Introduction to Embedded System Design
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Lecture 19
Physical Interfacing 5

Hello. Welcome to a new session on this online course on Introduction to Embedded System Design. In the previous lecture, we had seen at various ways of driving LEDs in 2 modes called Low Side Driving and High Side Driving. And the purpose was how to control the LEDs or similar loads in a way that the switch was either connected to the VCC or switch was connected to the ground side. And we are going to continue that discussion forward. And I want to actually take this opportunity to actually calculate values of components for various options.

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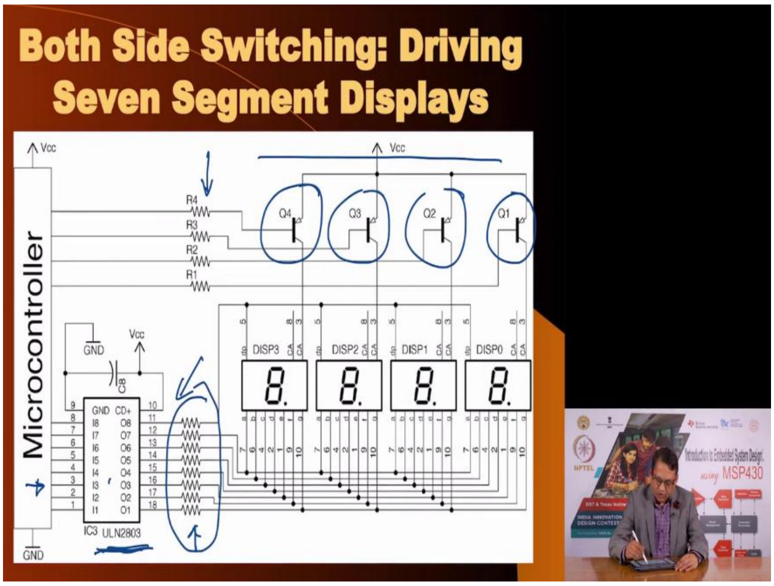

The last slide that we looked at in that previous lecture was talking about using a microcontroller to connect to a multiplex display. In this case, 4-digit Seven Segment Display using PNP transistors as high sides switches here, and NPN transistors available as IC ULN2803 and current limiting resistors for the seven segment displays, 8 of them here.

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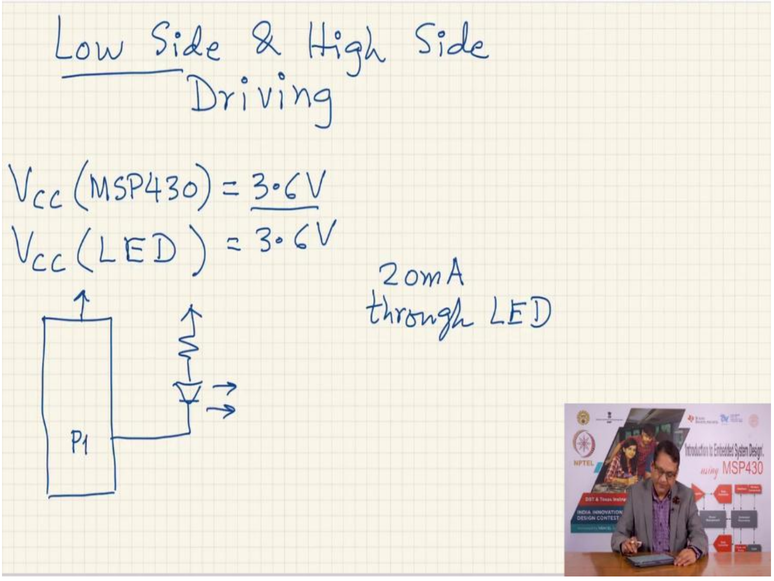

Now, I want to go back and review some of the concepts that we discussed for low side and high side driving. I am going to take first the low side part. And the options we had was that we have a microcontroller and we are going to control the low side part of this circuit, which means we have our LED and resistor combination, and we connect it to the output of a port, let us say P1 and this is supply voltage, in this case I have mentioned here that let us say this is a MSP430 microcontroller, it is having a supply voltage of 3.6. We also have the supply voltage of LED also 3.6 and this would be a low side driver.

Now, in case we want to increase the current through this configuration, we suggested the use of an external switch, an external transistor which is capable of handling much more current than would be possible with the maximum current capability of MSP430, as we have seen in the lectures related to MSP430 that the current is limited to a few milliamperes, and if we want more than that, then we have no other option but to use an external switch.

So, I am going, I have, I am going to use external transistors and take this discussion forward, how to calculate the values of various components that we use. So, let us take an example that we want to drive 20 milli ampere of current through the LED, 20 milliampere through our LED and we want to control the LED with the low side switch which we are discussing here.

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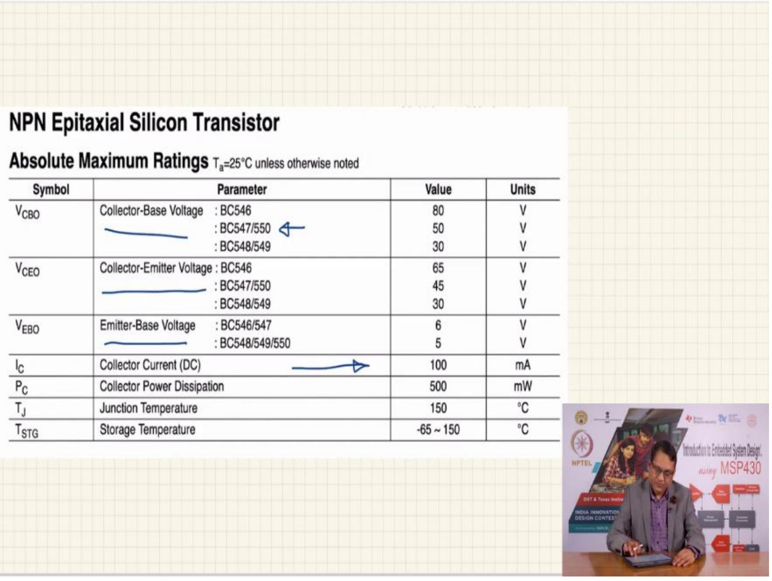

