infinite impedance at both the inputs, hence no current is drawn from the input circuit.

So, therefore,

$$I_1 = I_2 = 0$$

and it has infinite gain. So, infinite gains mean,

$$\mu = \frac{V_{out}}{V_{in}}$$

So, where is V_{in}?

$$V_{in} = V_{2} - V_1$$

So, infinite gain means that the V_{in} is going to be 0, and it means,

$$V_2 = V_1$$

and what does this mean? This means that there is a shorting over here this is denoted by shorting of the two inputs and usually some small resistance will be existing over here and it has zero output impedance, again one of the assumptions over here therefore, the output voltage does not depend on the output current and op-amp may draw current up to a limit depending on its power handling capacity. In this figure, you can see that this is the μV_{in} . Where, μ is the gain of the amplifier.

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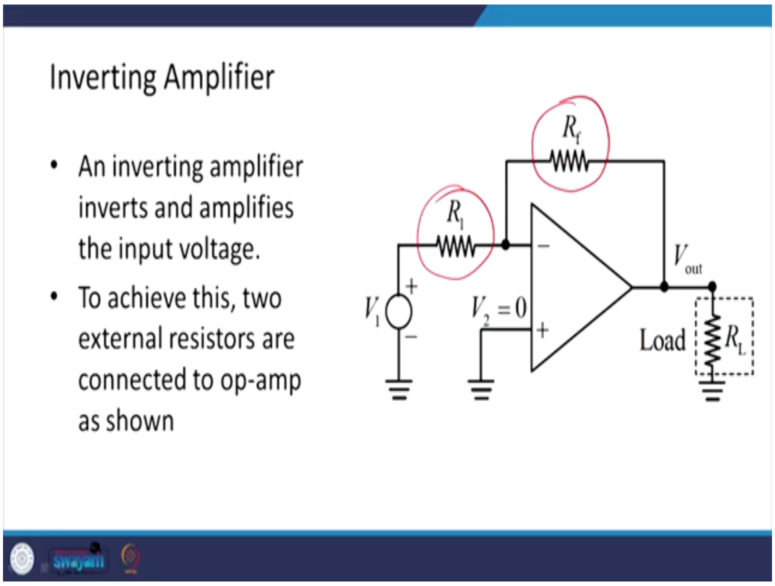

Then let us look at the inverting amplifier that is the one that inverts the input signal. So, in the case of inverting amplifier, it inverses the input voltage. So, here to achieve these two external resistances are connected to the op-amp. So, whatever op-amp circuit we have seen, we are using two external resistances one is R_1 at the input side of the inverting terminal, and the other is the R_f which is the feedback resistance in the feedback path. So, these two are the external resistances which I talked to you about, these are the two external resistances which we are using in order to invert the voltage signal invert and amplify the voltage signal.

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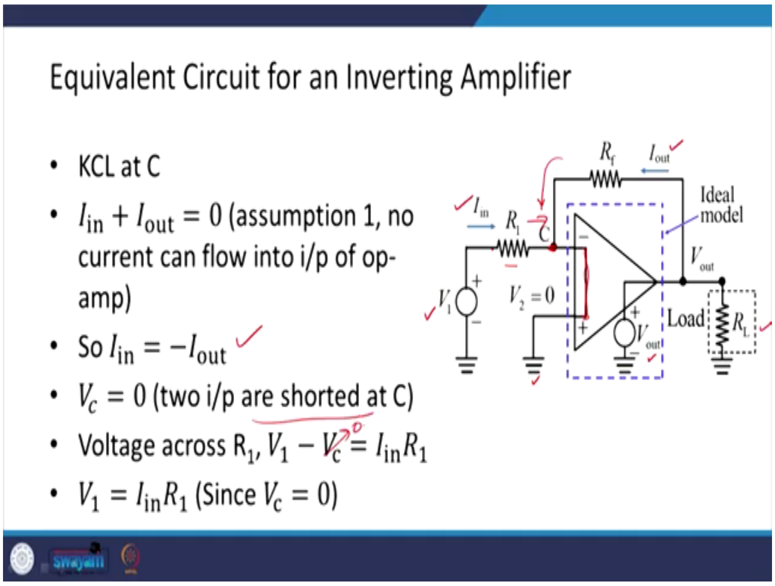

So, let us look at the equivalent circuit for an inverting amplifier. So, here as we assumed that this is, we shorted it here the signal is provided from the inverting terminal and the non-inverting terminal is earth grounded. So, this is the ideal model you have some load over here, you get the output voltage over here and this is the output current that is supplied through the feedback and you have the input current over here.

