Introduction to Embedded System Design
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Lecture 18
Physical Interfacing - 4

Hello and welcome back to a new session. In the last session we looked at various ways of controlling the LEDs through what we call as the low side switching. In that we looked at various options to increase the current through the LED and we came up with this configuration of driving LED with the help of a npn transistor operated in a switch mode.

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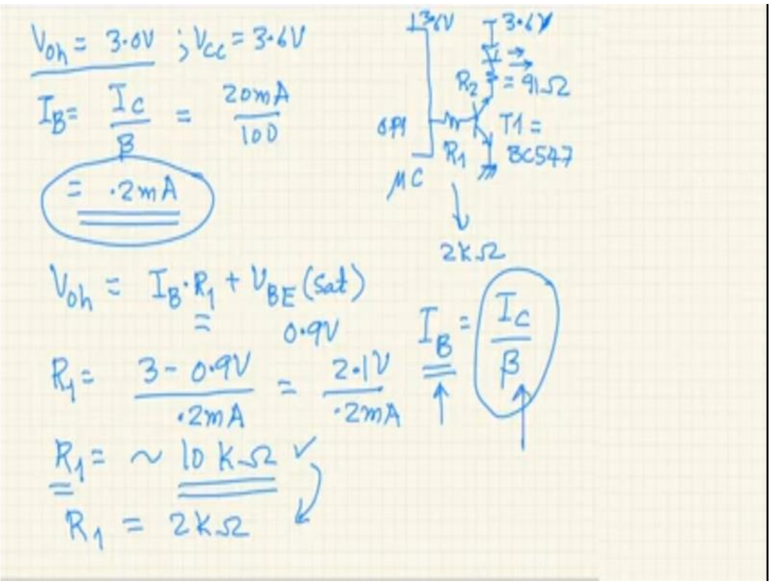

$V_{oh} = 3.0V$; $V_{cc} = 3.6V$

$I_B = \frac{I_C}{\beta} = \frac{20mA}{100}$

$= .2mA$

$V_{oh} = I_B \cdot R_1 + V_{BE}(sat)$

$V_{BE}(sat) = 0.9V$

$R_1 = \frac{3 - 0.9V}{.2mA} = \frac{2.1V}{.2mA}$

$R_1 = \sim 10\,K\Omega$ ✓

$R_1 = 2K\Omega$

$I_B = \frac{I_C}{\beta}$

So, to operate the transistor in the switch mode, it has 2 options. Either the transistor is saturated or the transistor is cut off. When the transistor is cut off, there is no current through the collector. Therefore, in our case the LED will be turned off. To saturate the transistor, we must drive a certain amount of base current which is much more than the base current you would require that you would get by merely this relationship that base current is equal to the collector current divided by beta.

If you get a certain amount of base current, if you want to operate the transistor in a switch mode and you want to saturate the transistor, the required base current should be much more than you get by this equation and which is what we saw in this example that the nominal value of base current from this equation is a certain amount which leads to a value of resistor R1 to be 10 kilo ohm, but to ensure that the transistor is driven deep into saturation, we reduce the amount of the resistor by a factor of 5. As you see here, we have gotten it down to 2 kilo ohm, which will ensure 5 times more base current than you would get this equation and driving large amount of base current ensures that the transistor is nicely saturated.

Now, this is all fine when you are driving an LED where the supply voltage is constant, but imagine a situation where the supply voltage is being derived out of a battery. As you use the battery the battery voltage will go down and, in this situation, the reduced battery would lead to a current through the LED which will keep on reducing why because your VCC is going down.

Now, how do we ensure that the LED current remains constant even though the battery voltage is going down. So, let me show you a configuration where we can drive the LED with a constant current source or current sink in this case so that for the entire lifetime of the battery, usable lifetime of the battery, it still provides a constant current.