NPN Epitaxial Silicon Transistor

Absolute Maximum Ratings T_a=25°C unless otherwise noted

Symbol	Parameter	Value	Units
V_{CBO}	Collector-Base Voltage : BC546 : BC547/550 : BC548/549	80 50 30	V V V
V_{CEO}	Collector-Emitter Voltage : BC546 : BC547/550 : BC548/549	65 45 30	V V V
V_{EBO}	Emitter-Base Voltage : BC546/547 : BC548/549/550	6 5	V V
I_C	Collector Current (DC)	100	mA
P_C	Collector Power Dissipation	500	mW
T_J	Junction Temperature	150	°C
T_{STG}	Storage Temperature	-65 ~ 150	°C

I have chosen to use a BC547 transistor here and I have copied the relevant portions of the BC547 transistor datasheet here. This one is the collector base voltage; this is the collector emitter voltage and this is the emitter base voltage. And this mentions that the maximum amount of current that you can collect a current that BC547 can handle is 100 milliampere. So, this is very safe to drive 20 milliamperes of current through the LED, it also talks of how much power dissipation this transistor can handle.

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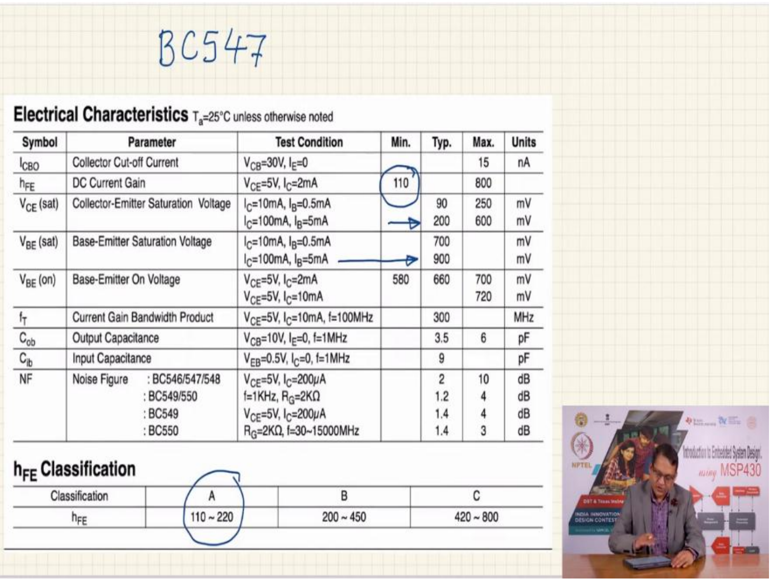

Electrical Characteristics T_a=25°C unless otherwise noted

Symbol	Parameter	Test Condition	Min.	Typ.	Max.	Units
I_{CBO}	Collector Cut-off Current	V_{CB}=30V, I_E=0			15	nA
h_{FE}	DC Current Gain	V_{CE}=5V, I_C=2mA	110		800	
V_{CE} (sat)	Collector-Emitter Saturation Voltage	I_C=10mA, I_B=0.5mA I_C=100mA, I_B=5mA		90 200	250 600	mV mV
V_{BE} (sat)	Base-Emitter Saturation Voltage	I_C=10mA, I_B=0.5mA I_C=100mA, I_B=5mA		700 900		mV mV
V_{BE} (on)	Base-Emitter On Voltage	V_{CE}=5V, I_C=2mA V_{CE}=5V, I_C=10mA	580	660	700 720	mV mV
f_T	Current Gain Bandwidth Product	V_{CE}=5V, I_C=10mA, f=100MHz		300		MHz
C_{ob}	Output Capacitance	V_{CB}=10V, I_E=0, f=1MHz		3.5	6	pF
C_{ib}	Input Capacitance	V_{EB}=0.5V, I_C=0, f=1MHz		9		pF
NF	Noise Figure : BC546/547/548 : BC549/550 : BC549 : BC550	V_{CE}=5V, I_C=200μA f=1KHz, R_G=2KΩ V_{CE}=5V, I_C=200μA R_G=2KΩ, f=30~15000MHz		2 1.2 1.4 1.4	10 4 4 3	dB dB dB dB

h_{FE} Classification

Classification	A	B	C
h_{FE}	110 ~ 220	200 ~ 450	420 ~ 800

In the next slide here, here it talks of the DC current gain and there is a number minimum current gain that you can have is 110, we are going to use a number of hundred. The VCE sat when the transistor is being saturated for various options, and we are going to use this that if the collector current is 100 milliamperes then what is the kind of VCE sat voltage you get, so you get 200 millivolts, so we are going to use this number 0.2 volts.

At the time that the transistor is being saturated, the base emitter voltage for this we are going to consider 0.9 volts and we do not need anything else. The transistor itself is available in 3 formats called BC547 A, B and C. So, we are going to think that we are going to assume that we use a BC547A transistor, and all our calculations are going to be based on that.

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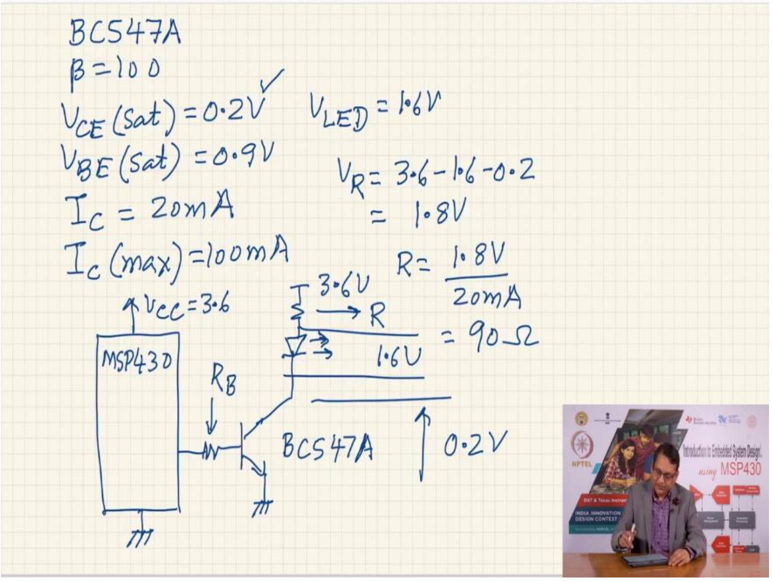

So, let me write down the information here that for our BC547A, our numbers are that beta is 100 VCE sat is 0.2 volts VBE sat the saturated voltage of base emitter junction is 0.9 volts, the current we want, IC that is through the LED is 20 milliampere, our transistor is capable of IC max the maximum current that the collector of this transistor is capable of handling is 100 milli ampere.

