Op-Amp Practical Applications: Design, Simulation and Implementation
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Lecture – 42
Digital to Analog Conversion Circuits and Experiment on 4-bit R-2R DAC

Hai, welcome to this module and in this module, we will look at digital to analog converters. Now we have seen some parameters in the last module which were related to the conversion of the ADC to for ADC NF for DAC as well. And, what kind of parameters we have to use, or we have to understand such as nyquist rate such as quantization error, coding right sampling. So, let us see what kind of DAC systems are there.

So, if you see the slide then there are two basic types, one is digital analog converters. When you talk about converters there are two basic types, one is digital to analog converter and one is analog to digital converter. So, digital analog converter, if you see the slide please, then output of an analog voltage; that is proportional to a reference voltage.

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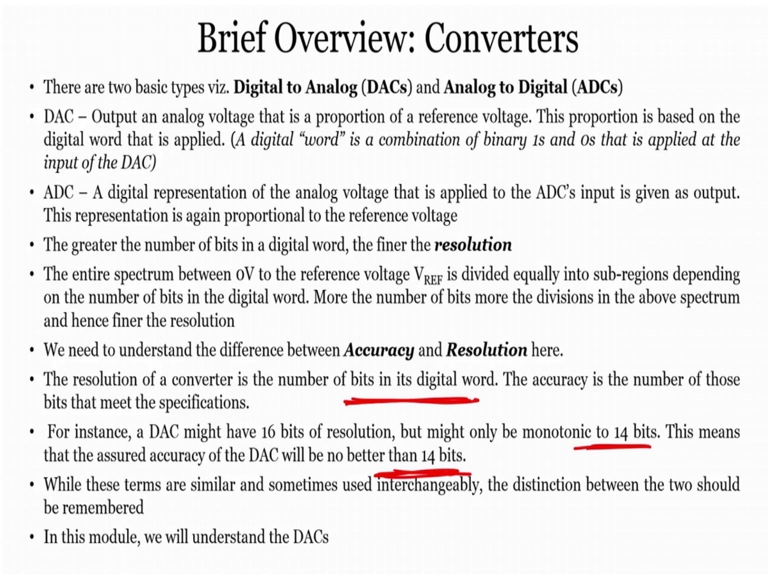

This proportion is based on a digital word; that is applied, right. Digital word is combination of binary 1s and 0s, it is applied at the input of DAC that is your digital to analog converter, but when we talk about analog to digital converter there a digital presentation of analog voltage, that is applied to ADCs input is given as a output.

This represents again proportional to reference voltage, there is a wearable digital converter box, very simple, right, the greater the number of bits in a digital world, the finer the resolution, greater the number of bits in a digital world, word the finer the resolution. The entire spectrum between 0 volts to reference voltage, which is v reference is divided into sub regions depending on number of bits in the digital word; more number of bits, more the division in the above spectrum and hence finer the resolution.

So, we understand that if you are ask a question, how you can have a final resolution in ADC, you can very clearly answer that by dividing the sub regions into more number of bits and more number of bits relates to more number of division and more number of revision relates to higher resolution. So, we need to understand difference between accuracy and resolution. The resolution of a converter is a number of bits in a digital world. And where accuracy is number of those bits that meets the specifications, there is a difference between accuracy and resolution.

So, you understand these two meanings. For instant, if you have a DAC which is 16 bit of resolution, but might only be monotonic; that is if it has to 14 bits, this means that the assured accuracy of DAC will be no better than 14 bits, right. So, resolution can be 16 bit, but the accuracy will be 14 bit, while these terms are similar and sometimes used interchangeably. The distinction between two should be remembered. In this module, we will understand The Digital to Analog Converters.