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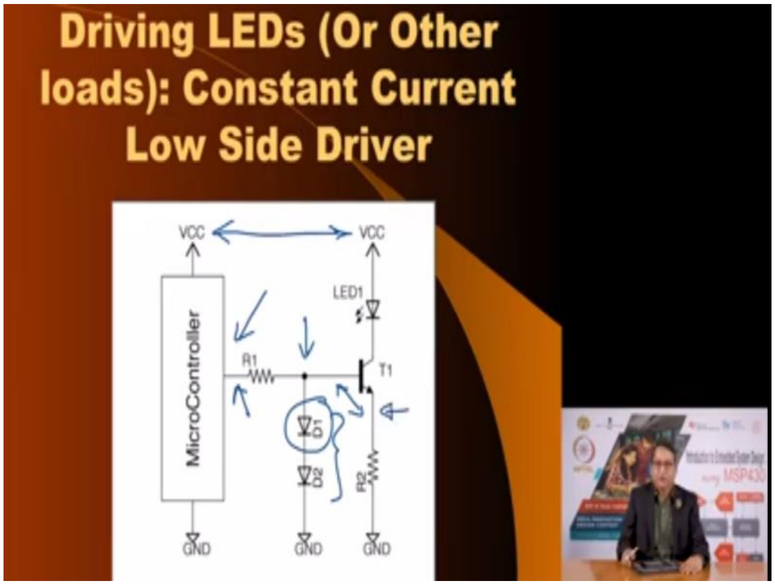

Driving LEDs (Or Other loads): Constant Current Low Side Driver

Here is the configuration. So, this is a constant current low side driver, which means this is a constant current sink because the current is sinking into the switch. Look at the configuration. Here is our output from the microcontroller. Our microcontroller is MSP430. Instead of regular VCC from a regulated output maybe this is a battery as would be the case let us say in a TV remote. The battery voltage will drop over a period of time but we do not want the current through the LED to vary and so what we see is the output voltage is high and I have used 2 diodes, silicon diodes.

One of the silicon diodes is to ensure that it compensates for this VBE across the transistor. Mind you that this transistor npn transistor is not operated as a switch. Here, the transistor is being operated in a forward active region and the configuration is actually emitter follower that is common collector. The voltage here would be 0.7 or VB voltage drop above the voltage at the emitter.

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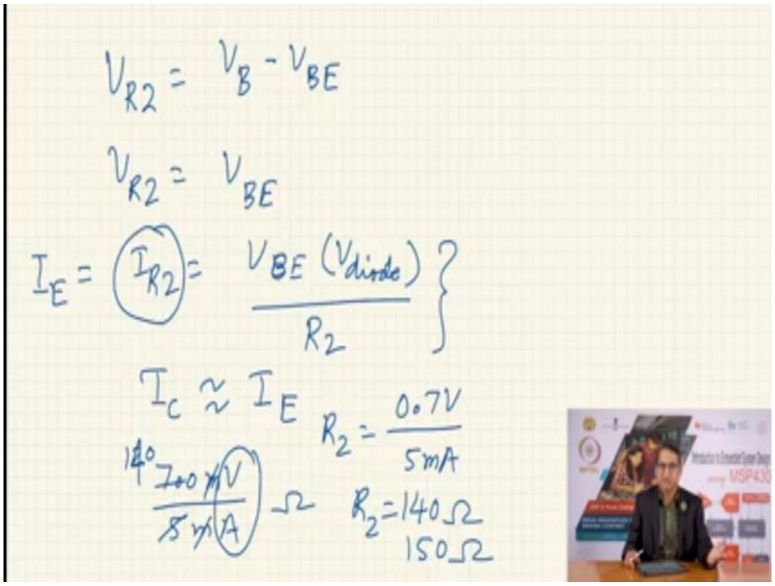

$$V_{R2} = V_B - V_{BE}$$

$$V_{R2} = V_{BE}$$

$$I_E = \bigcirc\!\!\!\!\!I_{R2} = \left.\frac{V_{BE}\,(V_{diode})}{R_2}\right\}?$$

$$I_C \approx I_E \qquad R_2 = \frac{0.7V}{5mA}$$

$$\frac{\overset{140}{\cancel{700}}\,\cancel{m}V}{\cancel{5}\,\cancel{m}A}\,\Omega \qquad R_2 = 140\Omega$$

