Basic electronics
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Lecture- 24

Mathematical operations
(Summing Amplifier, The Averager, D/A Converter..)

Hello everybody! In our series of lectures on basic electronics learning by doing let us move on to the next 1. Before we do that we will recapitulate quickly what we discussed in the previous lecture.

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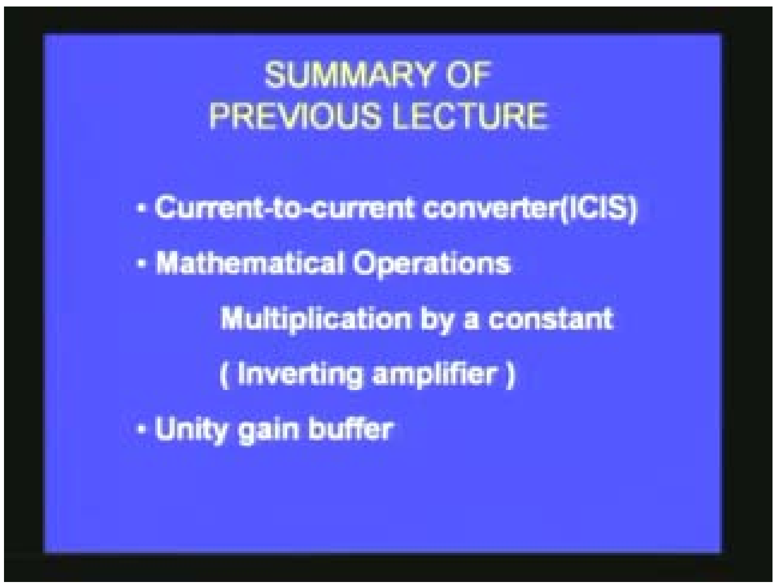

You might recall that we discussed about the different feedback configurations in an operational amplifier and we looked at some of the specific configurations and how they lead to specific types of different amplifiers. In that last time we discussed about current amplifier or current to current converter, current controlled current source ICIS. Then after the negative feedback we discussed why operational amplifiers are called operational amplifiers because they can perform different types of mathematical operations on electrical signals. We discussed some of the mathematical operations that can be performed with the operational amplifier and out of that the first 1 we discussed was multiplication by a constant which is in principle a very simple amplifier, the linear amplifier. The output is A times the input voltage that means the input voltage is multiplied by a constant factor called A which is otherwise known as the gain of the amplifier. A normal voltage amplifier can be considered as an amplifier which is capable of performing multiplication by a constant. We saw two simple configurations 1 is non-inverting amplifier and the other 1 is the inverting amplifier. We also actually performed an experiment on the inverting amplifier. Then we also discussed how by giving full feedback we can get unity gain. The gain becomes unity but even then it is a very useful circuit because it can be used as a buffer. What I mean by that is this amplifier even though gain is not the main concern it offers a large input resistance and a very small output resistance. Therefore it can be used as a buffer amplifier, unity gain.

Now let us continue with our discussions on the mathematical operations. I just want to show you the same set of operations that we discussed last time, the different types of operations. For example the first 1 is already what we have discussed multiplication by a constant something like y is equal to k times x.

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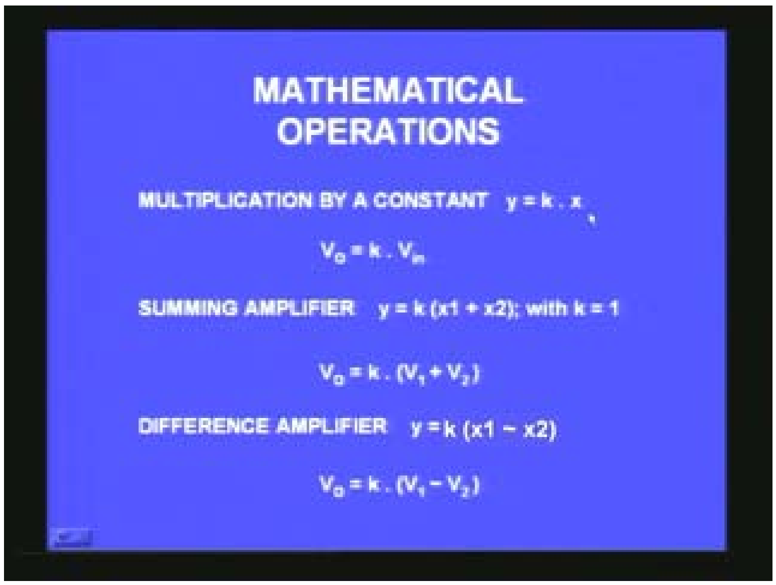

In this case in an amplifier voltage output is equal to k times voltage input could be a simple voltage amplifier with the gain of k here. Then we can also add two signals which is called a summing amplifier. So y for example is equal to k times x1 plus x2 and with the value of k equal to 1 this becomes a simple summing amplifier without any multiplication factor. You can think of an amplifier v output is equal to some gain times where the gain can also be 1 or any larger number multiplied by the sum of the inputs V_1+V_2. When I have this type of an amplifier I call this as a summing amplifier because the output is proportional to the sum of the input voltages. We have taken typically here two signals. But in principle you can have more than two also. You can have 3, 4; what ever number that you require. This is 1 circuit which perhaps we will discuss in detail today and there is also another amplifier called difference amplifier. If you can sum two signals in principle it should be possible for us to find the difference between the two signals also which are connected at the input. In a difference amplifier the output will be proportional to the difference in the two inputs. I have taken two typical example V output is k times V_1 difference V_2. If V_1 is larger than V_2 it will have a positive value and output voltage will be positive. If V_1 is less than V_2 then you would get a negative result here and output voltage will have a negative value. Whatever may be the gain the output is proportional to the difference between the two inputs V_1 and V_2. This amplifier is called difference amplifier. You have other operations which we also menti1d last time. Integration where the output voltage is the time integral of the input voltage as well as differentiation where the output voltage is the time differential of the input voltage.

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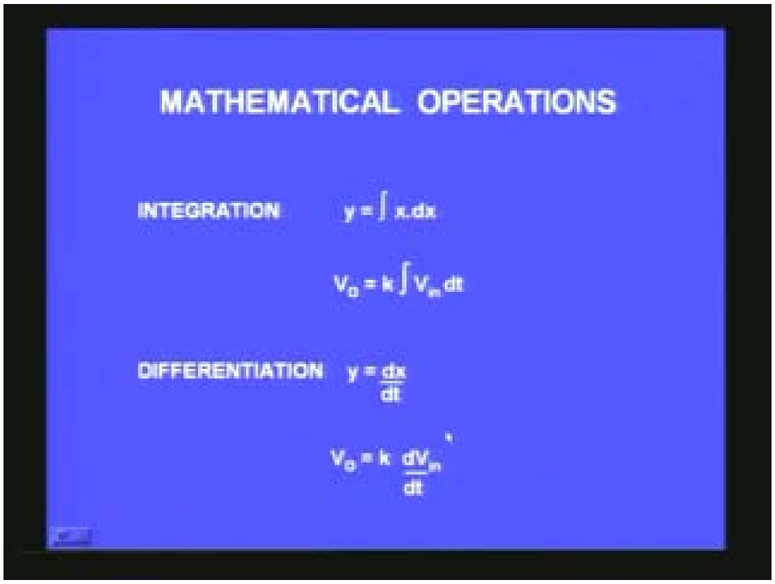

These two if there is enough time we will look at this time otherwise we will take it up in the next discussion.

How do you construct a summing amplifier?

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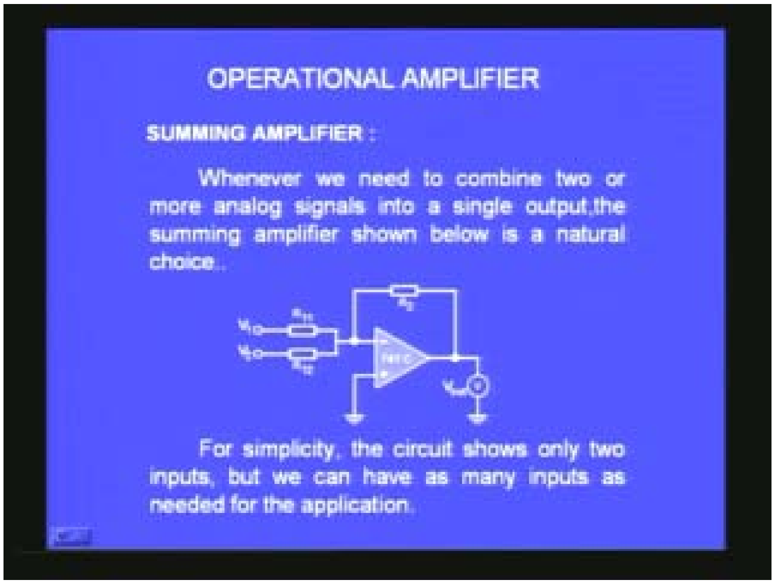

The construction of the summing amplifier is very simple as you can see on the screen. If I have 1 resistor here with 1 voltage this becomes a simple inverting amplifier. Now what we have done is we have added 1 more resistance in parallel and we give the V_2 input in parallel to V_1. They are connected together to this point which is also called the virtual earth point because the other input, the plus input of the op amp is grounded. Therefore there cannot be very different voltage on the negative input because this difference cannot be larger than plus or minus few 100 microvolts that we have already seen and if this is going to be zero this is going to be very close to zero within plus or minus few 100 microvolts. This is a virtual earth point I would like you to remember that because it will be useful to understand the working of a summing amplifier.