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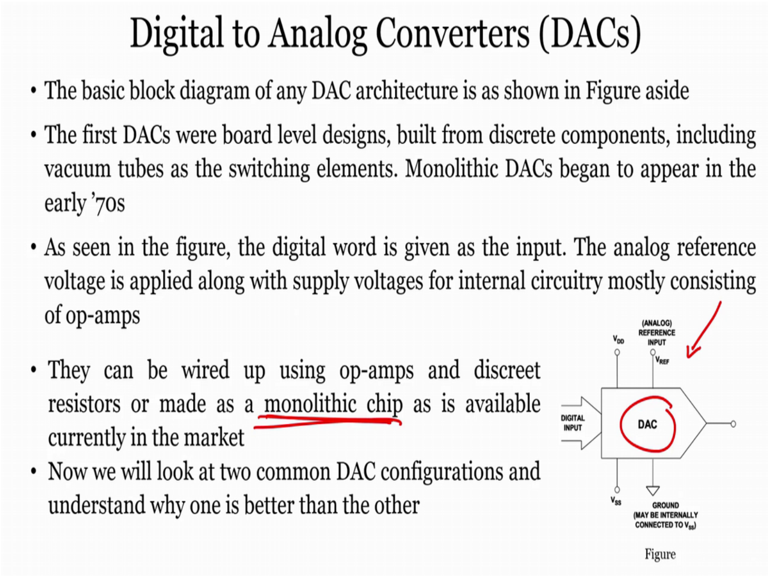

Now, the basic block diagram of any DAC architecture is generally shown in this way where digital is the input there is a v reference voltage there is a VDD, there is a VSS and there is a ground and I, output should be in analog format. So, the first DACs were board level designs built from discrete components including vacuum tubes as switching elements, monolithic DACs began to appear early 1970s. And as seen in the figure the digital word is given as the input and analog reference voltage is applied along with the supply voltage for internal circuitry mostly consisting of operational amplifiers.

So, these consist of operational amplifiers, they can be wired up using op amps and discreet registers are made up of monolithic chip as is available currently in the market. So, we can either make using the op amps and discreet components or we can also make a monolithic ic.

Now, we will took, look at two common DACs. Let us see two common DACs and understand which one is better than other, so, the first one, we talk about is binary weighted network.

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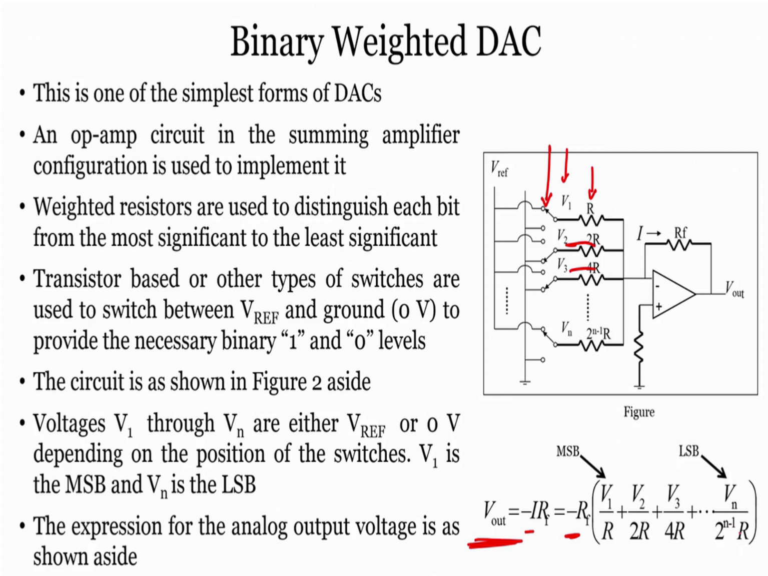

Now, again if you see the circuit it is this similar to our adder, if you go back and understand how the adder works or you can say summer. So, this one is simplest form of DACs, an op amp circuit in the summing amplifier, right, summing amplifier configuration is used to implement it. Weighted resistors are used to distinguish each bit from the most significant bit, it is very simple V 1, V 2, V 3, V n, we have a V (Refer Time:04:40) reference voltage.

Now, the reference voltage, reference voltage is a set voltage and according to that we can select a one of this, one of this input until two raise to n minus r, and the weight resistors are used to distinguish these are the registers which are R 2, R 4, R up to 2 raise to minus n r right each bit from the most significant to the least significant.

Now, transistor based other types of switches are used to switch between V reference and ground, right. So, this switch, now we are talking about, there can be transistor switch, another switches. And to provide the necessary binary 1 or 0, now this circuit which is shown here voltage is V 1 through V n are either V reference or 0 volt depending on the position of the switches, right. So, if it is connecting here, it is V reference, if it is not connecting it is 0. Or if it is connecting in a, in a different direction because this one let us say V 3 is connected to ground, right. So, this will be 0.