$$150\Omega$$

And therefore the voltage across the resistor R2 would be equal to VR 2 is equal to VB that is the voltage at the base minus VBE and because we have used 2 diodes, VR2 is equal to the voltage drop across the second diode, which would be equal to VBE because the second diode is also a silicon diode and therefore the current through R2, IR2 is equal to VBE which in this case is actually V diode divided by the value of R2 and now you see the current is independent of the supply voltage and so for the entire duration of the lifetime of the battery, the resistor would ensure that a constant current equal to VBE divided by R2 would keep on flowing through the emitter of the transistor.

If the beta of the transistor in this case is large enough then IC will be approximately equal to IE and this IR2 is actually equal to IE, the emitter current and therefore this would ensure that the collector current which is the LED current remains constant equal to this equation determined by this equation. So, this is a method to drive the LED with the constant current source equal to value of VBE, which is 0.7 divided by R1. So, let us say, if I want 5 milli ampere current constant current through the LED, VBE is 0.7 volts divided by 5 milli ampere. This is the value of R2 is equal to 700 milli volt divided by 5 milli ampere.

This and this goes away, the V divided by ampere leads to this and this is roughly 12 and 120. So, the value of R 2 is 120 ohm, which incidentally is a standard value. It is not actually 120 ohm, it is 140 ohms so the value of R2 is R2 is equal to 140 ohms. The nearest standard value is 150 ohms. So, you could use a 150 ohm resistor then you would get a little less than 5 milli amperes of current but the current would remain constant throughout the lifetime of the battery. This is what is normally used in the LED driver part of a TV remote or other such applications where you want the current through the LED to remain constant, even if the supply voltage fluctuates.

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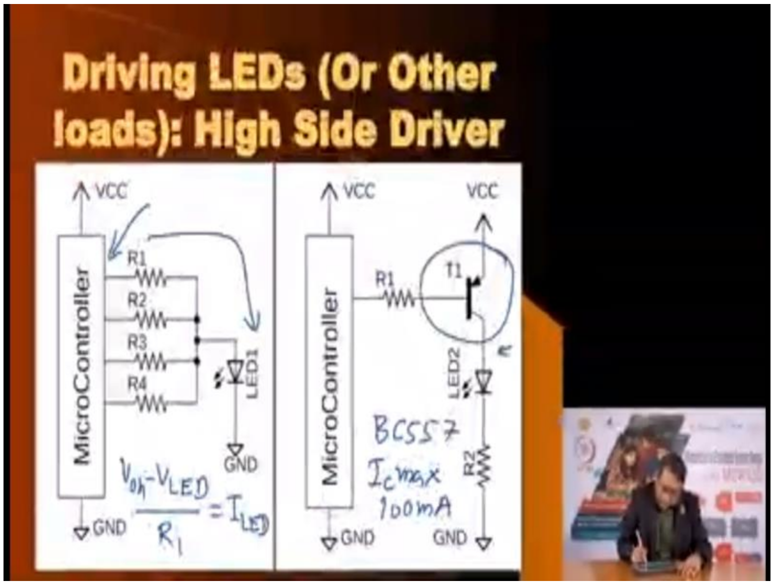

Driving LEDs (Or Other loads): High Side Driver

Now, apart from the so we have seen till now various ways of driving the LED or similar loads using a low side switch. Let us look at other ways of driving the LED, in this case the high side driving which means the control of the current is towards the higher side of the voltage which means connected to the VCC. Now, we have configured LED1 here and we have grounded the cathode of the LED. The anode of the LED is connected to the same four resistors R1 R2 R3 R4 and we can use this configuration to increase the current through LED1.

If we turn the voltage, the LED will be turned on whenever any of the inputs here is logic 1 and it would flow a current through the LED equal to the equation that we have previously seen that is VOH minus VLED divided by the value of R. In this case, say R1 will be the current through the LED and since we have 4 resistors and if these values, if these 4 resistors are equal, we would have a sum of all these 4 currents flowing through the LED and we can drive the LED with a higher amount of current than is possible with a single LED, single microcontroller pin.