And using these numbers, we are going to design a circuit which can achieve, what we are planning to do, which is with our MSP430 microcontroller powered with VCC of, this is MSP430, this is one of the ports which is equal to 3.6 volts, we have a base resistance, this is our transistor which is BC547A, this is grounded here and we have a resistor and the LED, red LED, we are going to use, so I am going to write here that VLED is equal to 1.6 volts for these 20 milliamperes of current.

You should of course, verify it for the LED that you are using, what is the forward voltage drop across the LED when you want to repeat this calculation with different settings, so here supply voltage is also 3.6 volts. And now here, now what do, what do we have to estimate?

What is the value of this current, this resistor, and what is the value of the base resistor? So, since we are assuming that when the transistor is saturated, it should handle 20 milliamperes of current, at that time the voltage at the collector will be 0.2 volts, and this information we get from here.

The current flowing through, we want it to be 20 milliamperes, the voltage drop across the LED will be 1.6 volts. So, the voltage across the resistor VR, let me write here VR is equal to 3.6 minus 1.6 minus 0.2 volt which is equal to 1.8 volts. And so, since the current I expect is 20 milliamperes therefore, R is equal to 1.8 volts divided by 20 milliampere and therefore, R comes to be about 90 ohm. So, this is as far as the current limiting resistor in series with the LED is concerned. Now, the second calculation is to calculate the value of the base resistor.

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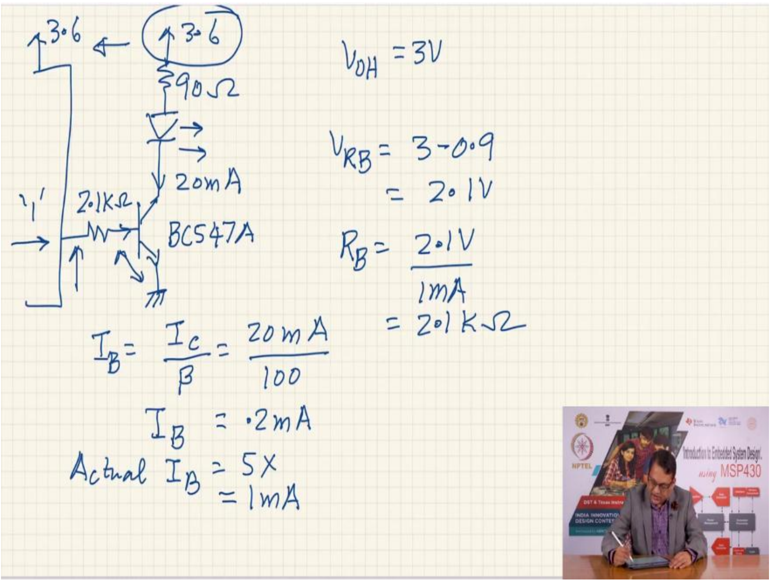

And for that we are going to have, so let me repeat this diagram here, this is 3.6 volt, this is the circuit here, this is BC547A. We have already estimated now, that for 3.6 supply volt, my resistor will be 90 ohm. I will have a LED in series, a red LED and the current going here is 20 milliampere, the beta is 100 therefore, the base current will be IB required out of this, IB is equal to IC by beta therefore, it is 20 milli ampere upon 100.

In my previous presentation, I had made a little mistake in these calculations, so this lecture is to correct that and so this becomes 0.2 milli ampere, the base current required is 0.2 milli ampere, but when we want to drive a transistor in saturation, we always choose a base current which is much more than the one determined by this relationship.

So, in this case it is base current should be 0.2 milliampere but since we want to drive it hard into saturation, we choose a certain amount of current more than that, and so let us say that I want to go 5 times that base current, so therefore actual base current that I want to drive, actual IB is equal to 5 times, 5x therefore this becomes 1 milliampere.

Also, the voltage at the output here, when the logic is 1, I will assume that it is for a 3.6 supply volt, VOH for this transistor is 3 volt and therefore, this voltage VBE sat is 0.9 volts as we saw from the datasheet therefore, VRB, that is the voltage across RB is equal to 3 volts at the output, the base at the input of the resistor minus 0.9 volts, 0.9 volts. So, it is 2.1 volts and therefore, RB is equal to this voltage which is 2.1 volt divided by 1 milli ampere and therefore, this becomes 2.1 kilo ohm.

So, now I have my circuit ready, I need a 90 ohm collector resistor, I need a red coloured LED and I have 1 (2.), base resistor of 2.1 kilo ohm. If you configured your circuit like this, it will work exactly as you expect. Now, one of the nice things about low side control using NPN transistors is that there is no requirement that the supply voltage which is connected to the load, in this case the load happens to be a red LED that the supply voltage should be 3.6 volts equal to the supply voltage of the microcontroller, there is no such necessity.

In fact, this value of the voltage can be any higher value and we can repeat this exercise, what if we wanted to control a LED or a bunch of LEDs in series, where the supply voltage is more than the supply voltage of the microcontroller. We can repeat that this exercise for such a configuration.

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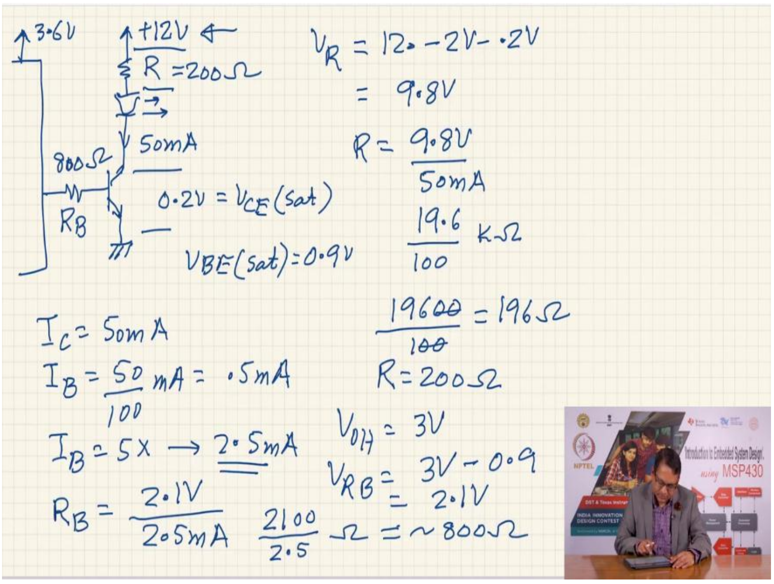

So, I am going to take my microcontroller MSP430 still powered with 3.6 volts. I still have that transistor BC547, but now I am going to pump up the current through the LED that is the load to a slightly higher voltage, higher current and I am saying that my supply voltage is now plus 12 volts. I will still need a current limiting resistor, I have a LED and now I want the current to be say, 50 milli ampere.