You have two inputs here V_1 and V_2 connected to two resistors R_{11} and R_{12} and the feedback resistor is R_2 and you have the voltmeter to measure the output voltage. This is a very simple configuration of a summing amplifier but in principle you can have more than two inputs. You can have 3 inputs or 4 inputs as you require. To understand the summing amplifier its nice to recall a known circuit for you I hope every 1 of you can recognize the first 1 I have shown here. What is it?

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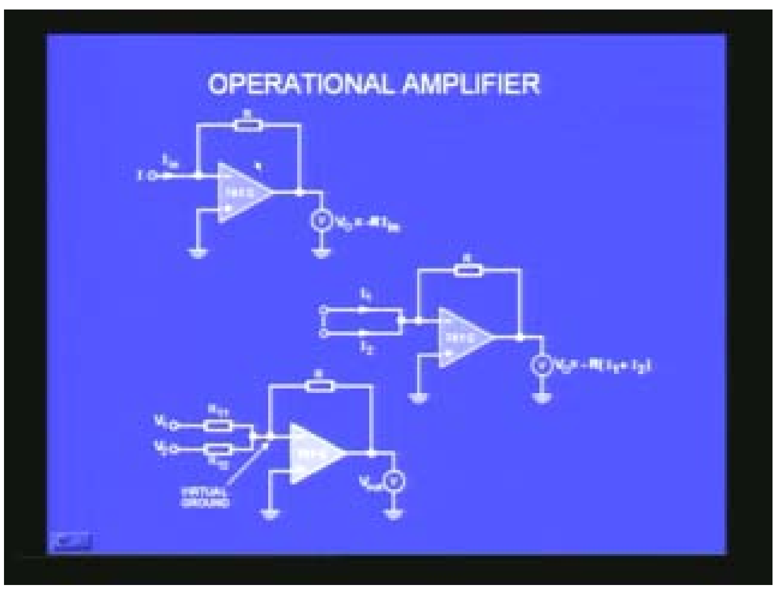

It is a current to voltage converter. It is 1 of the feedback configurations that we discussed and you have a I_{in} here and the output voltage V out is equal to -R times I_{in} where R is the feedback resistance. This circuit is a well known circuit. We have already discussed; we have demonstrated also. Now what I am going to do is because this is a virtual earth point I can add multiple current inputs to this point. That is what I have done in the next circuit that you can see in the figure. I have connected I_1 as well as I_2. What is going to happen is because the current going through the op amp is very, very small which is called the input bias current, about which we will discuss later, this current which is actually flowing into the op amp is going to be a very, very small magnitude and the entire current I_1+I_2 by Kirchhoff's current law will have to go only through the feedback resistor. Very little comp1nt, small comp1nt only flows through the op amp and almost the entire current $I_1 + I_2$ start moving through R and because it is moving towards the output terminal the output voltage should be minus and the voltage here that we measure is between the output point and the ground and because this point is as good as the ground, this is the virtual ground. The voltage developed across the resistor is the voltage that we would measure here. That is the voltage with reference to ground and it will be -R times I_1+I_2. The two currents combine together and flow through R and produce the voltage which is -R times I_1+I_2 by simple Ohm's law. This is a current summing amplifier. This amplifier is summing the two currents I_1 and I_2 and the output is proportional to current $I_1 + I_2$ the sum of the currents.

We are going to exploit this idea by introducing a voltage source V_1 and a resistance. Because this is a ground point the current through that will be only decided by R_{11}. The current here is V_1 by R_{11} that is the current I_1. Similarly you have a V_2 here and R_{12} here. Because this is a ground you have V_2 by R_{12} as the current I_2 flowing through the second 1. We know output is -R times where R is the feedback resistance R times $I_1 + I_2$. We have obtained I_1 I_2 by using two voltage sources V_1 and V_2 and two resistors R_{12} and R_{11} and V output is equal to - R by R_{11} V_1.

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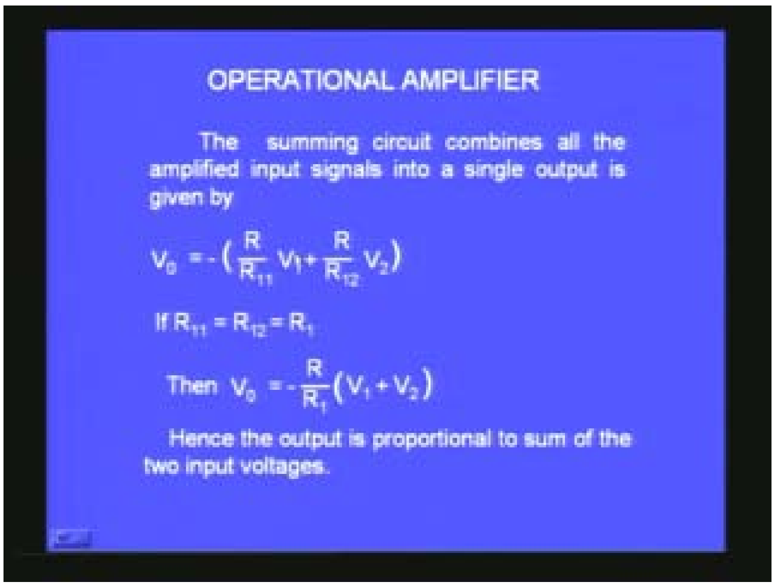

V_1 by R_{11} is the current I_1 multiplied by R is the voltage due to this current plus V_2 by R_{12} is the second current I_2 multiplied by R gives me the second voltage. I sum these two voltages because I have to sum the two currents. If R_{11} is equal to R_{12} and is also equal to R_1 I take it as R_1. If the two resistors become equal for simplicity then I can take out this R by R_1. The output voltage is -R by R_1 multiplied by V_1 plus V_2. If I also make R is equal to R_1 then this factor will become 1, the multiplication factor. Then the output voltage is the sum of the two input voltages V_1 plus V_2. But there is a negative sign which shows that it is going to be 180 degrees out of phase. You can also have dc or ac inputs. The instantaneous values at every point will be the sum of the two instantaneous inputs V_1 and V_2. So V output is equal to -R by R_1 V_1 plus V_2. That output is proportional to sum of the input voltages. So it's a very simple way to obtain the output voltage in terms of the input voltages. This is basically a summing amplifier. Let me quickly do a simulation of the summing amplifier.

You have a bread board and you have the dual supply here and you have two voltage sources. It's a 1 box in which two voltage sources are there. They can be increased or decreased and you have a multimeter to measure the output voltage; you have the op amp and the various resistors etc and this is the summing amplifier circuit that is shown here. Same as what we just now discussed the R_1 R_2 and R_3. R_3 is basically to compensate for the differences in input bias current. Right now we need not bother too much about that. The basic idea is you have 1 voltage here that produces the current V_1 by R_1. There is another voltage V_2 that produces the current V_2 by R_1. These two currents add here at the virtual earth point and that flows through the feedback resistor. You get an output voltage which is proportional to the sum of the two currents and the currents are produced by two voltages and ultimately it becomes the sum of the two voltages.

Let me quickly build the current circuit. You can see the op amp goes and sits in the proper place and the different resistors are put in place and the wiring is carried out. The pin number 4 is connected to a negative; the blue line is the negative of the power supply and the red line is the positive of the power supply that is connected to pin number 7 of the op amp and the black is ground that is connected to 1 of the rail lines here and that is also connected to the negative of the multimeter. In the pin number 2 you have 1 resistor. Another resistor is also connected to pin number 2 but they are connected to two different sources. This red line comes from 1 voltage source the other red line comes from the other voltage source. They are adjacent points but they are different and the common ground is all connected to the same ground line. So two voltage sources are connected at the input and this is connected to the ground; the pin number 3 is connected to the ground as it is shown here in the circuit and this feedback resistor is here and that is connected as the feedback resistance between pin number 2 and pin number 6.