Now, let us take point C over here, now if I apply the Kirchhoff current law at this point then what I get current in plus this current and this current both are coming to this junction. So,

$$I_{in} + I_{out} = 0$$

no current can flow to the input of the op-amp. So, that is why we are taking this as 0. So, from this,

$$I_{in} = -I_{out}$$

and also the,

$$V_c = 0$$

because the two input is short at C.

So, the voltage across this one R_1 is going to be what?

$$V_1 - V_c = I_{in}R_1$$

And, since this V_c is 0, then

$$V_1 = I_{in}R_1$$

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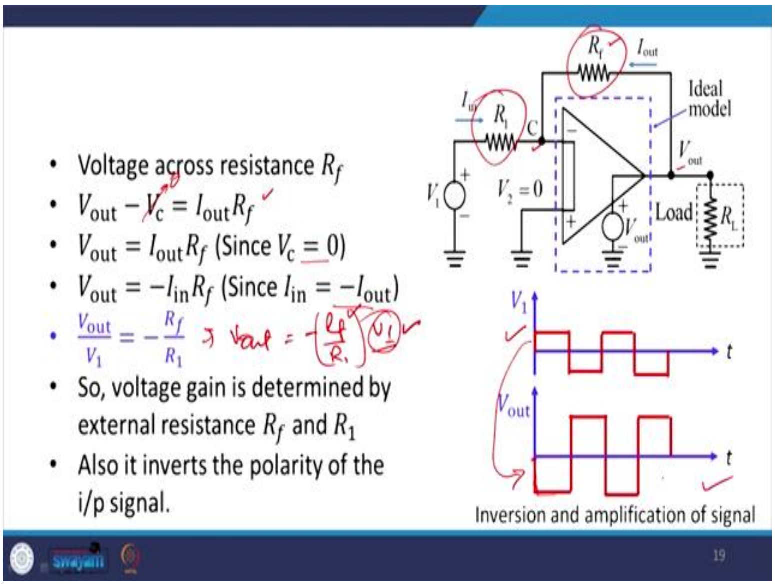

Now, let us look at the voltage across this feedback register R_f. So, I have V_{out} and I have V_c. So,

$$V_{out} - V_c = I_{out} R_f$$

Again V_c we take it as 0. So,

$$V_{out} = I_{out} R_f$$

So, I_{out} is we have already found out in the previous slide is equal to $-I_{in}$.

So, I put this,

$$V_{out} = -I_{in} R_f$$

and we have already seen that,

$$V_1 = IR_1$$

So, if I divide this, this is what I get. So, here is what we have got?

$$V_{out} = -V_1 \frac{R_f}{R_1}$$

V_1 is the input signal which I have supplied through the inverting terminal and so, depending on what value of R_f and R_1 I am going to get a gain of it. So, my V_1 signal is going to be amplified by this particular ratio $\frac{R_f}{R_1}$ and this R_f and R_1 its dependent on the user because these are the external elements as been put into the op-amp circuit.

So, what we have done? So, this was my input signal. So, here since there is a negative sign it means that the signal is getting inverted and if your R_f is more than R_1, then you are getting the signal amplified also. So, this is how you are going to get it. So, this is there is an inversion from here this is positive, but here this is negative as well as you can see the amplitude also being increased. So, this is what is the inverting of the signal.

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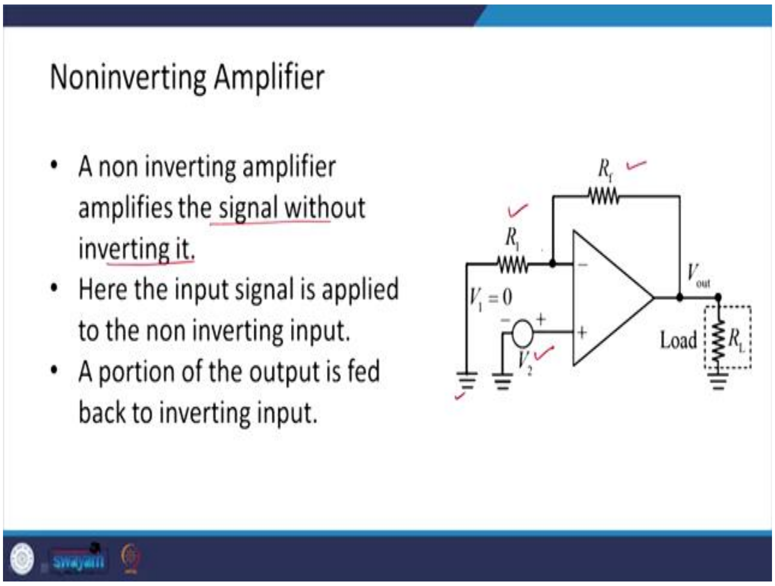