So, now I have to estimate the value of this R and RB for a different setup where the supply voltage is 12 volts. I am going to repeat the same VCE sat is going to be 0.2 volt is equal to VCE sat, the VBE sat, VBE sat will still be 0.9 volts as maximum as we saw through that datasheet but because the currents have increased the collector current will be more, so therefore, VR, the voltage across this resistor is equal to 12 volts minus the voltage drop across the LED, of course at 50 milli ampere, the voltage drop across the LED will also increase.

So, let us say that it will climb up to 2 volts, so I am going to do 2 volts minus 0.2 volts of the VCE sat, this is the voltage and therefore, this is equal to 18 minus 0.2, so this is 17.8, oops, 12 minus 2, 10, 10 minus 0.2, this is 9.8 volts. So, the voltage across the resistor is, has increased to a much larger value of 9.8, the current is expected to be 50 milliamperes therefore, R is equal to 9.8 volts divided by 50 milli ampere.

So, this becomes 19.6 divided by 100 kilo ohm, so 19600 upon 100, so this cancel out, so this becomes 196 ohms. So, you can take a resistor value of 200, nearest is 200 ohms, R is equal to 200, so this is what we have. Now, our collector current is IC is equal to 50 milliampere therefore, IB will be equal to 50 divided by 100 that is the minimum base current, we must have, so this is equal 0.5 milliampere but as I mentioned, we should pump in much more base current to ensure that the transistor is driven hard into saturation.

Let us say I want IB to be equal to 5 times, so this leads to a 2.5 milliampere of base current and therefore, VOH is equal to 3 volt from this microcontroller, therefore VRB is equal to 3 volt on one side minus 0.9 volts, this leads me to 2.1 volts and therefore RB is equal to 2.1 volts divided by the current, base current I am pushing is 2.5 milliampere. And so, this will be roughly 800, 800 ohms or something like that.

So, it is 2100 divided by 2.5, these many ohms, roughly 800 ohms. Now, you see compared to the earlier calculation where this resistor was 2.1 kilo ohm, it has dropped down to 800 ohms. So, if you now, you take here 800 ohm, this resistor, we have estimated to be 200 ohm, if you do this, it is going to be able to drive (two hun) 50 milliamperes of current through this.

Now, what is, what we have learned out of this configuration is that the supply voltage need not be the same value as the supply voltage for the, supply voltage for the load need not be equal to the supply voltage of the microcontroller. And this is often a requirement when where your load requires higher voltage for, for right now we have taken a simple example where the load is LED, but we could easily change this to say, okay we have a bunch of LEDs in series, and that would change the values of resistors and so on and so forth. So, this was one of the topologies, we saw. The other topology was that now we want to, let me go back and let us, let me show you all the topologies that we looked at.

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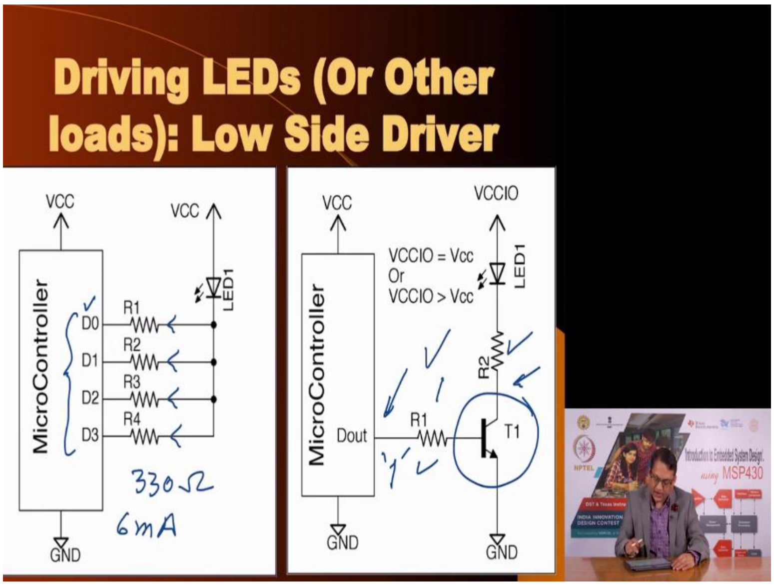

So, we looked at this topology right now, we have made calculations for the base resistor and the collector resistor. This is for the low side driver.

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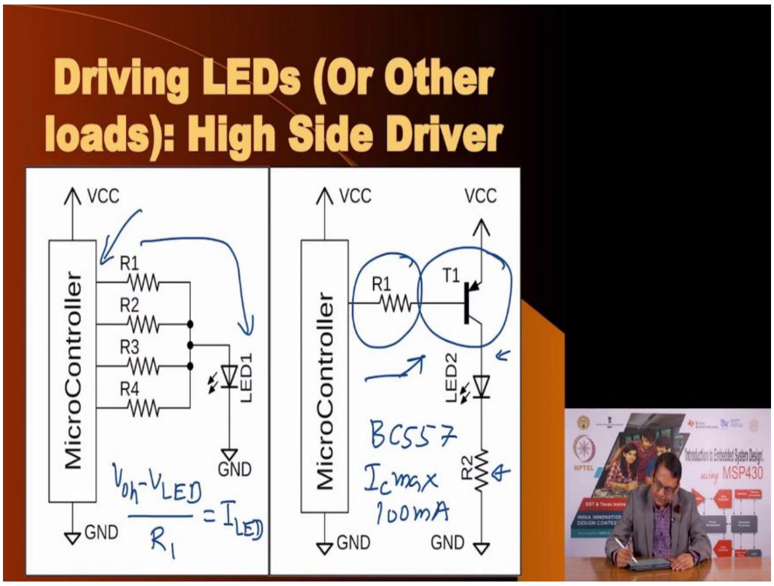

And then we saw that if you want to do high side driving, now, we have to use a PNP transistor, let us repeat this exercise for a high side driver using one example of say, 50 milliamperes.