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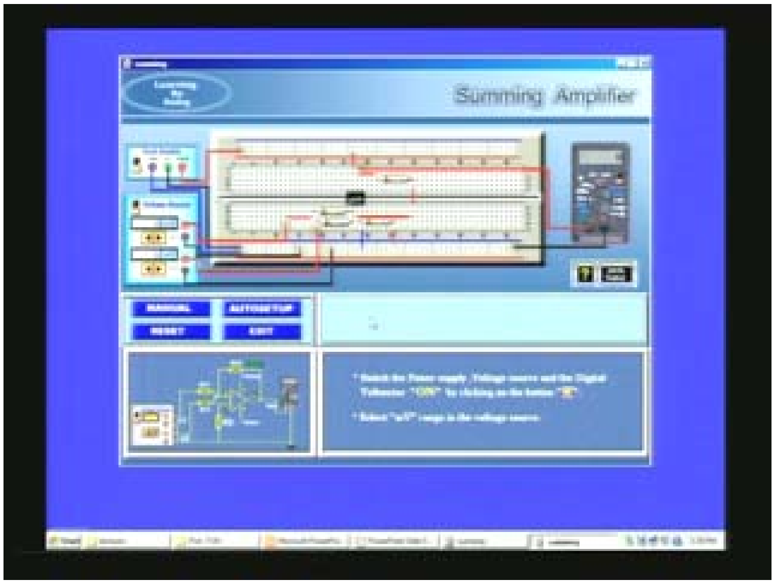

The wiring is exactly similar to what you have seen here and now we are ready to perform the experiment. We will switch on the dual power supply. We will switch on the voltage sources and we will also switch on the multimeter which is also connected between the pin number 6 and the ground to measure the output voltage. Let us start giving input voltages in millivolts. Let me increase here. It is about 100 millivolts and this is zero and the gain is 10. The feedback resistor is 10K, the input resistors are 1K each. Therefore there is a gain of 10. 100 millivolts multiplied by 10 is 1.1 because I have not given the other input anything.

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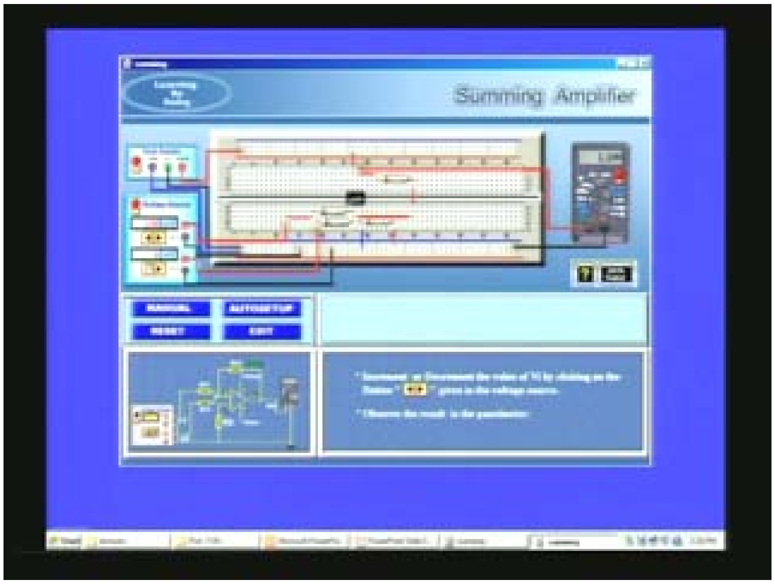

Now if I give another 100 millivolt here it has become 100 + 100 = 200 millivolts together. This 100 millivolt and this 100 millivolt will have to be summed together at the output with a gain factor of 10. When you do that you get about 2.2 volts. If I keep increasing the voltage the output also changes to some 3 volts or 4 volts. This is 200 millivolt input; another input is 200. So output is proportional to 400 millivolts. This is 10 times multiplication and it becomes 4 volts. The slight difference that you get in terms of an additional value here can be accounted for in terms of the tolerances of the resistors. The resistors may not be precise and there is also what is known as an off set voltage. Every op amp can have some finite voltage at the output even when the two inputs are connected to the same voltage or connected to the ground. This voltage we call off set voltage. That means it is already having a residual voltage of about 400 millivolts and when you connect the output, the output comes in combination with that additional off set voltage. That is why it is showing 4.4 volts. It is a very, very simple configuration. 1 can easily do the circuit and I have also got some data here where you can see how the different numbers come.

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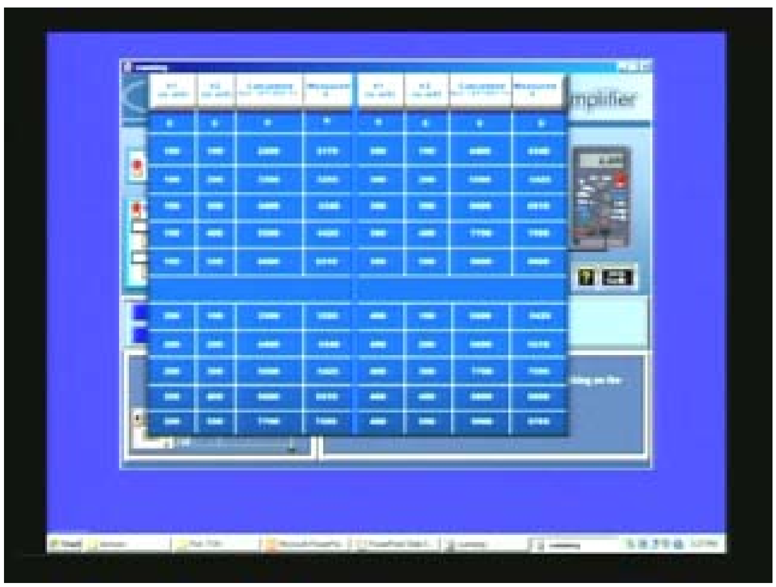

It is not important. May be when we do the actual experiment we will be able to see that. Once I get a summing amplifier then this can be used in different situations. For example in case I need an average voltage of all the voltages that I have with me then it must be very easy to do. For example in the circuit I have shown V_1, V_2 and V_3 are three input voltages. I have got everywhere 3R, 3R, 3R as the resistor and R is the feedback resistor. What will be the output voltage? It is the same summing amplifier. The only difference is the input resistors are three times the feedback resistor. All of them are equal and three times the feedback resistor. The output voltage will have to be $–V_1$ plus V_2 plus V_3 by 3. Because this is R this is 3R the output will be 1 by 3 times V_1. The output at the second input is V_2. That again is 1 by 3 because R by 3R. Feedback resistor is R input resistor is 3R. The amplification or the gain factor is R by 3R. Similarly for the third 1 it is R by 3R. When I combine them together $–V_1/3$, $-V_2/3$, $-V_3/3$; that means minus of V_1 plus V_2 plus

V_3 by 3. This is nothing but the average of the three input voltages. V output is an average of three input. There is negative sign that shows there is a phase difference between the input and output. This is another mathematical operation that you have now determined to get the average of the three input voltages.

We will try to do the demonstration of the summing amplifier. Here you can see the circuit of the summing amplifier with V_1 and V_2 and the two resistors and the feedback resistor all in place.

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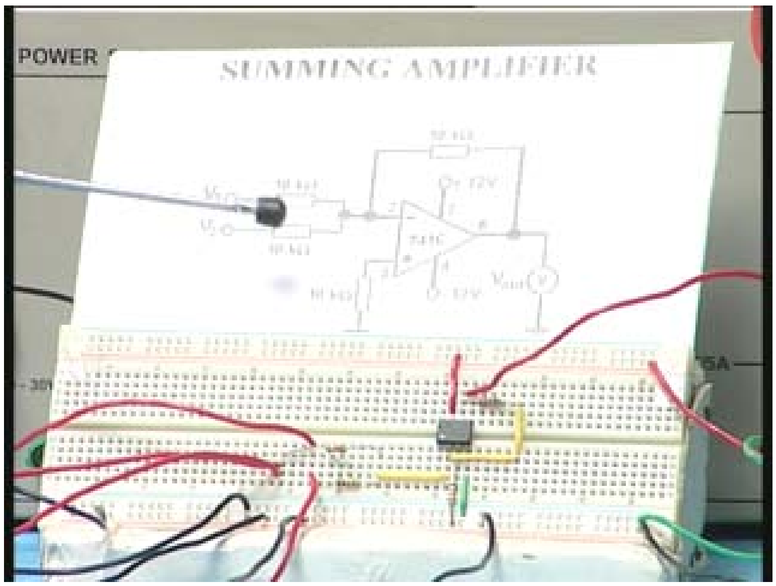

This is the voltmeter. You can see in the bread board the actual operational amplifier and the two resistors at the input and the R_3 which is connected to the ground from the pin number 3 and this is the feedback resistor which is here. The circuit is the same as what we have seen here and what also you have seen in the simulation. This is the basic summing amplifier with two inputs. To get the two inputs you can see I have connected 1 voltage source. This is the voltage source and you can change the voltage input from millivolts to volts and that is connected to the bread board as 1 of the input and that voltage is also monitored by this voltmeter that you see here. It is kept in voltage mode and what you read is the voltage applied from this voltage source. 300 millivolts is the voltage that I apply here and therefore it is also reading 0.30 volts. That is nothing but 300 millivolts; 0.3 volts is 300 millivolts. If I now change it to 200 millivolts then it shows 0.2. If I change again back to 0.3 or 300 millivolts the multimeter reads 0.3. This voltage source and this voltmeter corresponds to V_1 first of the two inputs. The second input is got from a power supply part of the power supply which has got a variable input here and that voltage is connected as the second input on the bread board. This red wire is corresponding to the second input and this multimeter is the input voltage corresponding to this power supply here. I have two independent power supply 1 from these and the other from the voltage source and this voltmeter reads the second voltage input V_2. Both are connected and the output is monitored by a third multimeter which I have connected here and this is the reading corresponding to the output voltage and that is connected to the third multimeter.