Now, let us see the non-inverting amplifier. So, in case of non inverting amplifier what we do is that we supply the signal through the non-inverting terminal over here and this R_f is already there and this R_1 is already there and this end is that is inverting terminal end is connected to the ground. So, as the name indicates non-inverting amplifier amplifies the signal without inverting it and here the input is applied to the non-inverting input, and a portion of the output is also fed back to the input.

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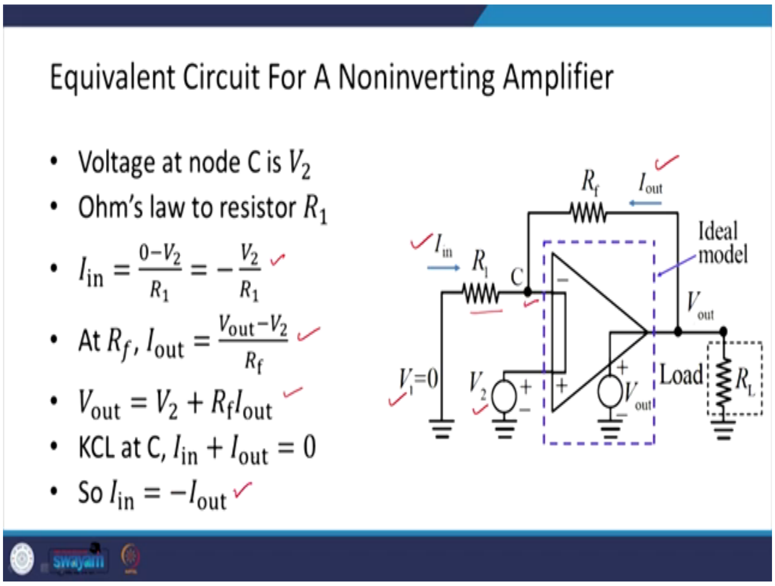

Now, let us look at equivalent circuit in order to analyze this thing. So, if we look at the equivalent circuit over here. Again this is the input voltage this I have grounded. So, this is 0, this is my input current, this is my output current and these two terminals are shortened with the assumption which we have taken.

So, the output voltage at node C over here is going to be V_2 because this side is 0. So, Ohms law if we apply across the resistor. So, this is,

$$I_{in} = \frac{0 - V_2}{R_1}$$

Similarly at R_f

$$I_{out} = \frac{V_{out} - V_2}{R_f}$$

So,

$$V_{out} = V_2 + R_f\, I_{out}$$

So, and what is here? This V_2 is you are going to get the V 2 over here this side.

$$I_{out} = \frac{1}{R_f}(V_{out}\text{-}V_{2})$$

So, Kirchhoff's current law at C will be giving,

$$I_{in} = -I_{out}$$

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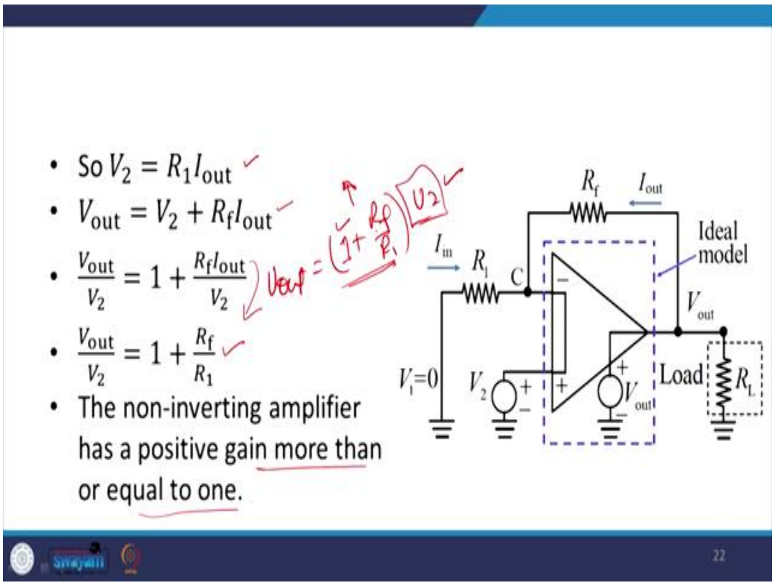