This is one configuration and the other configuration if you want high side switch, high side control of the current we can use a PNP transistor as a switch. Here we have used a PNP transistor, a similar transistor to BC547 corresponding PNP transistor is BC 557. It can handle IC max of about 100 milli ampere and using this configuration, we can apply VCC to this part minus of course the VC SAT of this transistor and using the same arguments, we would be able to drive LED2 with larger current and let us go through the equation here again.

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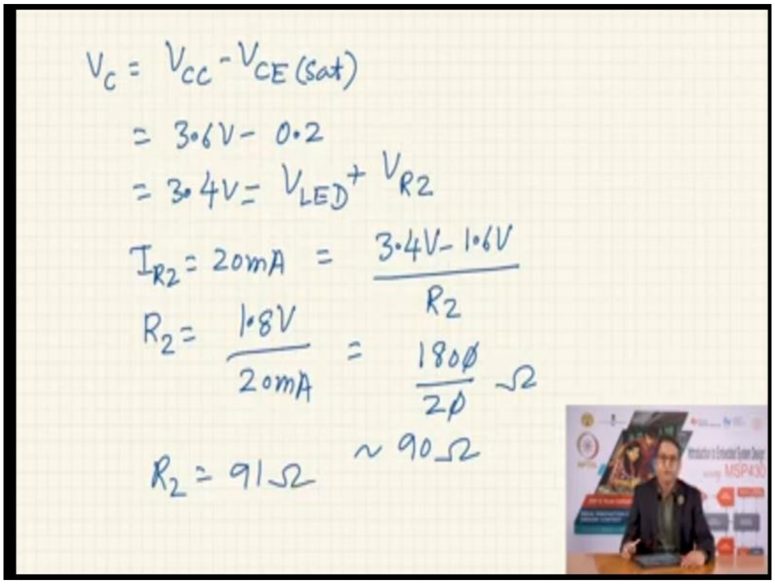

$$V_C = V_{CC} - V_{CE(sat)}$$
$$= 3.6V - 0.2$$
$$= 3.4V = V_{LED} + V_{R2}$$
$$I_{R2} = 20mA = \frac{3.4V - 1.6V}{R_2}$$
$$R_2 = \frac{1.8V}{20mA} = \frac{180\cancel{0}}{2\cancel{0}}\,\Omega$$
$$R_2 = 91\Omega \quad \sim 90\Omega$$

When the transistor is saturated, the Collector voltage VC is equal to VCC minus VCE SAT and we can assume the same voltage is here, VCC is say 3.6 volts and VCE SAT is say 0.2 volts. So, the collector voltage will be equal to 3.4 volts which is equal to VLED that is the voltage drop across the LED plus the voltage drop across the resistor. In this case, it is VR2 and so we can find out the value of the resistance based on the current that we need. Let us say we want 20 milli amperes so IR2 is equal to 20 milli ampere which in this case will be 3.4 volts minus V LED which in this case is say 1.6 volts divided by R2.

So, to estimate the value of R2, we have R2 is equal to 2.2 volts. Sorry. Since the voltage drop across the LED is 1.6, it will lead to 1.8 volts. 1.8 volts divided by the current which we want to be 20 milli amperes which will lead to 1800 by 20 ohms and so this will lead to about 90 ohms and we can use therefore R2 is a standard 91 ohm resistor we can use and using the high side switch control, we can allow more current through the LED than is possible with a single pin of the microcontroller and the same equations can be applied if you want even more current than 20 milli amperes.

If you want to have 500 milli amperes through the LED, we have to find a different PNP transistor, which has a higher current capacity. If we want to control, if you want to allow 500 milli amperes to pass through the transistor, we must select a transistor which is capable of handling at least 1 ampere and then similar equations could be used and you could use to estimate the value of the R2.