I have given here around 300 millivolt. It is 0.3 volts or 300 millivolts and here it is about 330. Together if you add you should get about 600 and odd and what you get in the third multimeter is the sum of the two; 0.068 because in the circuit if you observe I have used all of them 10K, 10K, 10K. The gain factor becomes 1 here and output is simply the sum of the two and I would draw your attention to the sign on this multimeter which shows minus.

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These two inputs are positive but at the output you get an inversion because it is -R times V_1 plus V_2 and R_2 by R_1 and the minus sign comes because there is an inversion involved at the output. Now when I change the input voltage of 1 of the voltage source to 400 that is 0.4 volts or 400 millivolts plus whatever that was previously there 3.7 together makes it 0.78 or 780 millivolts. Every time I change these two the sum of the two is what I get at the output. I will keep decreasing; I would like you to look at this and also this. 0.3 + 0.37 gives me 0.68 and 0.2 and 0.37 gives me about 0.57 and now I am going to still reduce it. This is 0.1 here. V_1 V_2 is about 0.37. Together it should be around 0.47 and this reads 0.48. So the two voltage sources connected at the input and the output is the sum of the two voltage input. This becomes a summing amplifier.

Having seen a demonstration of the summing amplifier we can also look at some of the applications. Already we have seen 1 circuit which is an application of the summing amplifier. Do you remember that? Yes! That is the averaging circuit. We have seen the averaging circuit where the output voltage is an average of the input voltages V_1 V_2 and V_3. Now we will see 1 more example which is of great importance and that is the digital to analog converter.

What is a digital to analog converter?

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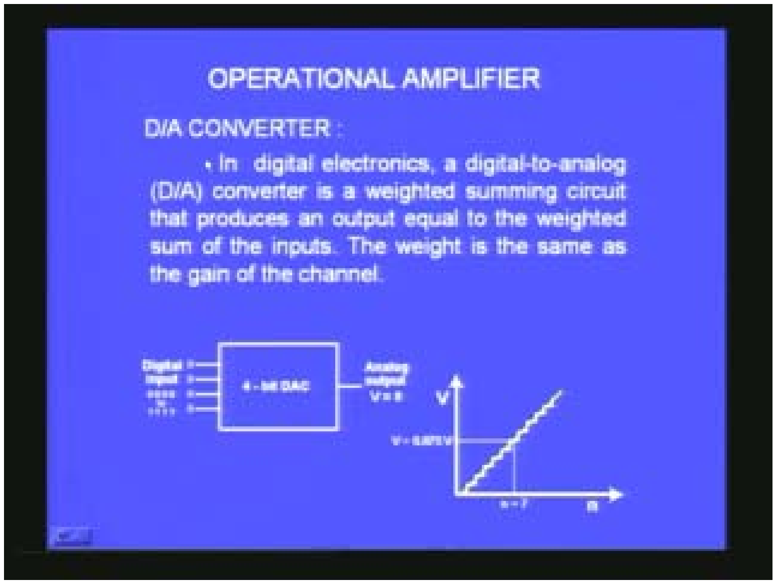

A digital to analog converter is something like a circuit that is shown here in the form of a box. You have digital input. The digital input is having only 2 values either 0 volts or 5 volts or in terms of numbers 0 and 1; logic 0 or logic 1 and this output here is a continuously changing number or voltage. What is that we want to do? We want to convert the digital number. In this case it is a 4 bit number where a 4 bit means binary digit. It can be either 0 or 1; four of them. You can have, as you see on the screen, 0, 0, 0, 0; all zeros to all 1s. You can try all permutations of the input. There are nearly 2 to the power 4 possibilities. That is from 0, 0, 0 to 1, 1, 1 you have 16 possibilities of different numbers. Equivalent decimal numbers if you look at it will be 0 to 15 because the weights for 1, 1, 1, 1 is 8, 4, 2, 1. If you add them all together it is 15. So 8, 4, 2, 1 is 15. 0, 0, 0 to 15 is the number that I can send here for different inputs and what I get will be a proportional analog voltage. So it converts a digital number into a corresponding analog voltage. For example if I send 0, 0, 0, 0 as it is now you get V is equal to 0; output is 0. But if I send 1, 1, 1 all these inputs 1 that means 5 volts if I connect everywhere this is a digital input then the output becomes a maximum value for example 15 volts. So if I send a number 3 corresponding to a bit pattern 0, 0, 1, 1 which is 3 I will get 3 volts. If I send a pattern corresponding to 8, 1, 0, 0, 0 the output voltage will be 8 volts. If I keep changing here the number there is a proportional corresponding analog voltage here and this is what we call the digital to analog converter.

If I want to bring about this circuit how to construct the circuit which will perform what I just now explained to you. That means if I give a digital input with 4 inputs either it can be 0 or 5 volts nothing else in between then I should get a proportional voltage which is proportional to the particular number that I send here. If I send 5 I should get 5 volts. If I send 7 I should get 7 volts etc. That is what I have shown here in the graph on to your bottom. You can see on the X-axis I put the number ‘n’ which is the digital number that I send in 4 bit format and what I get on the Y-axis is the output voltage. You can see that for every number I change here there is a corresponding change in the output voltage. When I keep changing the number continuously from 0, 0, 0, 0 to 1, 1, 1, 1 the voltage keeps increasing by small amounts every time; every time I increase the count. What I get here will be something like a staircase. For every number that I have here, there is a corresponding level of analog voltage. If I increase the number by 1 it increases by a small value and if I increase still further it increases by the next number. If I have here in this case 4 bit I can go up to 15 here and output voltage will correspond to the corresponding analog that I get here. In this example when I send the number 7 I get 0.875 as the voltage and when I send a 15 it will be 1.875 volts. This is what is called a digital to analog converter in a simple way

How do we implement? I can take a summing amplifier as I did before.

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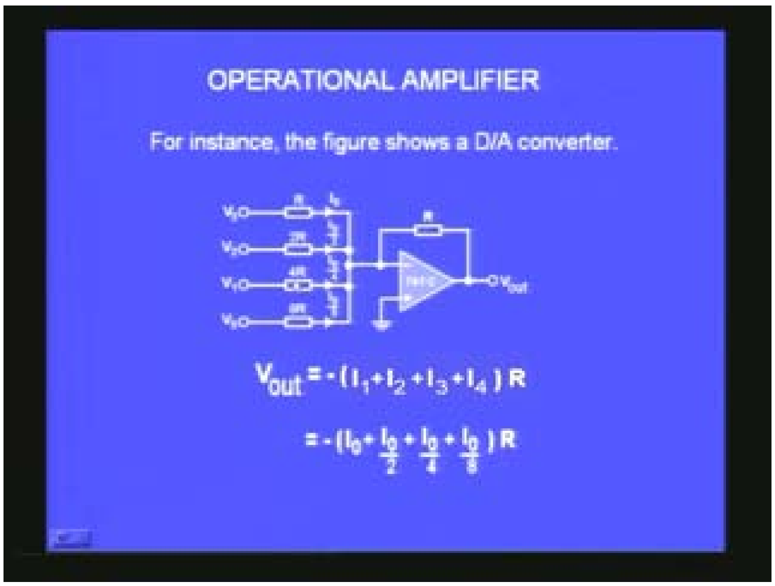

But there are very certain specific differences in the sense I have used the resistors R for 1 of the inputs I have used 2 R for the second input I have used 4 R for the third input I have used 8 R for the fourth input. That means the resistors are according to the weightages of the binary digits. This is the most significant bit as it is known as and this is the least significant bit and the corresponding resistors are also changed accordingly. I should put it like this. This is the least significant digit and this is the most significant digit. The least significant digit gives you a least current. The current here is voltage divided by resistance by Ohm's law; V zero by 8 R and if I call V_0 by R as I_0 then I_0 by 8 is the current in this. Because here it is 4 R, this arm, the current produced when I have V_1 applied is I_0 by 4 because of the 4 R and in the third line it will be I_0 by 2 and in this it is I_0. You have the currents here which are proportional to the binary positions of the positional value of the digital number and these currents are going to be summed here and that will be proportional to the V_{out}. So V output is going to be minus I_1 plus I_2 plus I_3 plus I_4 this R should be I two I three and I four times R and in this case I_1 is I_0, I_2 is I_0 by

2, I_3 is I_0 by 4 and the last 1 is the I_0 by 8 multiplied by R. This is the voltage that I will get when I apply all of them with 5 volts. If I apply all of them with 0 volts there will be zero currents. The entire current will be zero multiplied by R the output voltage will be zero. So the maximum voltage is when I apply all the voltages here all the four voltages and that will correspond to this current.

What is the gain factor for each of these? For A_3 it is -1 because it is just –R/R that is equal to -1. For the second one is –R/2R; it is 0.5.