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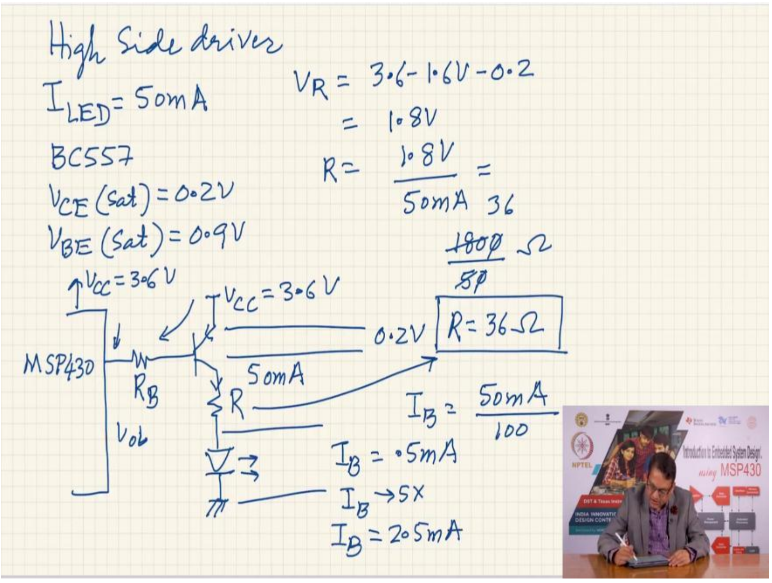

So, we are going to do this, that we have High Side Driver, our I LED, the current through the LED that we want is 50 milli ampere, our transistor will be now a PNP transistor, so the corresponding transistor to BC547, which is a similar transistor with similar parameters is BC557, and we are going to assume the same numbers for it. Of course, you should refer to the datasheet of is 557 to ensure that what are the numbers and if they are different to use them in these calculations.

We will say, VCE sat is 0.2 volts, VBE sat will be 0.9 volts. And so now what we have is we want a microcontroller, which is operating at VCC equal to 3.6 volts, which is our good old MSP430. Now, it is exercising a high side control over the LED and now so we have the configuration where the transistor becomes now PNP, this is your VCC. We are going to show the same VCC of 3.6 volts and we will see what changes when the supply voltage becomes higher.

And now, we have the resistor here on the collector and the LED connected to ground. And we want to calculate the value of this R and this RB. And the current through this configuration, we have chosen to be 50 milliampere. Alright, now, when the (transist) when will the transistor be saturated? When it is forward biased, heavily forward biased and that will happen when the output is VOL, VOL is the output voltage here, then this transistor will be saturated.

Of course, whether it is saturated or not will depend on the value of RB, so we will ensure that the value of RB is low enough for the transistor to saturate. At that time, the voltage drop across the VCE will be 0.2 volts, so in this case, we will get 3.6 minus the drop across the LED, we will assume it to be 1.6 volts minus the VCE sat, the 0.2 volts is equal to the voltage across the resistor, and that is equal to, again 1.8 volts. And so, R is equal to 1.8 volts divided by 50 milliampere and that will give me a value of 1800 divided by 51 ohm.

So, I will get a value of R is equal to 36 ohms, and I can either use a standard value of 33 ohm or 39 ohms. Let me say that I can arrange a 36 ohm resistor. So, this is what I am going to use for this resistor. Now, we have to calculate the value of the base. Here again, I am going to assume that for 50 milliamperes, the beta load, the collector current, the beta of this transistor is 100, and so IB is equal to IC which is 50 milliampere divided by 100, and so this becomes IB, required minimum IB is 0.5 milliampere, and because I want to drive it hard into saturation, so I choose a 5x, IB is 5x, and therefore this becomes IB is equal to 2.5 milliampere.

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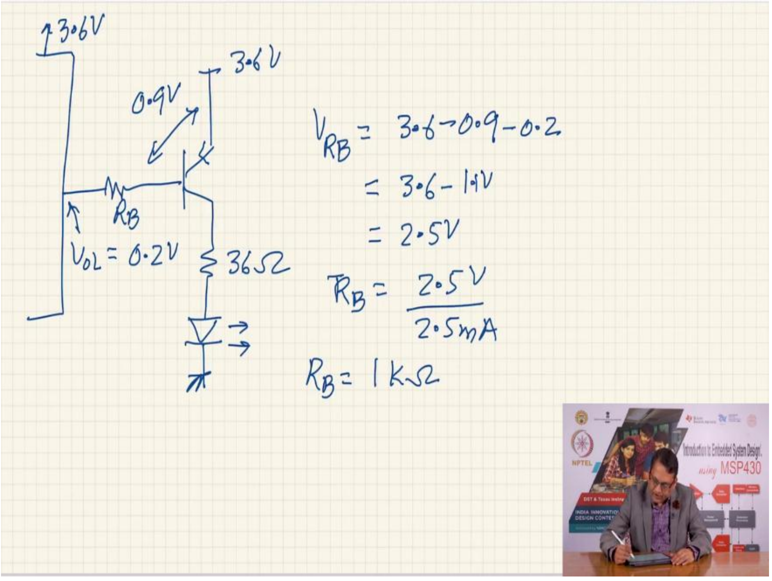