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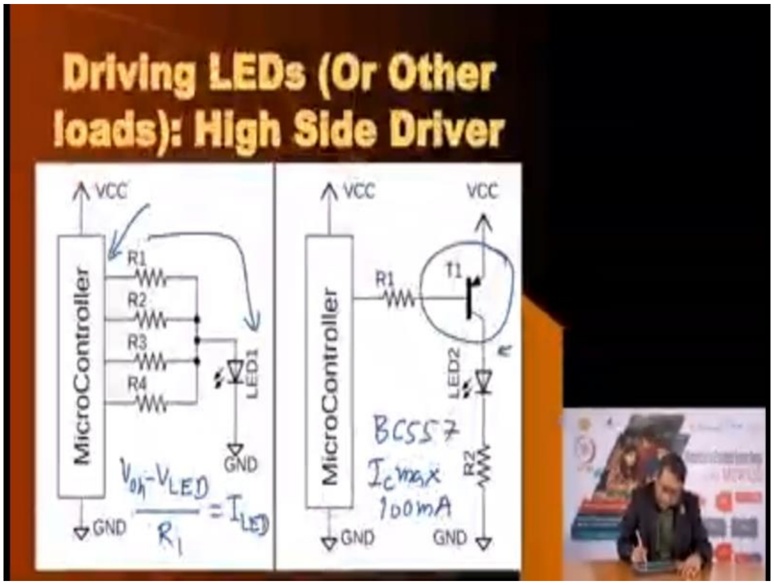

Driving LEDs (Or Other loads): High Side Driver

$$\frac{V_{oh}-V_{LED}}{R_1} = I_{LED}$$

BC557

$I_c$max 100mA

Apart from that, you also need to like in this equation, we need to estimate the value of R1 and similar arguments can be presented. How? Let us see.

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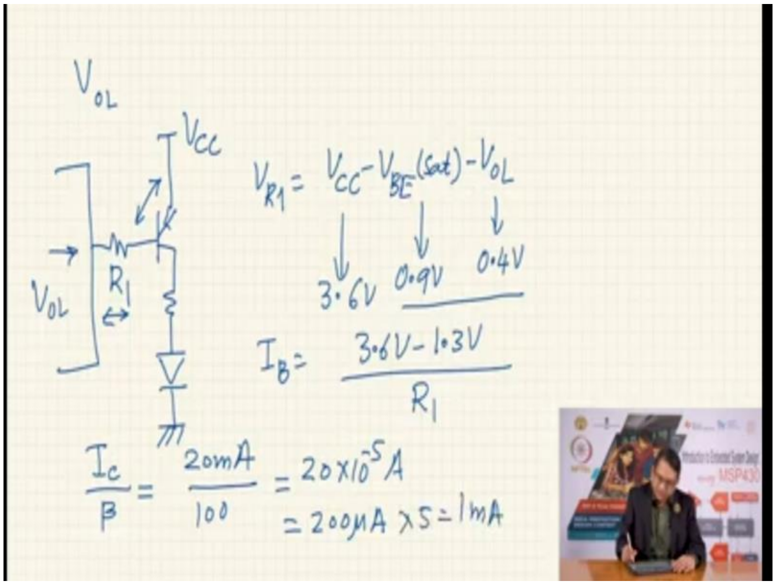

So, the output voltage in this case of the microcontroller to turn the LED on now has to be low. Then only the LED will be the transistor will be turned on which will enable the LED to have that current. So, VOL is the output voltage. So, let me draw this schematic. Here is my resistor, here is my PNP, it is my resistor and my LED and we want to estimate the value of this resistance, which is R1 this voltage here from the microcontroller is VOL. This voltage is VC, the voltage drop here is VBE SAT and therefore the voltage across resistance, VR1 is equal to VCC minus VBE SAT minus VOL. So, let us take similar numbers. Let us say VOL is 0.4 volts, VBE SAT is 0.9 volts and let us say VCC is 3.6 volts.

Therefore, the current that will flow in this case is equal to the difference of this voltage IB will be equal to 3.6 volts minus 1.3 volts. The sum of these 2 voltages divided by R1 and how much base current we want. We want the base current to be many times over the actual base current where IC that was 20 milli ampere is divided by beta that is the base current in a linear region but since we want to saturate, we will allow much more current. So, this is 20 milli ampere.