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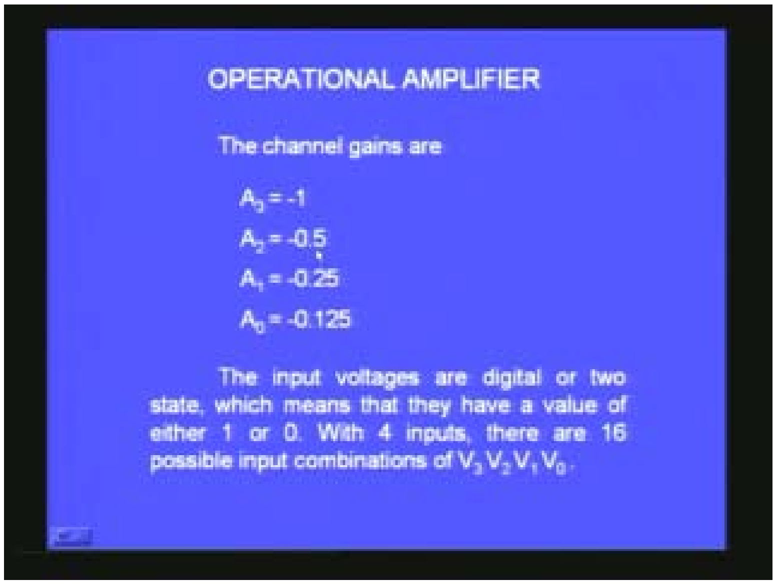

For the third one it is R/4 therefore -0.25 and the last one is 1/8 so -0.125. These are the gains by which I should multiply the input voltages and that is how I will get proportional analog voltage. The input voltage are two stages either 1 or 0 in logic or either 0 volts or 5 volts. There are 16 possibilities from 0, 0, 0 to 1, 1, 1. When I have all input 0 the output voltage is 0 as I already explained to you. When only one of them is high that is the least significant digit 1 that means I will have 0, 0, 0 1 in binary the output voltage is only multiplied by 0.125 times the R/R. Because R/R is 1 it is just 0.125 voltage minus.

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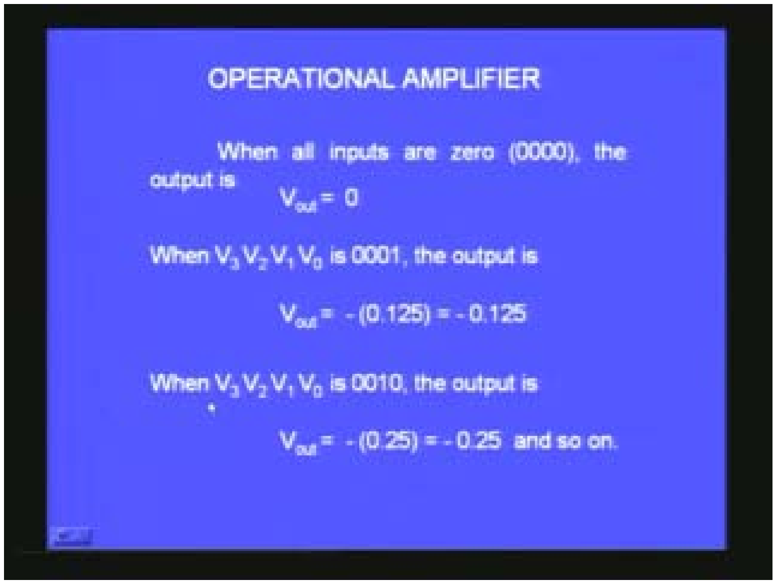

When the signal is 0, 0, 1, 0 the binary number is 0, 0, 1, 0 then the output is corresponding to the second point which is -0.25 and therefore is -0.25 volts. The output voltage is proportional to the magnitude of the digital number that I connect at the input with the 5 volts or 0 volts as the case may be in terms of binary digit and when I get all the inputs 1, 1, 1 the output is maximum that will have 1, 0.5, 0.25 and 0.125 all together coming and summing together and therefore you get -1.875 volts.

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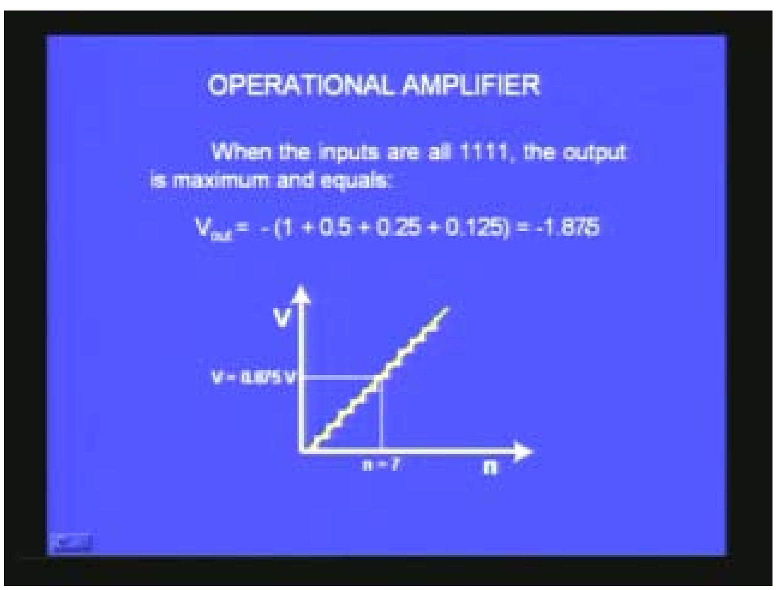

That is what you will get when the input, all of them are 1 and this corresponds to 7. That means this alone is 0; rest of the things 1 and you will get 0.875 volts. This is actually a digital to analog converter.

Now what I am going to show you is actually a demonstration of the digital to analog converter. I will go down to the table and show you the working of a digital to analog converter. Here you can see the circuit diagram of the digital to analog converter; a 4 input resistors and they are all 10K, 20K, 40K and 80K. They have to be R, 2R, 4R and 8R.

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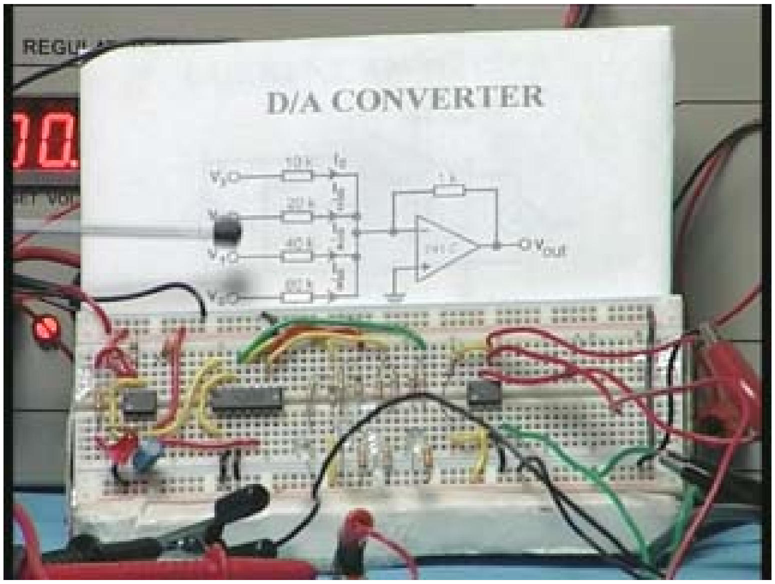

The R is 10K; so 10K, 20K, 40K and 80K. You have the four inputs here V_0, V_1, V_2 and V_3. You have the summing amplifier here. This is a feedback resistor which is also 10K in this case and we measure the output. In order to give the digital number here what we have done is we have used this 10K etc by standard values. We have used 10K here. For this we have used two resistors two 10K resistors in series. That's what you will see here in the circuit. For the sake of 40K we have used 33K and a 6.8K resistor together in series so that together they form 40K and for 80K we have used 47K and 33K two resistor in series. You can also buy from the market very precise value of resistors and try them out. It will be much better in performance.

These are the resistors and in order to give different binary inputs here what we have done is we have constructed a clock circuit using ne 555 and it is a very low frequency clock as you can see from the light emitting diode here.