So, V 1 is the MSB and V n is the LSB, the expression for the analog output voltage is as shown in figure with aside which is V out equals to minus I R f and minus R f. What is I?

I is nothing, but V 1 by R plus V 2 by 2 R plus V 3 by 4 R until V n by 2 raise to n minus R, this is your output voltage.

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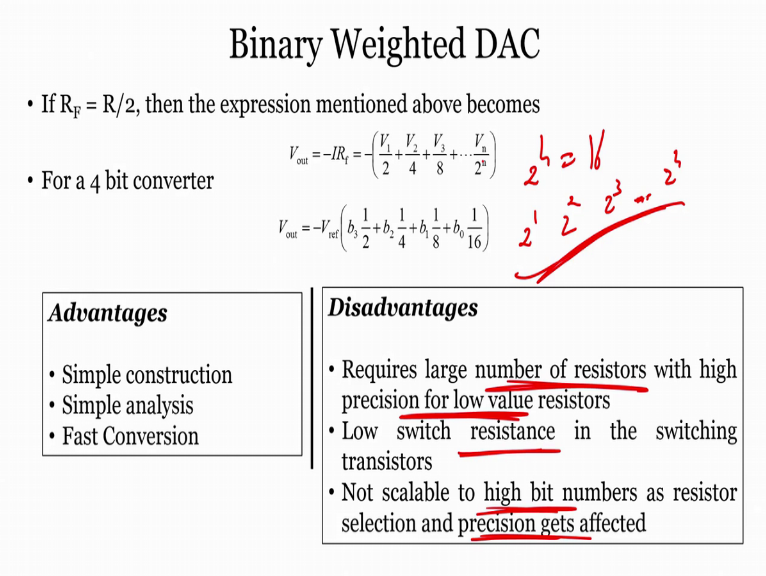

So, if R F equals to R by 2, then we can write V out equals to minus I R f equals to minus V 1 by 2, until this one. So, for a 4 bit converter, it will be b 3, b 2 b 1, b 0 and 1 by 2, 1 by 4, 1 by 8, 1 by 16, right because 2 raise 2 n, 2 raise to n is 2 raise to 4, 2 raise to 4 is 16, right.

So, you start with 2 raise to 0, then 2 raise to 1, then 2 raise to 2, then 2 raise to 3 like that. So, here is 2 raise to 1 because first bit is 2 raise to 1 2, 2 raise to 2, 4, 2 raise to 3 8 until 2 raise to 4 which is 16. So, now, you do not have to really do until, right because there are only 4 bit converter. Thus, the advantage here is the simple, it is very simple in construction, as you can see it is very simple in analysis and there is very fast conversion. Why there are some limitations which requires large number of registers with high precision of for low value registers.

Low switching resistance is required in switching transistor and not scalable to high bit numbers as resistor selection precision gets affected right, because if you keep on increasing the value of register, as you can see here until when you can increase the value of resistors very difficult to have very high value of registers, same way it is very difficult to have very low value of resistors as well.

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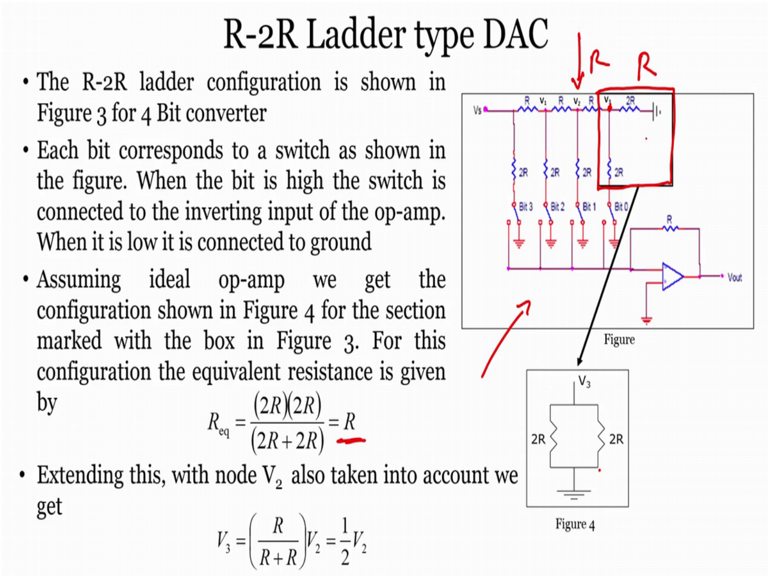

So, there are some of the limitations of the weighted binary network, but when you talk about R 2 R ladder typed a DAC, which is you again as shown in figure here, here what we do? Here, this is again shown for 4 bit DAC converter each bit corresponds to a switch. So, you see here bit 0, bit 1, bit 2, bit 3. So, each bit is corresponding to a particular switch.