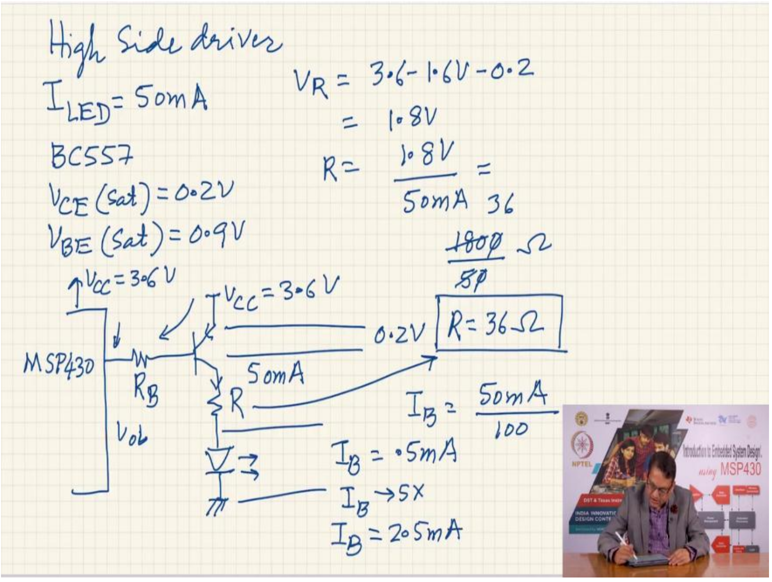

Now, let us take a new page. Now, we have the, here voltage is VOL, and so I am going to assume a VOL of 0.2 volts. Here is my resistor, the transistor, the transistor here, this supply voltage is 3.6 volts and on the load I have this resistor, which we already calculated, the LED, this was 36 ohms, this is red LED and this voltage will be 0.9 volts for this VBE sat and therefore, what I have is V, if this is RB, the voltage across RB is equal to 3.6 volts from here minus 0.9 volts minus 0.2 volts, 0.2 volts, the VOL saturation and that leads me to 3.6 minus 1.1 and that gives me 1.1, that gives me 2.5 volts, that is the voltage across the base resistor and therefore, I, RB is equal to 2.5 volt divided by 2.5 milli ampere.

The amount of current as you saw here, we want through the base so as to saturate the transistor hard and so the value becomes RB is equal to 1 kilo ohm. This is what we have.

Now, let us take another example, because this is a tricky example, when you are doing a high side switching where the supply voltage, this is still 3.6 volts, but in the situation where the load voltage is more than the supply voltage of the microcontroller, which drives, the things complicate and we already seen the configuration.

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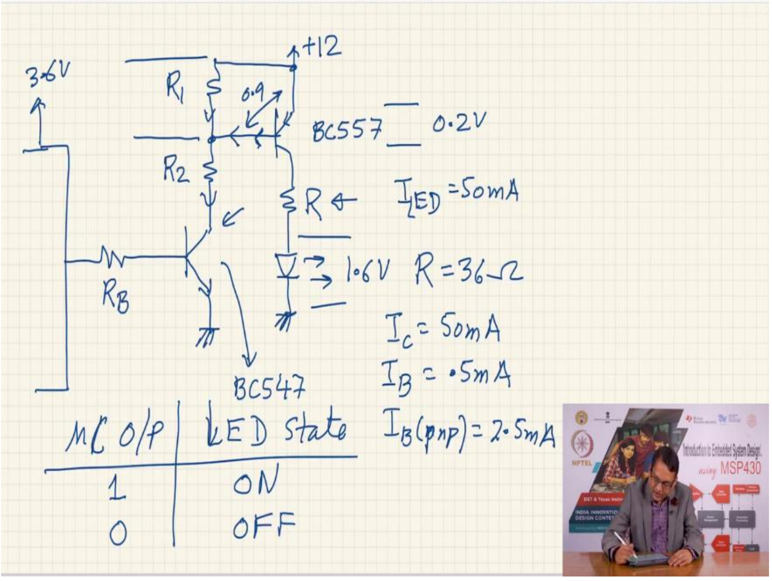

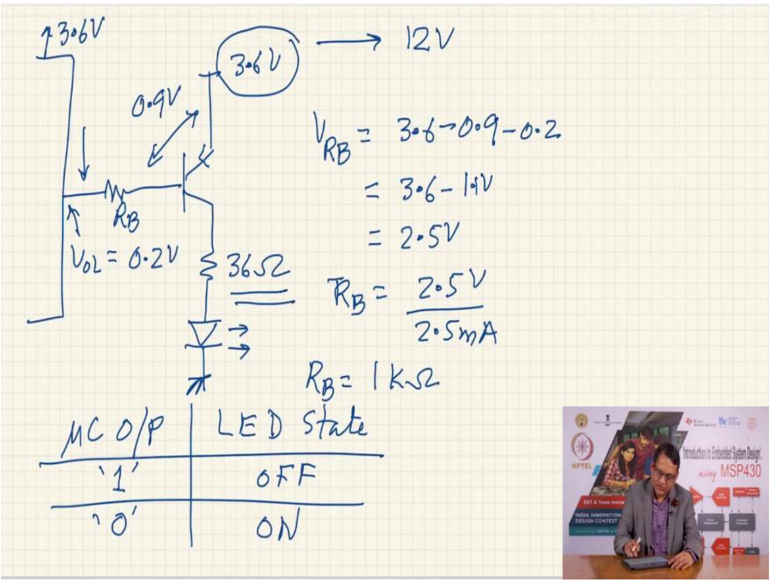

The configuration is that we have to use a mechanism, so this supply voltage is 3.6 volt. Now, if we were to, let us go back here, if this supply voltage here, 3.6 volt changes to 12 volts, suppose, then this 12 volts will never be the output voltage here will never be able to turn this transistor off because when it is logic 1 you are going to get about 3 volts that will still make the transistor saturate and when it is logic 0 even then it will saturate the transistor.

So, we actually lose control over this PNP transistor in this configuration. And so, we had to find another method so, that we can (satu) where we can cut this transistor off when we want and we should be able to saturate. And so, we had seen the configuration, so, I am going to choose a supply voltage of 12 volts. Here is my PNP transistor and my load is this resistor and this LED, and to be able to drive this, I have shown you the configuration is in this fashion. This is the method to turn this transistor on, which is a BC557.

I will need another NPN transistor and I can choose this transistor to be BC547. I need additional resistor, so this is my current limiting resistor with the LED, I have let us say, R1 and R2 and I have RB. Now basically, the introduction of an additional transistor basically becomes an inverter, and so now, the LED will be on. So, if I see the earlier case, LED state and rather the microcontroller output as a function of LED state, what do we have? That if the microcontroller output is 1, this transistor cuts off, so LED is off and when the microcontroller output is logic 0, the LED becomes on.