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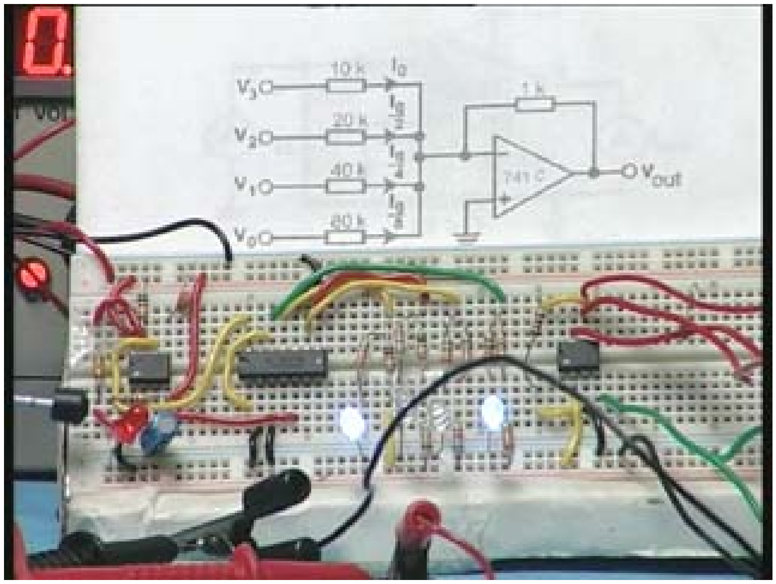

It is glowing very, very slowly. This is 1 hertz approximately and that is given to a counter, a binary counter 7493. This binary counter output will go from 0, 0, 0, 0 to 1, 1, 1, 1 in a sequence regularly every time a clock input comes and those four outputs 0, 0, 0, 0 to 1, 1, 1, 1 is now connected by using these wires to the input of the binary here V_0, V_1, V_2, V_3 and it is going to keep on counting as you can see from the light emitting diodes that are connected to the output. You can see all of them are now glowing; all of them have gone zero. Now this is the first one. This is two; this is 3, 1, 1 then 1, 0, 0 is 4; 1, 0, 1 is 5. So it goes in binary sequence here. As it goes the input will keep increasing; the summing amplifier output is measured using this multimeter. This voltage whenever there is a change here this is also changing the output voltage here.

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It goes one after another; you can see that. Because it is going in sequence this output voltage will keep increasing in a sequence upto a maximum and then again come to 0. To see that instead of looking at the multimeter we have taken the output and connected to an oscilloscope here. This is an oscilloscope and the output of the summing amplifier is now connected to the oscilloscope. I am going to connect it and then for increasing the speed I am going to remove the capacitor here and connect the small capacitor which I have here. I have removed the earlier capacitor which is about 100 microfarad and replaced with a very small capacitor 0.1 microfarad. You can see the frequency of these LED's glowing has increased enormously now.

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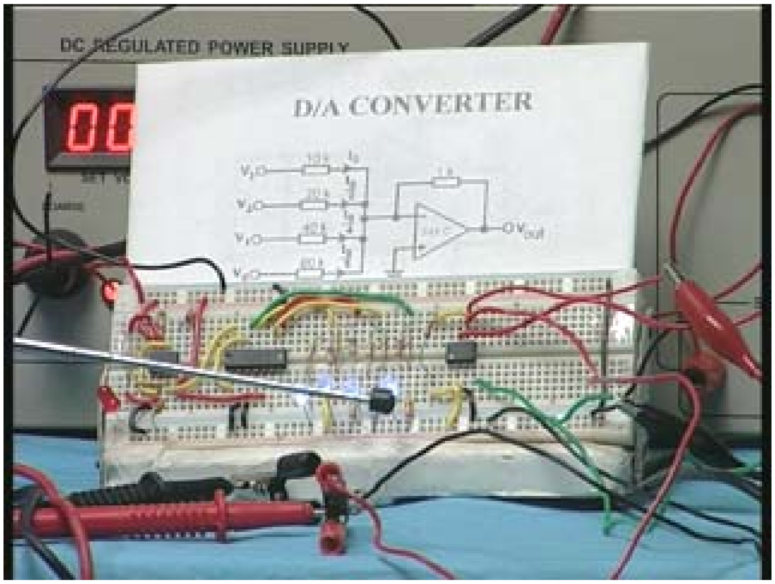

You can only see the most significant bit flickering rest is not flickering. They are also going in the sequence but because they are going at a very high frequency you are not able to see that and this only you are able to see; little bit of the second digit but you are not able to see the rest. The changes are too fast and the output voltage will also keep increasing in a staircase type. That is what you see on the oscilloscope here. You can see the voltage is increasing and this is actually on the negative side. It is increasing on the negative side.

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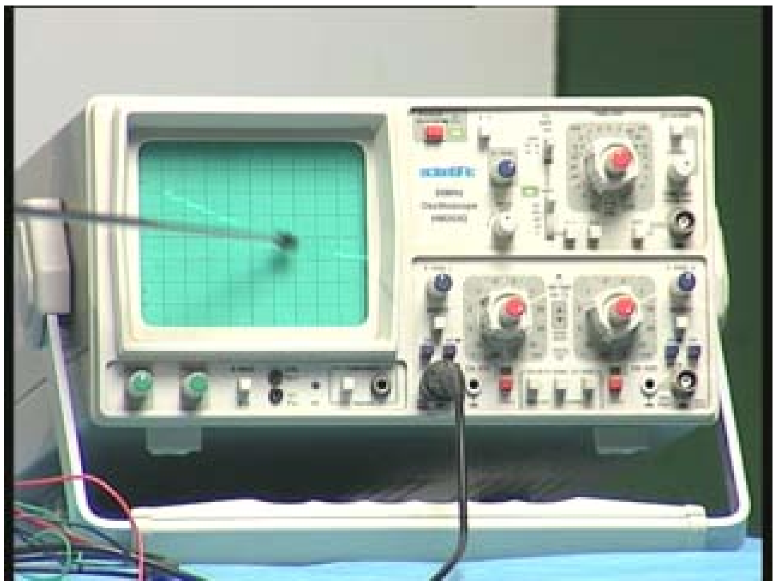

This is the corresponding output of the digital to analog converter when you have continuous change from 0, 0, 0 to 1, 1, 1 using a counter. So you get a staircase generated here. It is negative going staircase that is what you get and this becomes a digital to analog converter. Instead of giving this continuous input I can connect them specifically to 5 volts or 0 volts, the number that I want and the output will be a constant value corresponding to that at this stage. Because I am continuously changing here the output voltage is also continuously changing. This is an example of an application of the summing amplifier with the digital to analog converter.

We will move on to the next mathematical operation. We have already completed the summing amplifier and now we will move on to the next application of the operational amplifier which is a differential amplifier or difference amplifier. You have seen the summing then you look for the subtraction. What is a difference amplifier? I have shown on the screen a very simple configuration of the differential amplifier or difference amplifier. You can call it by any name you want and you can see there is op amp; you have got two resistors R_1 and R_2 and it is an inverting amplifier and you also have another R_1 R_2 on the other non-inverting input. This becomes the difference amplifier or differential amplifier because the output voltage V_0 is equal to some constant A times V_2 difference V_1 where V_1 and V_2 are the two input voltages.

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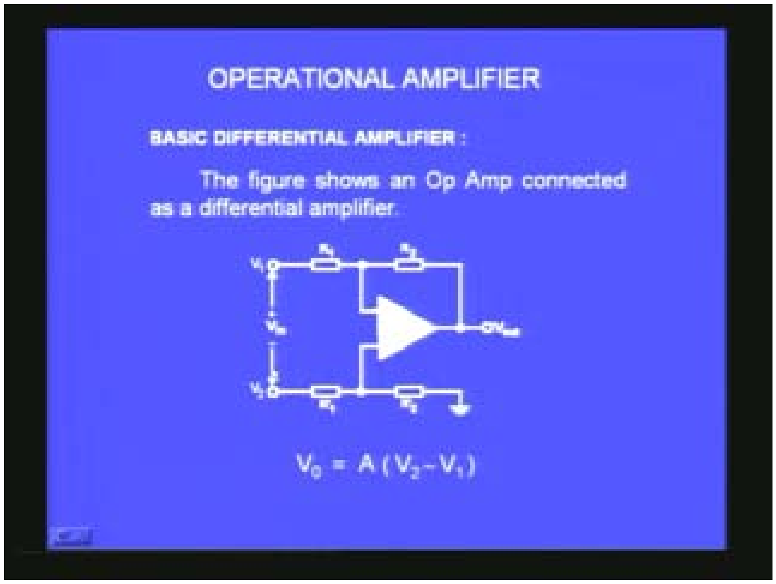

So you see that in the previous summing amplifier the two different voltages were applied to the same terminal, the negative terminal. In this case the two inputs are connected one to the negative inverting input the other to the non-inverting input. You have A into V_2 difference V_1. If V_2 is larger in magnitude to V_1 you get a positive voltage at the output. If V_2 is less than V_1 you will get a negative output voltage. The output is proportional to the difference in the two input voltages. There is an advantage in using this type of a difference amplifier or differential amplifier because it is sensitive only to the difference in the voltages between the two inputs. So all the inputs which are common they are called common mode signal. Can you identify the voltages which are common to the two inputs? You can immediately recognize all the extraneous noise voltages that is around us due to the 50 cycles, due to the various other sources all of them will be common to both V_1 and V_2. In addition to whatever voltage you apply there is also going to be the noise voltages due to the surroundings. All of them because they are common to both the inputs they will never be appearing at the output in principle. Because this amplifier is only looking for the difference between the two inputs whatever that is common will be rejected. Therefore this difference amplifier has got a great advantage in terms of noise rejection and that factor basically in a difference amplifier is called a figure of merit which is called common mode rejection ratio which is the ratio of the differential gain to common mode gain ad by ac.