We can assume the beta to be 100. Therefore, this is 20, 200 micro amperes. This is actually 20 into 10 raise to power minus 5 amperes and so this is also 200 micro amperes. So, the base current is 200 micro amperes and so we will allow let us say 5 times more current into 5 is 1 milliampere. So, we will use this 1 milliampere in this equation and so what does this lead to.

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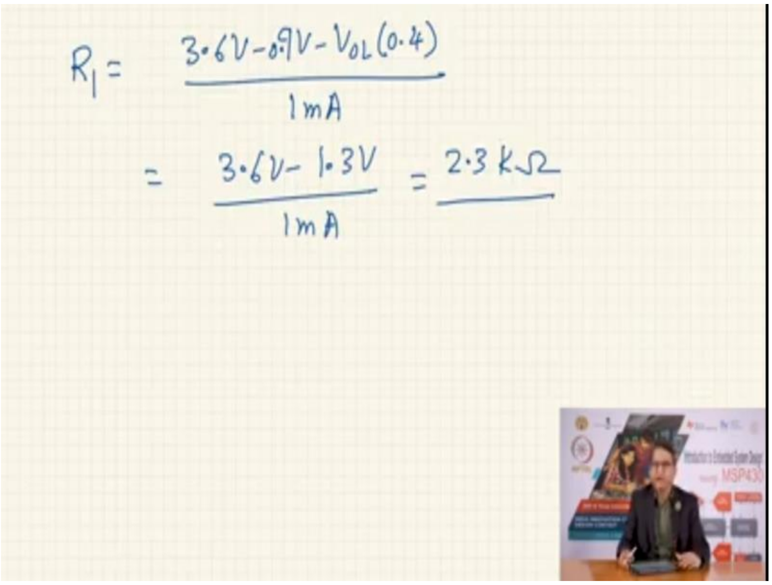

$$R_1 = \frac{3.6V - 0.9V - V_{OL}(0.4)}{1mA}$$

$$= \frac{3.6V - 1.3V}{1mA} = \underline{2.3\,k\Omega}$$

That R1 value is equal to 3.6 volt minus VBE which is 0.9 volt minus VOL which is 0.4 volts. So, this divided by 1 milli ampere and therefore it is 3.6 volt minus 1.3 volts divided by 1 milli ampere and so this becomes 2.3 kilo ohm. So, the resistor value at the base has to be 2.3 kilo ohm to allow about 20 milli amperes of current through the LED. This is the way to control a high side switch.

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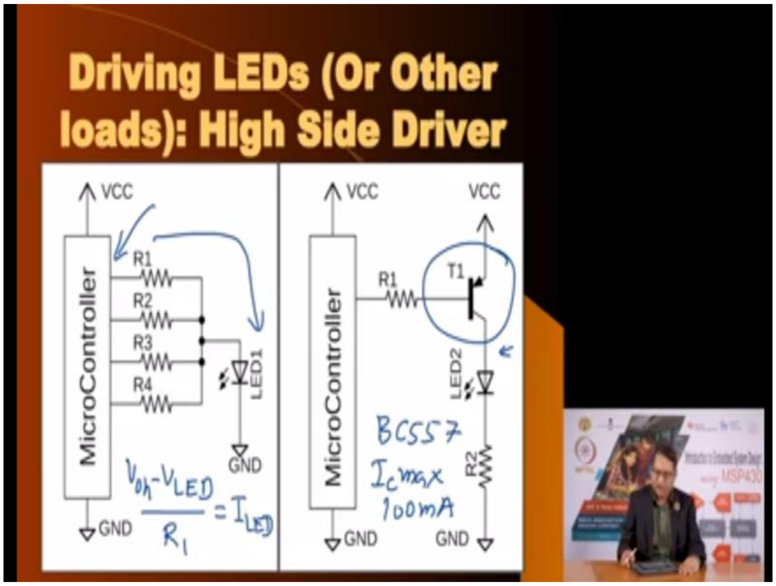

Driving LEDs (Or Other loads): High Side Driver

This is the high side switch and this is the way to calculate the value of the base resistor. We already seen the value, the way to calculate the value of the series resistance. Let us see what other configurations we have.