Now, when we introduce this NPN transistor, let us do the same mapping, microcontroller, microcontroller output versus LED state. Now, if microcontroller is 1, this will saturate transistor, NPN transistor, which will pull the base to ground, which will saturate the PNP transistor, I will turn the LED on.

So, when this is 1, LED is on, when this is 0, this transfer cuts off, this floats the base. So, base is now being pulled up to the same supply voltage of 12 volts, the PNP transistor is not going to saturate, and so the output is off, so this is off. So, it has become different from the earlier time where 1 was off and 0 was on, here, 1 is on and 0 is off. So, that is the case, we will see how to calculate the value of R1 and R2 and RB, so that we can put it in the configuration like this.

So, let us see how in this configuration or how to calculate the value of R1, R2 and the base resistor, we can easily, there is no need to recalculate the value of this current limiting resistor. If our configuration is that ILED is going to be 50 milli ampere, our VCE sat is going to be 0.2 volts, our VBE sat is going to be 0.9 volts, the voltage across this, we are going to assume to be 1.6 volts. Then the value of resistor will be the same as last time and the value of resistor was 36 ohms.

So, we are going to get the same value here R is equal to 36 ohms. Now, the issue is in this case, the current is going to flow here, when the transistor is saturated and no base current will flow when the transistor is cut off. Now, we already seen that the current, the collector current is IC when the transistor saturated is going to be 50 milliampere, and so IB for beta of 100 will be 0. 5 milli ampere.

And so, for hard saturation, that is I want to allow 2.5 times current. So, IB for the, just to make differentiation IB for the NP, PNP transistor here will be 5x and so it is 2.5 milliampere when the transistor is saturated that 2.5 milliampere current is going to flow here, it is going to flow in this path, but some current will also come from R1. Now, how much current will flow through R1 will depend on the value of R1 and the voltage dropped across R1 and that volts when the transistor, the PNP transistor is saturated, we have already estimated to be 0.9 volts.

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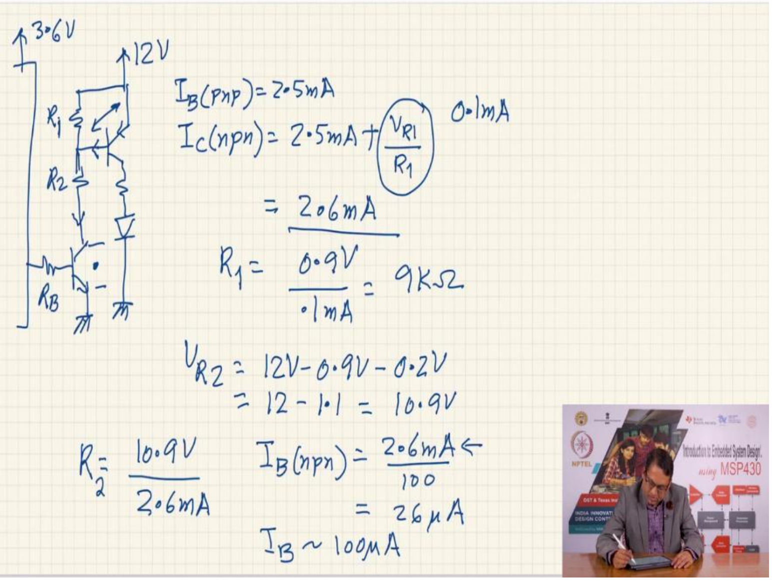

And therefore, the collector current of NPN transistor, so, the collector let me redraw the circuit here for easy reference, here is my NPN transistor, here I have R1, here I have R2, here is my base of the second transistor, here is my resistor and my load and this supply voltage is 12 volts whereas the supply voltage of microcontroller is 3.6 volts, and this is R1 are R2 and is RB.

This current we have estimated to be, so IB of PNP, we have estimated to be 2.5 milli ampere. IC of NPN, this transistor here will be equal to 2.5, the base current coming from here, 2.5 milli ampere plus the current generated because of, because of R1. The voltage dropped across R1 will be point 0.9 volts plus VR1 divided by the value of R1. And it is up to us, how much current we want to flow and so let us say that we want to flow 0.1 milliamperes of current.

So the total collector current becomes, so this value we want to be 0.1 milliampere and, so the total collector current through the NPN transistor becomes 2.6 milliampere. At that time, if the current through this resistor is 0.1 milli ampere and the voltage dropped across is, across it is 0.9 volts by virtue of the saturation voltage VBE sat therefore, R1 value becomes 0.9 volt divided by 0.1 milliampere, so this becomes 9 kilo ohm.

All right, whereas, or also what will, when this transistor is saturated, the voltage dropped across this will be 0.2 volts therefore, VR2 is equal to 12 volts minus the voltage drop across R1, which have estimated to be 0.9 volts minus the saturation voltage across the NPN transistor, which we take to be 0.2 volts and therefore, this becomes 12 minus 1.1 which is equal to 10.9 volts.

So, the voltage across the resistor R2 is 10.9 volts and therefore, R2 is equal to 10.9 volts divided by the current which is 2.6 milliampere, and that way you estimate the value whatever it is. Similarly, the current now flowing in the collector is 2.6 milli ampere, the base current again will be, will have to be determined and from that the value of RB of this will have to be determined.

Therefore, IB of the NPN transistor is equal to 2.6 milliampere divided by 100 which is equal to, which will give me a value of, oops, this is the collector current, and so I get 26 microamperes. This is the value of the base current that has to be, that has to flow through the NPN transistor and I, again make it 5 times therefore, the actual IB, I want to push through the NPN transistor will be 5 times this. So, let, let me approximate this to be about 100 micro ampere. So, it is closer to 4 times than 5 times just for ease of calculations.