Now, when a bit is high the switch is connected to the inverting amplifier, right. So, if I connect this here right then it is connected to the inverting terminal of the operation amplifier. And when it is low, it is connected to ground like this, correct. Now, assuming ideal op amp we get those configuration as shown in figure 4. So, for this one, if I use this particular square, right what I have? I have 2 R and 2 R again here, right. So, what will be the R equivalent circuit, R equivalent will be 2 R into 2 R by 2 R plus 2 R which is your R.

So, if I put this value as R then extending this with node V 2, which is our V 2 is right over here, right. Then what we have? V 3 equals to R by because this is V here, right. This one and this guy is R. So, this is also R, right. So, the V 3 will be R by R plus R into V 2 equals to 1 by 2, V 2 same thing.

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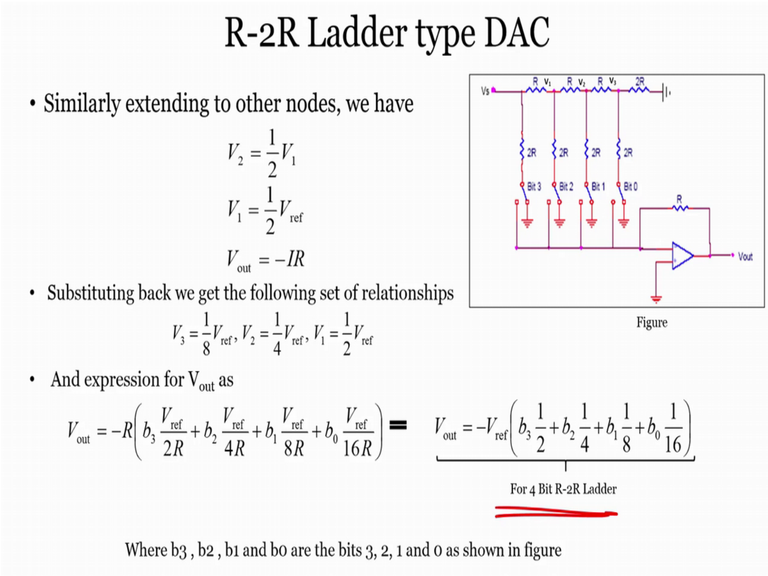

If, I go on extending V 2 equals to 1 by 2, V 1, V 1 equals 1 by 2, V reference V out equals to minus I R substituting the values of the following relationship what we get V 3 equals 1 by 8, V R reference V 2 equals to 1 by 4 V reference, V 1 equals 1 by 2 V reference an expression of V out would be V out equals to minus R into bits, bit 1, bit 3, bit 2, bit 1, b 0. And what do we have, a have V reference? V reference by 2 R, V referenced by 4 R, V referenced by 8 R V reference by 16 R.

So, V out will be nothing, but 4 bit R 2, R converter minus V reference in 2 b 3, 1 by 2, b 2 1 by 4, b 1, 1 by 8 plus b 0 1 by 16 where b 3, b 2, b 0 b 1 and b 0 are 3, 2, 1 and 0 shown in the figure.

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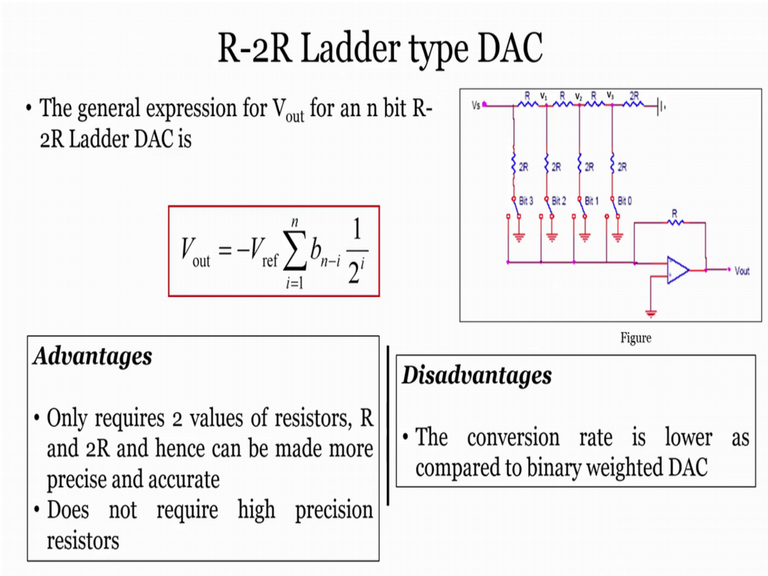