We will talk more in detail about the cmrr and other parameters of the operational amplifier at a later time after we discuss the mathematical operations. Basically in the difference amplifier the output voltage is proportional to the difference between the two input voltages. To understand the relationship between the output and the input in terms of the circuit I have given very simple scheme here. The same circuit is drawn in a slightly different way that is all. It is the same; there is no change here from the one that I showed you before.

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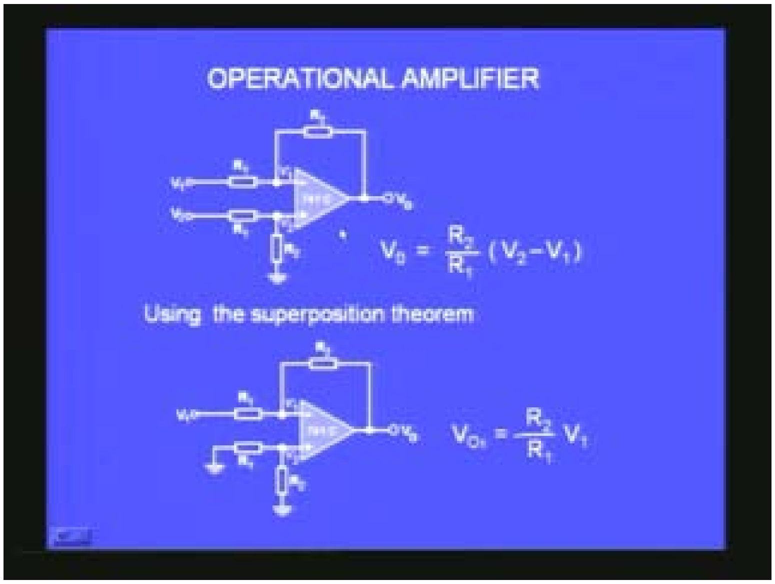

V output is R_2 by R_1 where R_2 is the feedback resistor R_1 is the input resistor which is common to both V_1 and V_2. We have used the same resistor, equal resistors R_1 and R_2. R_2/R_1 multiplied by V_2-V_1 is the output voltage. The output voltage is proportional to the difference. How do we get this expression for the output? It is possible by using superposition theorem. You assume that V_2 is not there. So you ground the V_2 input and apply only V_1 and find out the output voltage. Then what you do is you apply only V_2 and ground the V_1 input and find out now the output voltage. Then by superposition theorem the total output voltage when both the inputs are present will be the sum of these two outputs and that is what we want to do now.

The first figure here which I have shown I have grounded the V_2 input and there is only V_1 input and when I ground this R_1 R_2 are the plus terminals; they are coming in parallel and this becomes a very simple inverting amplifier. The configuration is identical to an inverting amplifier. The V_{O1} corresponding to V_1 alone being there V_{O1} is equal to R_2 by R_1 times V_1. Because it is an inverting amplifier there is also a minus sign here; - R_2 by R_1 times V_1. This is a very simple expression that I got only when V_1 is applied and V_2 is ground. Now we will do the other thing; that means ground the V_1 terminal and apply only the V_2. Now what happens? When you do that you are applying the voltage V_2 across two resistors in the potential divider arrangement. R_1 and R_2 are coming in potential divider arrangement and I can easily calculate the voltage at this point V_2 prime.

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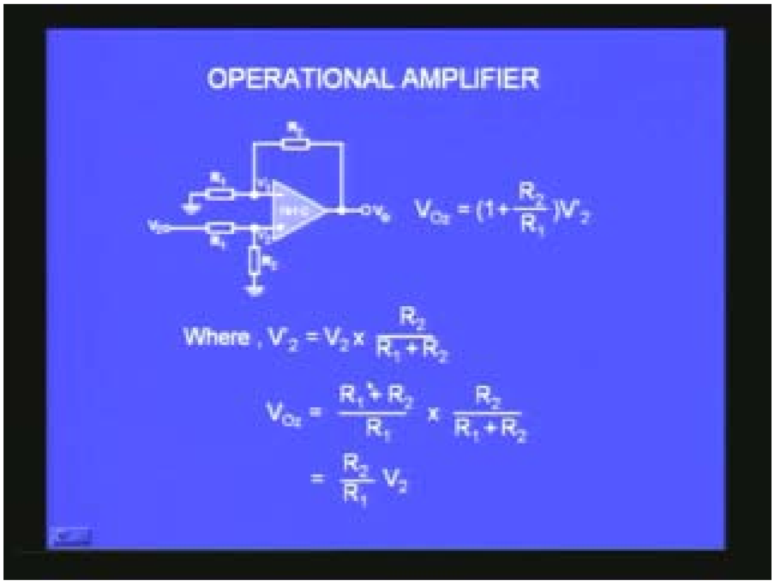

So V_2 prime is going to be V_2 the applied voltage multiplied by R_2 divided by R_1 plus R_2. So V_2 prime is V_2 times R_2 divided by R_1 plus R_2 and this voltage is the actual voltage applied at the non-inverting input of this op amp and because this is grounded only if you look at this part of the circuit you can recognize it as a non-inverting amplifier which we discussed in the feedback configuration at the first instance. The output is very well known. V output is equal to 1 plus R_2 by R_1 times V_2 prime where V_2 prime is the actual voltage applied at the pin number 3 or the non-inverting input of the op amp. R_2 R_1 are the feedback resistors and the R_1 is the input resistor. So V_{O2} is equal to 1 plus R_2 by R_1 into V_2 prime. But we have already seen V_2 prime is obtained using the potential divider; V_2 into R_2 by R_1 plus R_2. So I combine these two V_{O2} is R_1 plus R_2 by R_1 into R_2 by R_1 plus R_2. This 1 plus R_2 by R_1 is nothing but R_1 plus R_2 by R_1 into R_2 by R_1 and multiplied by V_2 that V_2 is missing here. If you cancel R_1 plus R_2 you get R_2 by R_1 times V_2. When I apply V_2 alone I get an output which is R_2 by R_1 times V_2 with a plus sign here and when I apply the V_1 alone you get – R_2 by R_1 times V_1. When I combine them together V output is by superposition theorem V_{O1} plus V_{O2} minus R_2 by R_1 times V_1 plus R_2 by R_1 times V_2 and that means R_2 by R_1 times V_2 minus V_1 and this is the expression that we already know.

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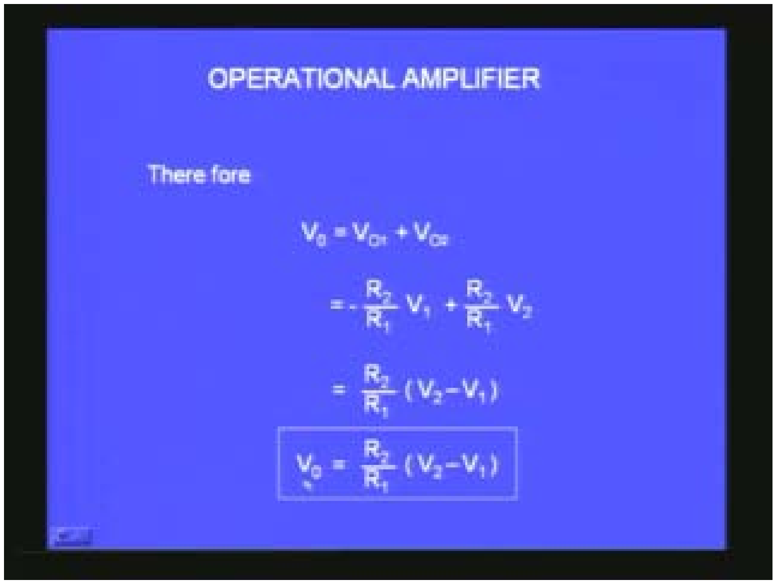

V output is equal to R_2 by R_1 times V_2 difference V_1. If V_2 is larger then this should be positive and the output voltage will be positive. When V_2 is less than V_1 then you will get a negative voltage here and the output also will become negative.

Now we will perform a simulation of this difference amplifier or differential amplifier. You have the bread board here. You have the dual supply and you have the two voltage sources as in the case of the summing amplifier and you have the multimeter and the circuit is shown here. This is the difference amplifier which we have already seen with the two input voltage, R_1 and R_2 resistors and the feedback resistor R_2 and the other resistor R_2 here. You have a voltage source two voltage sources and the multimeter. Now let me quickly set the circuit …. the differential amplifier. So you have the two resistors at the input and this is the one which is connected from the pin number 3 to the ground. This is the one which is the feedback resistor and they are all connected to the power supply, the dual supply, the voltage source and the multimeter. Now the circuit is ready. One voltage source is coming to this input which is actually going to pin number 2 and the other input of the voltage source is coming to the pin number 3 and then the 3 is also connected to the ground and the pin number 2 is connected through a feedback to another resistor which is R_2 here.