And so, I have,

$$V_2 = R_1 I_{out}$$

So, from here,

$$V_{out} = V_2 + R_f I_{out}$$

So, here let us divide this equation by V_2. So,

$$\frac{V_{out}}{V_2} = 1 + \frac{R_f}{R_1}$$

So, here you see what we have my output signal is equal to,

$$V_{out} = V_2(1 + \frac{R_f}{R_1})$$

So, this was my input signal and here this is the factor that amplifies my signal. So, the non-inverting amplifier has a positive gain more than or equal to 1 because you have added by 1. So, you have more than or equal to 1 that is there.

Then we have a buffer or follower this is again a very important modification or important use of the op-amp.

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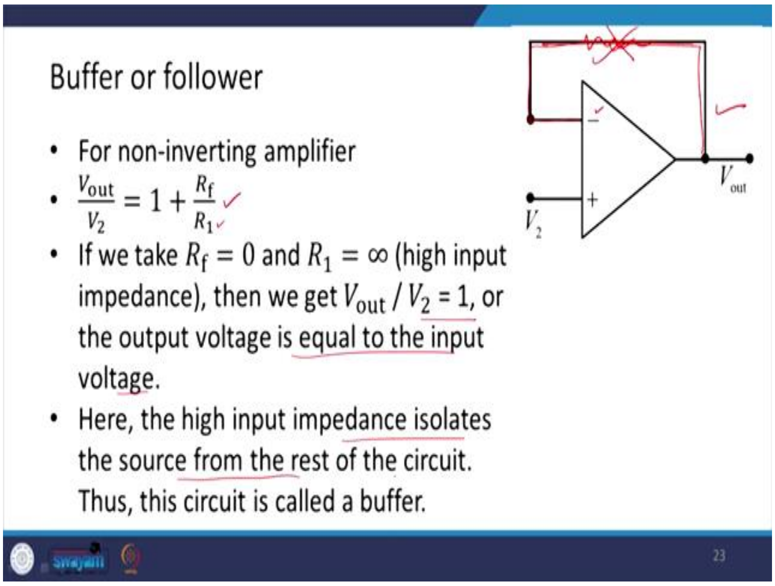

So, here what is done is that your output is shortened to the inverting input terminal over here as you can see in this figure. So, this is short end, this feedback now this is directly connected to this one that is the inverting terminal. So, for the non-inverting amplifier, we have seen,

$$\frac{V_{out}}{V_2} = 1 + \frac{R_f}{R_1}$$

in the previous one which we have devised this one. So, if we take here this R_f is equal to 0 that is whatever we had if I remove that and R_1 if I take a very high input impedance then we get what?

$$\frac{V_{out}}{V_2} = 1$$

V_{out} is equal to V_2 or the output voltage is equal to the input voltage and here the high input impedance isolates the source from the rest of the circuit and this is what is called a buffer.

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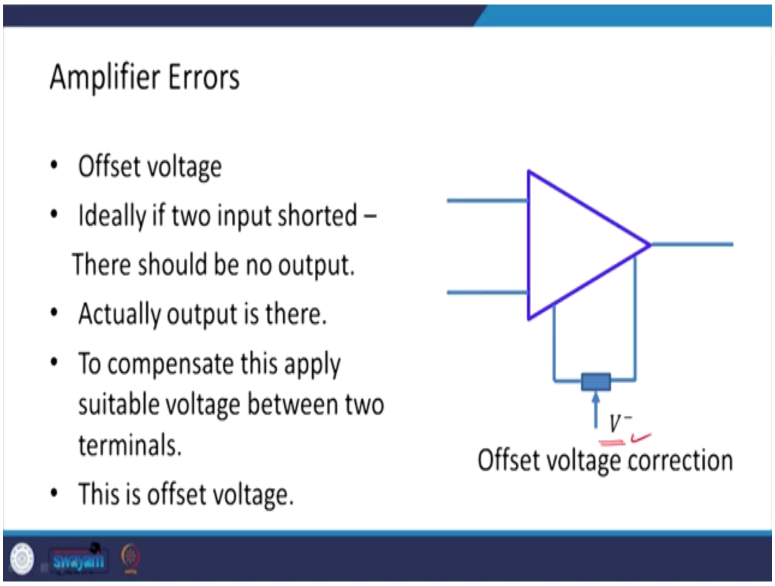