Now, so, if I going to have a generalized expression for R 2 R ladder, that is your digital to analog converter. Then what can I have? The general expression can be V out equals to minus V reference into summation of b n minus i into 1 by 2 to the power i where i equals to 1 to n.

And, the advantage of this particular R 2 R ladder is only requires 2 value of register. As you can see either R or 2 R, right 2 R 2, R 2, R 2, R, R, R and R.

So, we require either only 2 values of register, one is R and second value should be 2 times the original value of R. And hence, can be made broad piece as an accurate does not require high precision registers. The disadvantage here is the conversion rate is lower as compared to binary weighted digital to analog converter. Now, we have to see DAC weighted binary network and R 2 R network.

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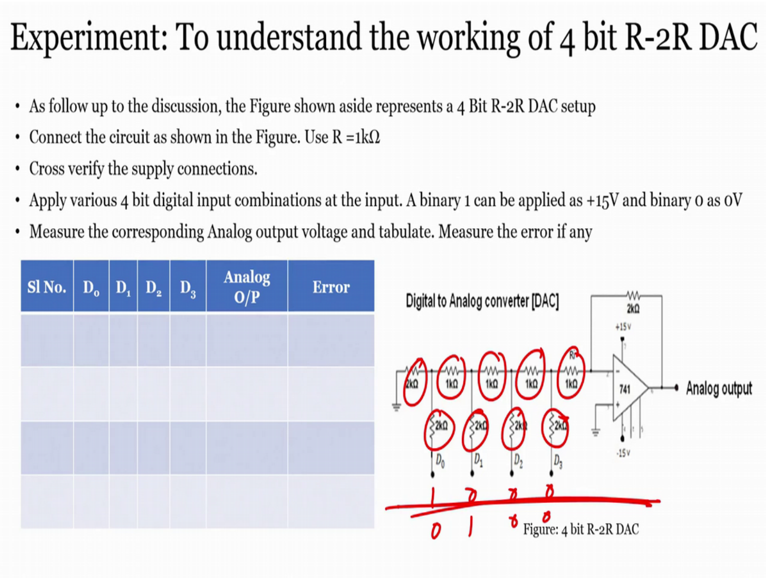

So, if you want to do the experiment to understand 4 bit R 2 R DAC, let us see how we can do it.

Now, we can see here figure, right which you can connected, right like I said you connect this circuit and then, you connect the circuit as shown in figure use R equals to 1 kilo ohm. These are R values which is 1 kilo ohm, all right. And then you have to R values which is 2 kilo ohm, correct. So, cross verify supply connections, apply various 4 bit digital inputs, I will apply 0 0 0 1 or 0 0 1 0, right depending on it will be connected and measure the corresponding analog voltage and tabulate measure the error if any.

So, we can put different values like as a 0 0 0 0, analog board should be 0, error should be 0 0 0 0 1. And then you have analog output which is error should be something. So, you had to do this experiment and measure the value of analog output at the output of the operational amplifier 7 4 1. And if there is any error you should measure the error as well, right.

So, what we understood that we have 2 types of DAC, one is your R 2 R network and one is your binary weighted network, right. So, you guys when you read this particular, module, understand this particular module then see how you can design a quickly R 2 R network and binary weighted network like I said it is a very simple design and very easy to understand. So, the try at home, try in a laboratory, it does not require a lot of components and we will also show you how to design such kind of converters. In fact, we will use probably in one of the experiments that we have designed, if it fits within the 30 hours of this particular course.