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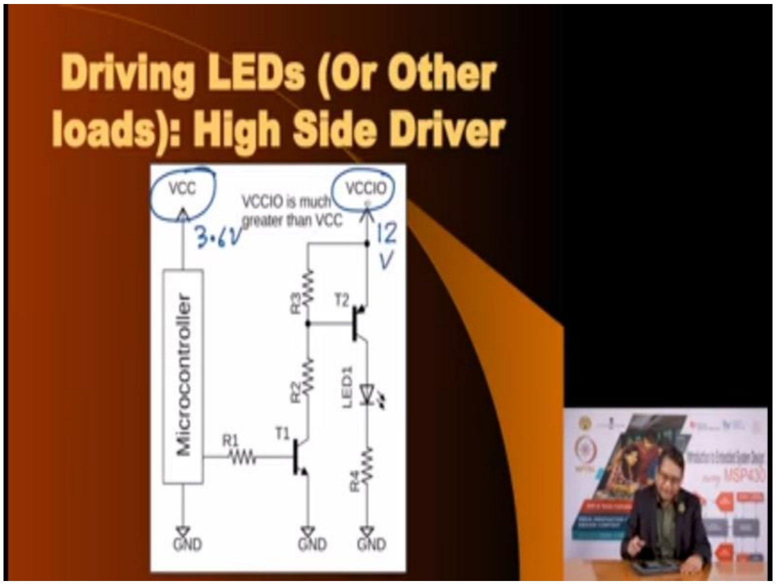

Driving LEDs (Or Other loads): High Side Driver

Now, in case the supply voltage that we want to connect to the LED is much more than the supply voltage of the microcontroller. Let us take an example that the microcontroller MSP430 has a supply voltage of 3.6 volts but VCC which is required to drive the LED is say 12 volts and then it will never be able to turn the LED of in the normal configuration.

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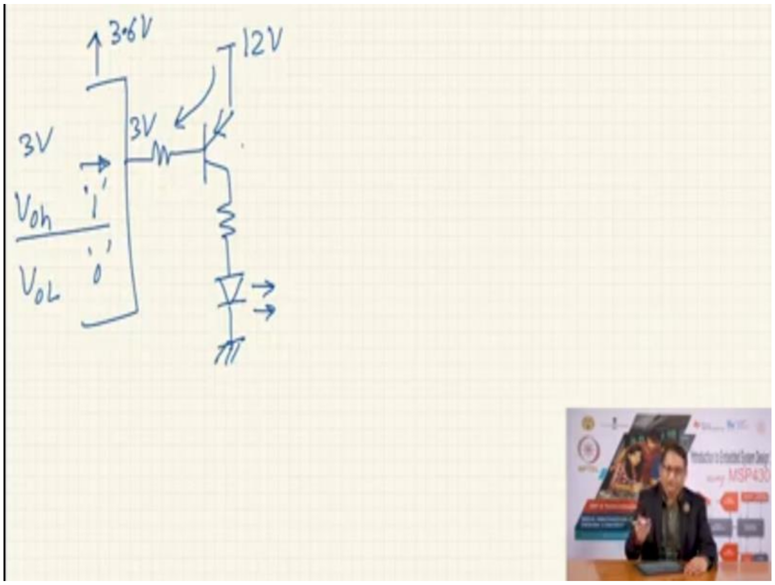

Why because if my microcontroller has a supply voltage of 3.6 volts and I have this resistor, here is my PNP transistor in the supply voltage, here is 12 volts and here is my resistor and the LED. I will never be able to turn this transistor off for whatever the state of the output pin whether it is 1 at which time the voltage will be VOH and if it is 0 it will be VOL. I will never be able to turn this transistor off if the output voltage is VOH because VOH as we have seen is can be maximum 3.6 volts, but usually it will be less than 3.6 volts. Let us say it can be 3 volts.