Then in the amplifiers there is some error what we call it as the offset voltage, ideally if two inputs are shorted then there should not be output, but some output is there. So, to compensate this apply suitable voltage between the two term terminals and this is what we call the offset voltage and this is how the offset voltage correction is provided. As we talked about the ideal op-amp and its characteristic we draw the equivalent circuit of it, but now let us look at how the real op-amp looks like and what is the characteristic of the real op-amp. So, the actual output deviates its characteristic from the ideal op-amp as I said and real op-amp has very high input impedance.

So, little current is drawn at its input, in the ideal op-amp we said that it has infinite input impedance, but you do not have exact infinite value, but you have a very high value and there is little voltage drop voltage difference between input terminals that are also there.

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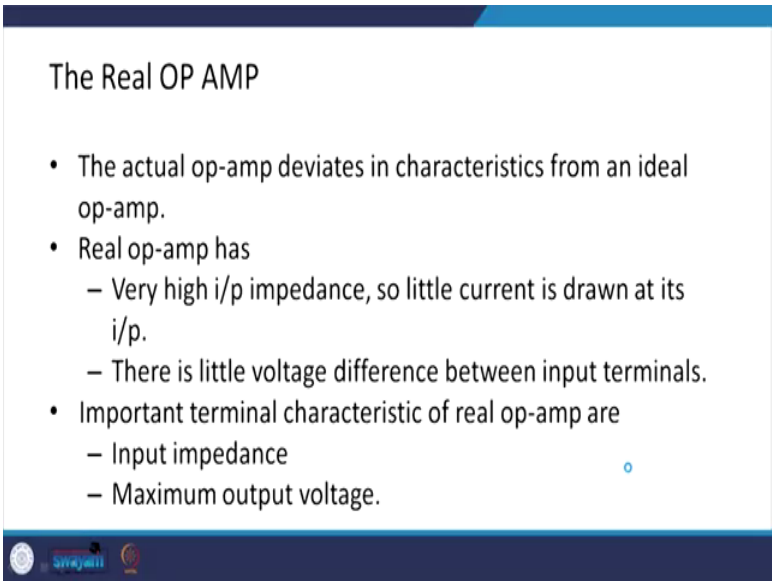

Important terminal characteristic of the real op-amp is input impedance and maximum output of voltage. Two other important characteristic of real op-amp are associated with its response to the square wave input, how does the op-amp responds to a square wave based on that the two other important characteristics of the real op-amp are defined. When we apply a square wave input to an amplifier circuit, the output is not square it exhibit a ramp from one level to the next and in order to quantify the op-amp step response which we get with the help of the square wave, two parameters are specified these are the slew rate and the rise time.

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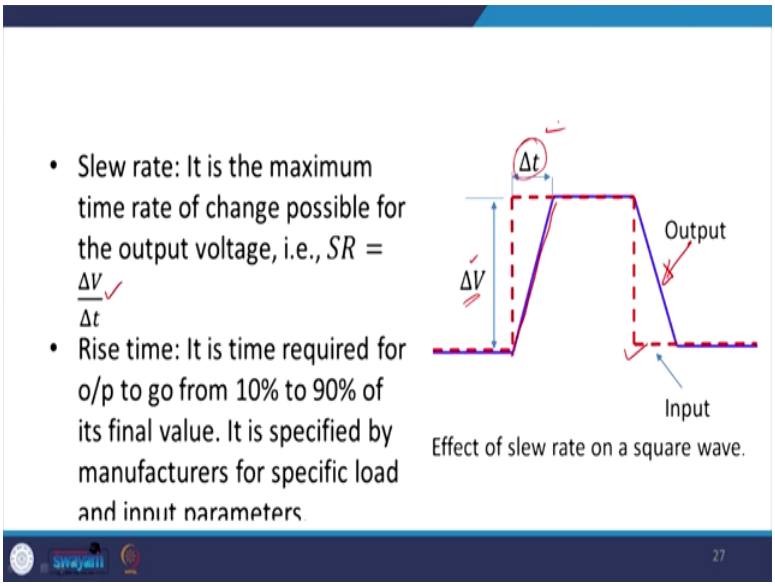