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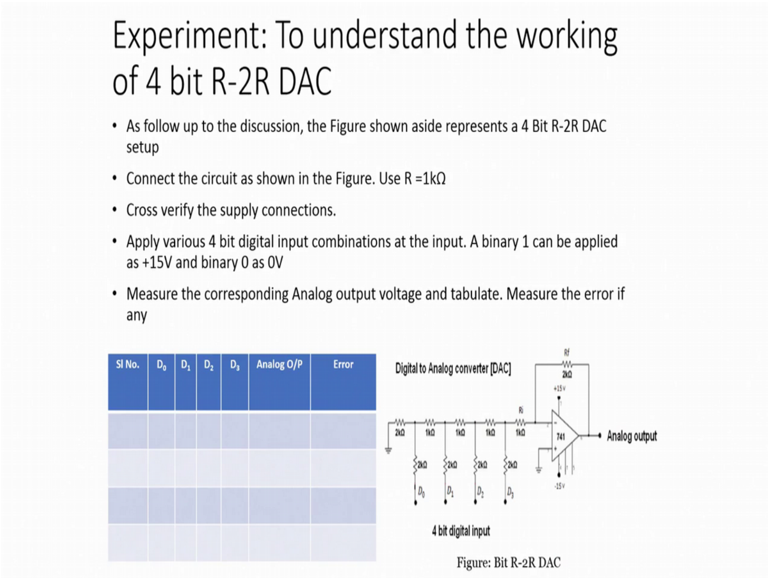

I will request now T a to help us with the circuit experiments and I will request him to join us. Now, we will see the simulation result of DAC. So, once we finish that once we verify then we will also look into the, the experimental one. So, in order to test the circuit and in order to compare with our theoretical values, we will go to multi sim, we will create the same circuit using this circuit simulation software.

So, now so, far our understanding what I will do is that, I will keep both the presentation as well as, this one side by side. So, it is easy for us to visualize the circuit and easy to build us. So, if you observe carefully, we have to use a total of 1 2 3 4 5 6 7 8 9 10 resistors, right 9 before you know, one resistor is in non inverting terminal. And so, I am also using the same 7 4 op amp and I will be using the same even for the experiment 2. And this is a negative feedback so, what I do is, I simply swap. And I will choose resistors. So, if I want to choose a resistor, I will be going to resistance palette.

So, I will choose all set of resistances here 1 2 3 little bit I will move in this direction 4 and 5, right. Then I also require one feedback resistor, I am taking the feedback, then I need resistors in this direction 1 2 3 and 4, right.

Now, what will we do, we also require these switches is not it? So, because it entirely depends the output voltage entirely depends upon which switch is on. So, as we have considered in theoretical first everything is grounded then everything is like 0 0 0, 0 0 1. So, we will in order to make it 1 2 like to make the d 0 bit as high d 1 bit as high rather than stopping the simulation again connecting to 5 volts. What we can do is, we can do is that we can take a switch here. We can go with the some SPDT switches, right let me reverse it.

So, we will take SPDT switches in every cases. And what I will do is that, one terminal I will connect it to the ground and other terminal we will connect it to 5 volts, this is 50, I values of which. So, I will be creating DC voltage, DC voltage will be connected here, this value, ok. So, I will make it as 5, we took 15 that time, 156 we took, right other terminal should be ground. So, I slightly change the settings I do not need this oh, fine. So, we will make it as V 1 ok, then.

So, other terminal should be connected to the ground because of power supply or yeah what we can also do is we can connect from here, this is 5 volts And so, this I will delete from here, I will connect the 5 volts all 1 switches will be connected to the 5 volts whereas, other will be connected to the ground.

So, the default state is all d 0, d 1, d 2, d 3 in this case S 1, S 2, S 3, S 4 are in 0, but whenever I want to make it higher meaning when I want to make it to 5 volts only thing is if I toggle the switch then it will connect it to the 5 volts; that means, that particular bit is higher so, that we can easily see. Now, I may complete connections here connections from here to the switch all the resistance to switch.

Now, this resistance should be all 2 k. So, I will change it to 2 k, even this value should be 2 k, this is also 2 k, 2 k. Now so, after doing these connections and this also has to be changed, but this should be 2 k. So, I will replace this with 2 k Then other connections, I will be doing now. So, connect all the resistors and this terminal should be connected here whereas, I will take one more ground and connect it here, because the positive terminal is connected to ground. Now this particular point has to be connect here, this point has to connect here, this one to here, this one to here whereas, this particular point is ground, right.