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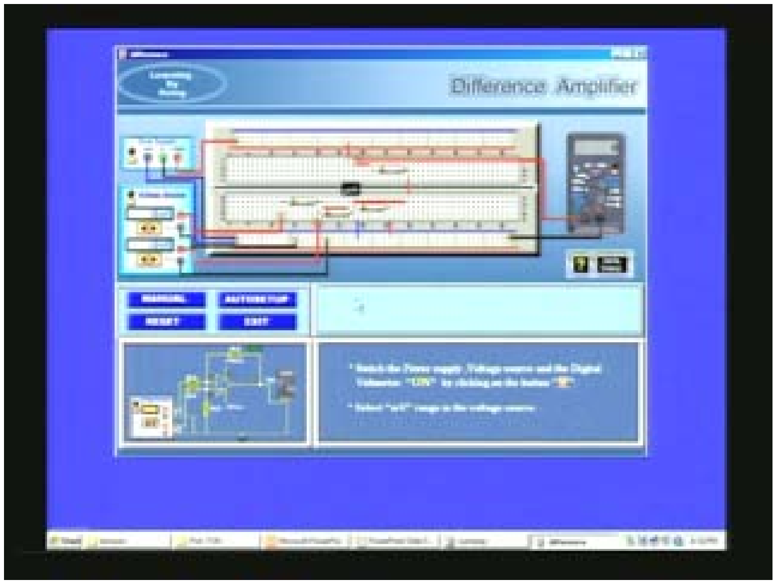

Let us switch on the power supply, the voltage source and the multimeter. Everything is switched on. Now we can start giving input voltages. I give 100 because this is connected to pin number 2 I get about 10 times this value due to the gain. So it is -1 volt; 100 millivolts minus 10 corresponds to -1 volt. I give 200 millivolts here at the V_2. So V_2 is larger V_1 is smaller. The V_2 minus V_1 is 100 millivolt and multiplied by 10 is 1 volt. That is what the multimeter reads here; 1 volt.

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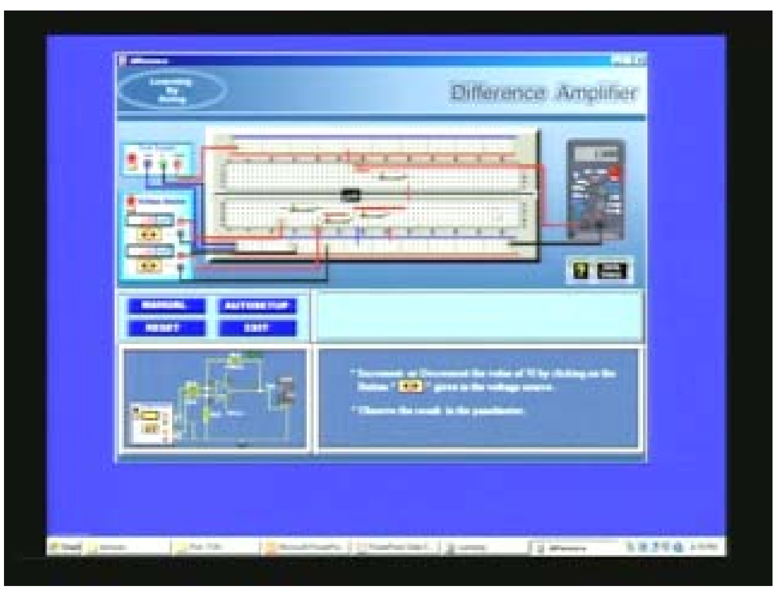

I now increase V_1. It is 300 millivolts. V_2 is 200 millivolts and there is a difference of 100 millivolts. But it is the minus input which is larger and therefore the output becomes minus. If I make them equal they appear to be zero. But in principle if you actually try it out in the lab it will not be exactly zero because zero is very difficult to obtain; it can be few microvolts or millivolts. There will be some residual voltage about which I have already mentioned earlier in the summing amplifier also and that is even when both inputs are equal to zero or to any constant value say 300 millivolts still the output need not be zero because there is always what is known as an off set voltage about which again we will discuss at a later time. The off set voltage is the residual voltage that you get when you connect both the inputs to zero. In principle it should be zero. For an ideal operational amplifier when the two inputs are grounded the output should be zero. But in actual practice even when you ground both the inputs the output need not be zero. It will have some residual value either positive or negative depending up on the op amp. Even though it shows zero here in this case, in an actual case in the lab it is not exactly zero. It has got a very small value of voltage. So this is the difference amplifier.

Now I would like to quickly go there and show you a demonstration of the difference amplifier. Here we have the difference amplifier. The circuit is shown here; the same as what we discussed already. You have the two inputs V_1 and V_2 and you have an output measured using a voltmeter and this is the difference amplifier. Here all of them are with 10K, 10K etc so they are the same.

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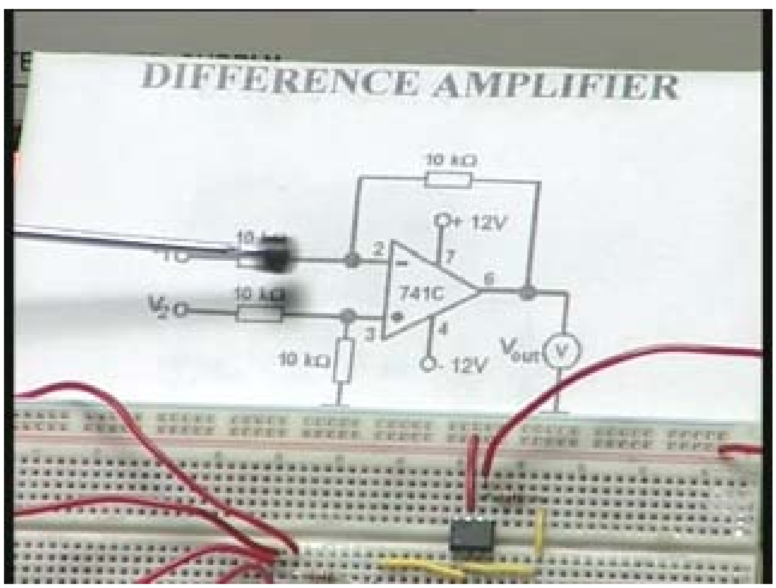

The gain A is 1 because all the resistors chosen in this circuit is 1 and in this circuit you can see the op amp here and the resistors, two resistors and the two other resistors are all shown here and all of them are 10K. The gain factor is 1. What we expect is if I give V_1 and V_2 then the output voltage should be directly V_1-V_2 or V_2-V_1 as the case may be. Now the two input voltages as we did in the earlier summing amplifier I have used here a voltage source which is also the one which I used earlier which can give in millivolts hundreds of millivolts input and this is the corresponding voltmeter which measures the output voltage of this V_1. So these two correspond to the V_1 and this voltmeter and the corresponding voltage source that I have here in the power supply I am using it as V_2 and this voltmeter here is the one which actually measures the output voltage of the difference amplifier. It is in voltage mode and what it reads is the output voltage of the difference amplifier. I have kept here 100 millivolts. I am sure you are all able to see 0.1 volt here that correspond to 100 millivolt. The same voltage which I apply is measured here at the input and the other input voltage is around 445 or 446 millivolts. 446 millivolts minus 100 millivolts should be 335 or 340 and what you get here is 0.337 millivolts which is actually the difference between the two inputs.

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Now if I increase one of the input source for example V_1 to 200 millivolts this reads 0.2 volts and this is I have not changed. So 0.445 minus 0.2 gives me 0.2. That is what you see here. So this is the difference between the two inputs. Now I still increase it further to 300 millivolts. This is reading 0.3 volts. V_2 is still 0.44 and so the difference is around 0.14; 0.138 is what it reads here. It is actually measuring the difference between the two inputs. The output is the difference between the two inputs. Now I can also vary the other source. What I will do is I will reduce again V_1 to 0.1 and I will change the other input. The other input reads about 0.67 and 0.67 – 0.1 is around 0.5. The second input V_2 is around 0.6 minus 0.1 gives about 0.5. If I increase it still further you can see this is 0.2. 0.6 minus 0.2 is about 0.4 and I keep increasing it till this becomes higher. Now I have 700 millivolt; 0.7 V_1 and V_2 is about 0.5. So the difference is what I get with a negative sign; -0.152. This is minus because this voltage V_1 is larger than V_2; V_2-V_1 net result is a minus and what you get at the output is also -0.17 or -0.16.

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Exactly the same way that the two input voltages the difference in the two input voltages is what I get at the output and if I want a gain then I can always increase the value of this resistor in the circuit or and this resistor if I make this 20K and 20K the output will be two times. If I make it four times the output will become four times. You can also get a gain factor corresponding to the resistor. It's very easy to have a differential amplifier where the output voltage is the difference between the two input voltages.

What we have so far seen is a summing amplifier and we also saw a simulation of the summing amplifier and we also saw how averaging can be done for the input voltages. Then we saw a demonstration of the summing amplifier and finally we also saw what is the digital to analog converter; how a summing amplifier can be used to construct a digital to analog converter and then we saw what is a difference amplifier and basic configuration of a difference amplifier using op amp and few resistance and we also saw a simulation and the demonstration of a difference amplifier.

In the next lecture we will take up another configuration of the difference amplifier and discuss the applications of the difference amplifier and we will move on to other mathematical operations such as integration and differentiation. Thank you!