So, this is how the slew rate is defined. So, this is the input the red color is indicating the input and the blue color is indicating the output. So, you can see that the output is not same as that of the input. So, this is your output. So, how much time this deviation is at, how much time it is going to peak this input voltage,e and what is this ΔV?

So, the slew rate is defined by,

$$SR = \frac{\Delta V}{\Delta t}$$

It is the maximum time rate of change possible for the output voltage and the other parameter as I said its rise time and it is the time required for the output to go grow from 10 percent to 90 percent of its final value and it is specified by a manufacturer for a specific load and input parameters and frequency response is an important characteristic of the real op-amp. Ideal op-amp exhibits infinite bandwidth. We assume that it is suited for any frequency range, but it is not so, a real op-amp has a finite bandwidth which is a function of the gain established by the external components that means whatever external components we are going to use along with the op-amp.

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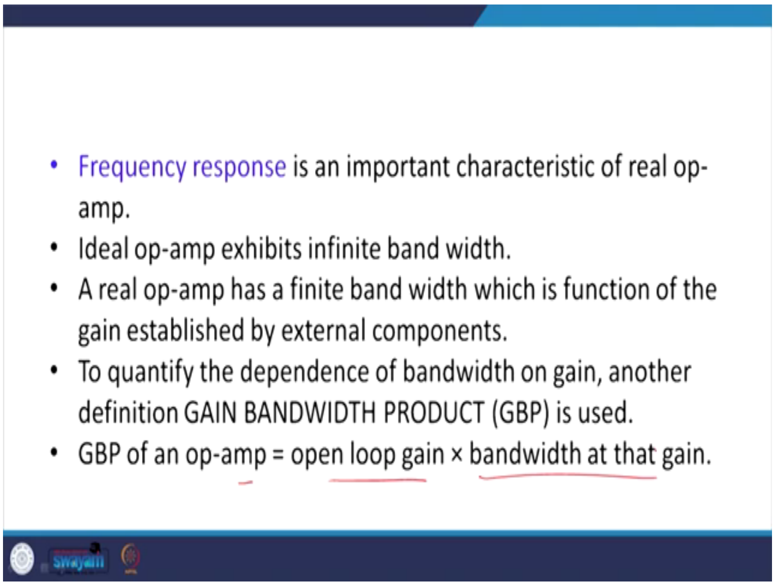

So, to quantify the dependence of bandwidth on gain, another definition what we call it as the gain bandwidth product (GBP) that is used,

$$GBP = Open\ loop\ gain \times bandwidth\ at\ that\ gain$$

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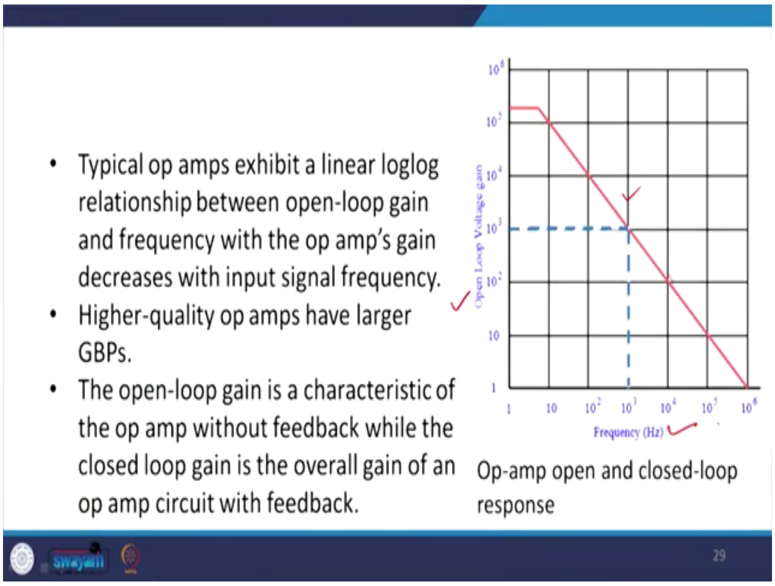

So, this is the typical op characteristic if we plot frequency versus open loop voltage gain. So, this is the curve which you are going to get op-amp and closed loop response, this is what we are going to get. So, the typical op-amp exhibits a linear log relationship between the open-loop gain and the frequency with the op-amp gain decreasing with the input signal of frequency.