Now, what we do the feedback resistance is also 2 kilo, we will go here, we will change it to 2 kilo. And the output has to be connected to here. So, this is my output and this is this one. Now what about power supply, yes, we also have to provide a power supply when you look into the details. So, the plus Vs is this particular terminal, is it? So, the 3, where are the 3 terminals are there, this particular portion is V, Vs plus and this is V s minus.

So, when I have to power it, I have to use this for Vs plus, right again. So, this particular bottom one is Vs, Vs plus. Now with that intention I will take one more power source from here, I will connect this 2, this as I am making it as 15 bits up to you whether to 15 or 12 volts anything is fine as long as op amp the op amp can function for the rated voltage, you can use that particular value and DC voltage, this should be 15 minus 15.

So, since the negative terminal is connected here, we do not have to make it as minus, but this value should be 15; then whereas, other terminals should be grounded. Now, to understand the value what I will do is that, I will connect voltage probe now. So, as we know as we have already seen how this particular circuit works, right. So, as we have already seen V naught is entirely depends upon the V reference value, right, V reference into whichever bit is higher right divided, that like since minus V reference into summation of 1 to n b minus 1 whichever bit is higher divided by 2 power i whichever based upon the bit 1, right.

Now, what I will be doing is since the reference value is 5 in this case when we see 181 microvolts so, which means that this is approx, this is almost 0. So, when I make it as voltage and minimum as z minus, minimum as 0, maximum as 10 volt or minimize as 5 volts and maximum is also minus 10, I will make it, right we can see the output is 0.

Now, when d 0 bit is higher, right since it is an inverting type and the reference value is 5, right. So, the maximum voltage will be 5. So, what I will do is that this voltage we will change it to minus 5 to 5, right. So, if I make all the bits as 1, right almost close to 5, ok. So, what about my other values, right, when I see. So, four cases, we have considered what are they 0 0 0 0, right 0 0 0 1, 0 0 1 1 and 0 1 0 0 0 1 1 1, we can consider any case this is just for a testing purpose.

So, when we look into that relations once again, we can see that V out is nothing, but minus V reference in to b 3 in to b 3 by 2 plus b 2 by 1 by 4, b 1 by 8 plus b naught by

16. Now, when I make d 1 as higher and all bits as grounded, meaning when I look into the voltage, when I look into the voltage only this particular terminal is higher, sorry only this d naught is higher. So, V reference is 5, 5 divided by 16.

So, when I calculate 5 divided by 16, 5 divide 5 by 16, the values.3125. Now, when I look into this one so.312312 millivolts, right make sense. Now I will make it as 0 0. So, this is the value for 0. Sorry this is the value 4 0 0 0 1.

Now, why do not we do it as 4 0 0 1 0 0 1 1 so; that means, even d 1 bit is also higher. When d 1 bit is higher so; that means, it is nothing, but minus V reference into b by 16 plus b 0 by 16 and b 1 by 8, right that is the relation right when I do that the value will be 5 by 16,one value and another value is 5 divided by 8, right.

So, when I do that.9375, right the value is 937.31 milli, but what if I change my reference, yes if I change my reference even the output voltage will change. Now for example, like say if I take a 15 volts, if I take 15 volts, if you observe for 0 0 0 right for 0 0 0, it is completely 0. Whereas, for this.93 937 milli, right whereas, this particular value 1, 1 right this is 1, 1, this is 2.81, 2.81, right how?

So, 15 by 16 plus, right 15 by 16 plus 15 by 8 when we calculate 2.81 now we have done for 2, why do not we take 0 0 1 0, right. So, when we see 0 0 1 0; that means, 0 0 0, this is 1 and this is 0. So, what is the value for 0 0 1 0. So, it is nothing, but minus V reference into 15 minus V reference into b 1 by 8, right.

So, when I calculate it 15 divided by 8 so, 1.875 observe the output voltage, 1.8748 which is also approximate which is, which is almost equal to the value 1.875, right. Now we will take one more which is 0 1 0 0. So, 0 1 0 0, so, this is 0, this is 1, but 0 and 0. So, what will be the value for this when I see for this particular value minus V reference into b naught by 16, right.