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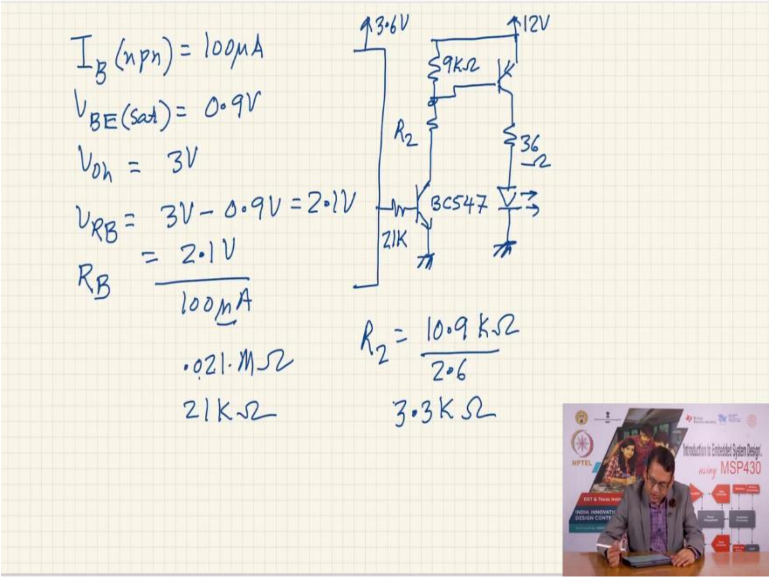

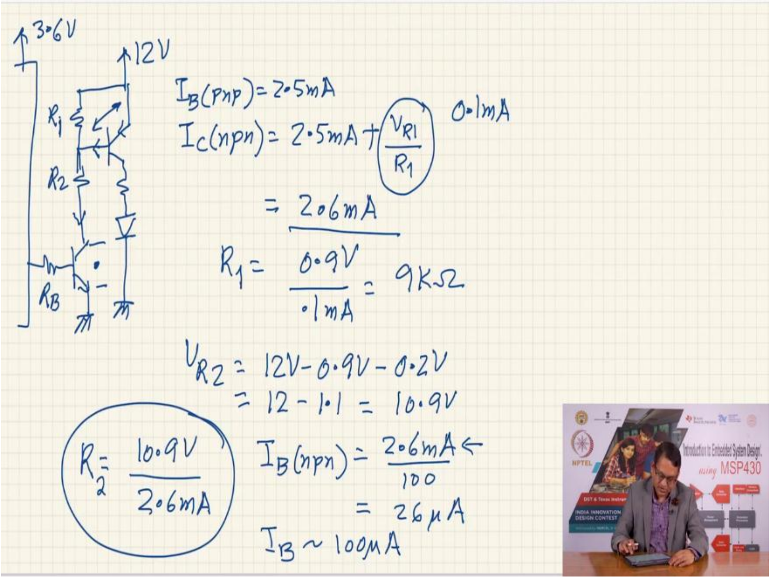

So, my IB through the NPN transistor is equal to 100 micro ampere. The VBE sat for the NPN transistor is again 0.9 volts, the VOH, now I have to consider, VOH for this will be, it becomes 3 volts as we assumed earlier for a supply voltage of 3.6. And therefore, VRB, the voltage across the base resistor of the NPN transistor is equal to 3 volts minus 0.9 volt which is equal to 2.1 volt divided by 100.

So, this is the value of RB equal to 2.1 volt micro ampere. And so, this is 0.021, the micro goes up, becomes mega ohm, so 1 2 3, 21 kilo ohm. So, what is, what does our final circuit look like? It look like, it looks like here is my MSP, it has a NPN transistor which is BC547, this is grounded, the supply voltage is 3.6 volts. I have a resistor R1, which was R1 is 9 kilo ohm. So this is 9 kiloohm. I have another resistor here, which is R2, I have a PNP transistor, the base is going here, the collector driving a red LED, and this was 36 ohm, and this supply voltage is plus 12 volts.

And the value of R2 was this 10.9 by 2.6 milliamperes. So, it is R2 is equal to 10.9 kilo ohm divided by 2.6. If we take this to be 3, 3 and 3 9, so a little more than, a little more than 3 say, 3.3 kilo ohm. So, R2 value is 3.3 kiloohm. I have R1 of 9 kilo ohm. The base resistor here is 21 kilo ohm. And what I have achieved is high side control over load using a supply voltage of supply, 12 volts driving the load, but the supply voltage of the microcontroller to be a much smaller value of 3.6 volts.

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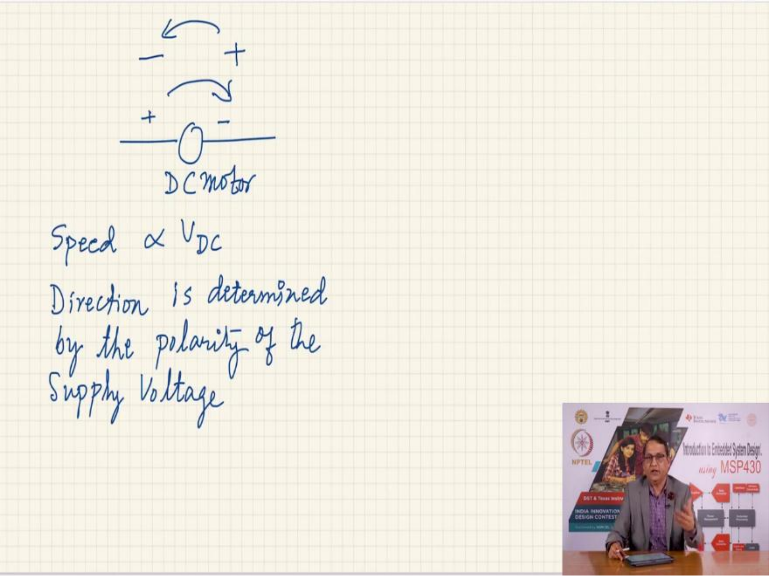

Now, often times we would require in a single configuration, both high side and low side control, and where are we going to need those? We are going to need those when we are driving load like such a DC motor. Okay? So, I am going to show this DC motor as this, and a DC, so I am going to write here DC motor.

So, the DC motor has two parameters, one, speed of DC motor is proportional to the supply voltage across the DC motor and the direction of the DC motor is determined by, by the polarity of the supply voltage, which means if by applying plus here and minus here, it is going to rotate in this direction, then to reverse the direction I must apply plus here and minus here and then it will rotate in this direction.

So now, I want a mechanism. If my requirement in an embedded application is to be able to control the speed and the direction of motion, I need control over both these parameters. And what we will do is in the next lecture, we will see how with an interesting combination of high side and low side switches, implemented either through NPN transistors or MOSFETs, we can exercise that control. See you soon.