So, you can see that as the signal frequency increases this gain decreases and higher quality op-amp has larger GBPs. The open-loop gain is characteristic of the op-amp without feedback while the closed-loop gain is the overall gain of the op-amp circuit that is with the feedback.

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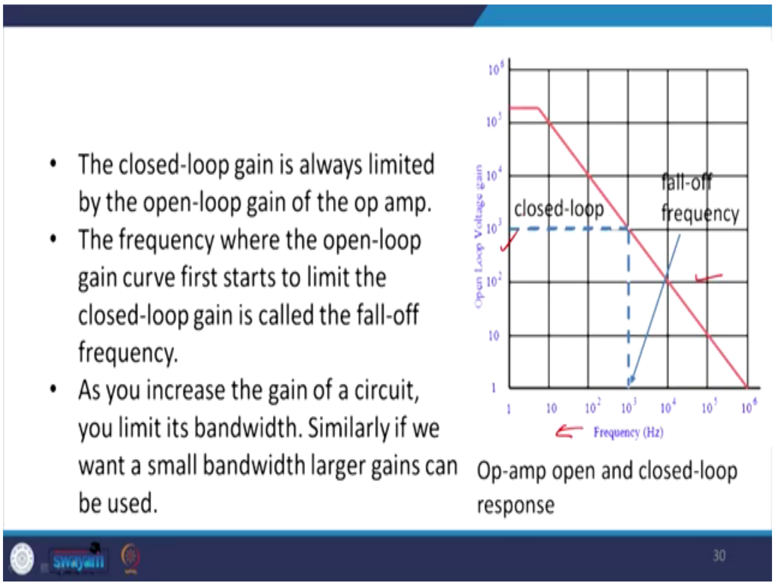

So, here you can see that the closed loop gain is always limited by the open loop gain of the op-amp. The frequency where the open loop gain curve first start to limit the closed loop gain is what is called as the fall of frequency. So, this is the frequency where that open-loop gain curve starts to limit the closed-loop gain and as you increase the gain of a circuit you limit its bandwidth as you can see in this particular figure. Similarly, if you want a small bandwidth the larger gains can be used. So, if your bandwidth is small you are going to be in this region naturally your voltage gain is going to be more.

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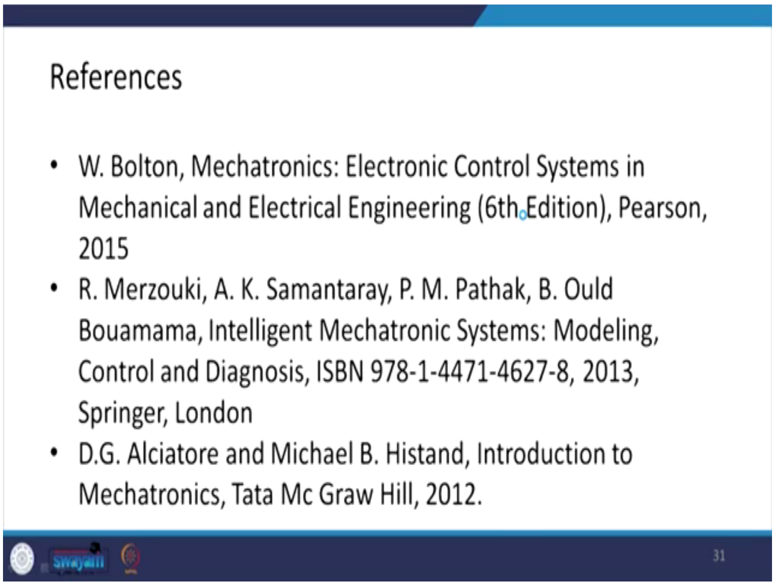

So, these are the references which you can look into for further reading. And these are the references which I have used to prepare this lecture for you, good luck.

Thank you.