In this case S 1,so, S 1 is 0, 0 by 16, it is 0 then b 2 by 8, b 2 is nothing, but sorry b 1 by 8. In this case S 2, S 2 is connected to 15, right it means higher. So, b 2 is 1 b 1 is 1 1 by 8 which means 15 by 15 by 8 is 1 value, right. And along with this, we also have one more which is s 3 which is nothing, but b 2 b it is also high b 2 by 4.

So, this is 15 by 4 and what about the other one, other one is connected to ground which means b 3 is 0, 0 by 2 which is 0. So; that means, I should get, I should get a value as 5.625, but in this case if I see this is 0 1 1 1 so, but whereas, we have calculated for 0 1 1 0, right 0 1 1 0, 5.624, 5.625, right. We will go with the other one, 0 1 1 1, all three when we see to this we have to add, we have to add 15 by 16, right. So, I will be adding 15 by 16. So, which is 5.6, 0.5625, 0.5625.

Now, what if I make all 1? So, what I will do, I will make everything 1, this also 2 1. Now, what should be the output voltage if everything is 1, it should be somewhere around 15, right. So, why do not we calculate, we will see. So, 1 is 15 divided by 16 is 1 value plus 15 divided by 8 is another value plus 15 divided by 4 is another value plus 15 divided by 2 is the last one.

When I see it, I should get it as 14.0625 is the, is, is the value output voltage that I should get when all switches are on d 0, d 1, d 2, d 3 ; that means, in this case S 1, S 2, S 3, 4, but now why it is not showing it as 50, 14.0625 ? The reason is that op amp, the op amp has been powered by using 15 and minus 15 volts and the reference value is also 15.

So, the maximum voltage depends upon op amp the maximum voltage is always lesser than the supply voltage, right, that is the saturation voltage. Since, it is a 7 4 1, the saturation voltage even lesser than that particular value. So, that is the reason when you see it has already gone to the saturation, what if I change to 5 volts here, why do not we check? So, if I change to 5 volts, the reference is completely changed.

So, since reference is completely changed. Now, the value will be so, 5 divided by 16 is 1, value and other values is 5 divided by 8. Then other value is 5 divided by 4, sorry yeah 5 divided by 4 plus 5 divided by 2, these are the values when I calculate it 4.68 right 4.687, 4.687, right.

So, the previous case what why it has only showing 13? The reason is because of the saturation. So, one important thing, one important consideration is whenever you are working with an op amp, you have to see, what is an expected voltage whether the expected voltage is lower than your saturation voltages or not, right. Now, so, since we will we are calculated our complete you know theoretical output voltages using reference as 15; I am going back to the 15, right. So, that is why it is showing it as 13. So, we will make it as last one we will say 1 1 1 0 meaning d naught bit is 0, but accept, but d naught bit everything is 1 1 1. So, what should be the value if it is a case we will calculate.

So, 1 is 0 divided by 16 because of b 0 bit and other one is 15 by 15 into 1 by 8, right V reference by V reference into b y b 1 by 8 plus V reference into b 1 by 4, sorry b 2 by 4. So, divided by 4 b 2 is high already then other one is V reference into b 3 by 2, when I make everything 13.125.

So, this is also approximately 12.996, I will also do one more, this is also 0. Now, we will calculate even this. So, in this case it will be 15 by 4 and 15 by 2. So, the value is 11.25. So, we can see it is also equal to 11, 11.25,itself, right.

So, by using the simulation, we can rather than even going with an experiment rather than completely wasting our time by struggling where exactly we have done a mistake. If you look into the simulation, it is easy for us to understand to do all the modifications. Once, the final design is done, we can we can do the same experiment in on the board and we can cross verify our simulation as well as theoretical with our experimental data 2.

I hope so, the simulation part of our d 2 R 2 R DAC is done. Now, we will do the same, we will connect the same thing using the Ta board, sorry we will connect the same thing using breadboard. So, we will take a 7 4 same 7 photo op amp, we will use 2 Ohm 2 kilo ohms resistors as well as 1 kilo ohms resistors. As we have connected, as we have shown in the power point as well as we have shown in the simulation.

We will do in the same way same procedure and we will see four test cases. We have considered in our theoretical, we will also consider the same test cases in our breadboard 2 and we will see whether even with the theoretical and experiment whether both are matching or not, right. So, we will go to experiment now.