Even with 3 volts here, this transistor is always going to be forward biased and so this switch will always be on and therefore it is not possible to control this LED that we cannot turn it off if the voltage is high. It will be turned on if the voltage is low as we have seen but outputting logic 1 on this pin will never turn this led off. Therefore, we have to find an alternative way to control this high side switch.

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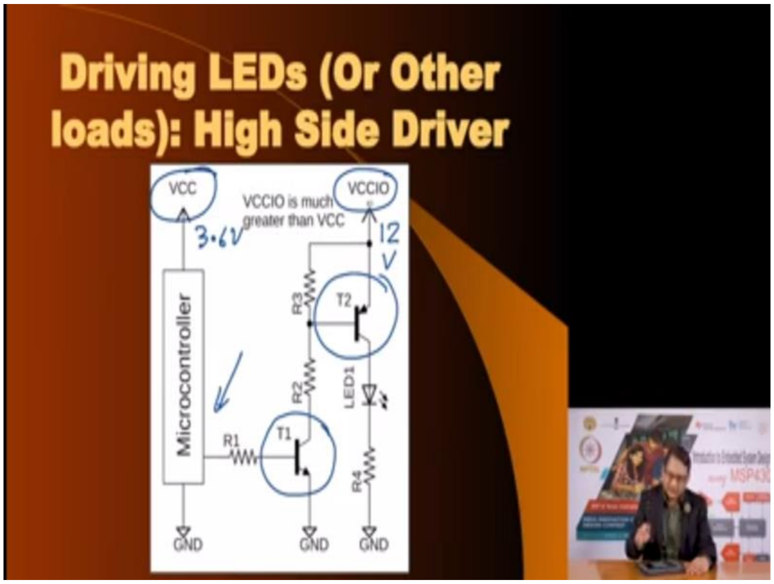

Driving LEDs (Or Other loads): High Side Driver

VCCIO is much greater than VCC

And this is the configuration that we require that instead of apart from the transistor T2 now, which is the PNP transistor, we also need another transistor T1, which will isolate the voltage that appears at the output pin and ensure that transistor T2 can be turned on or off. Let us understand the voltages that are available here.

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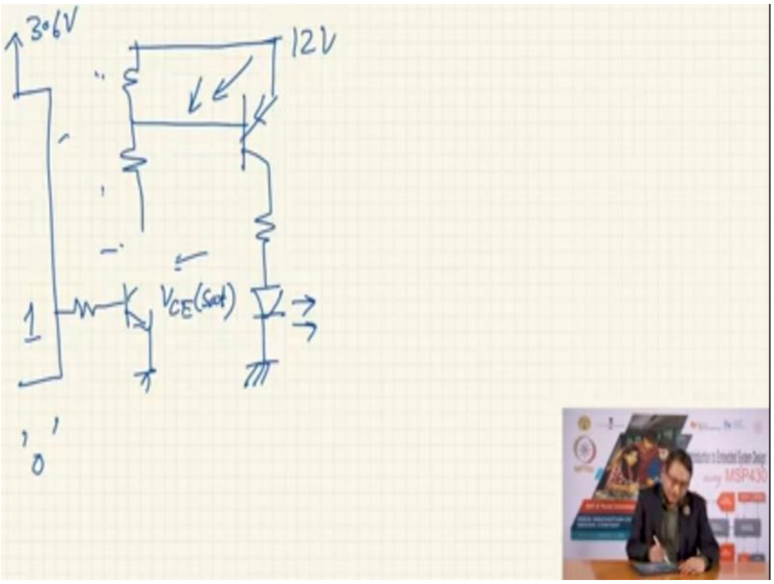

Now, we have a PNP transistor where the VCC is 12 volts. Here is our load through the resistor and LED and we have now registered driving a npn transistor and at the base of the resistor, we have created a voltage divider. This is connected to 12 volts. This has a supply voltage of 3.6 volts. Now, when I output logic 1, this transistor will be saturated and therefore the voltage here will be close to, this will be VCE SAT, which is a very low value say 0.2 volts.

Therefore, this voltage is at 0.2 and therefore out of 12 volts, I will create a voltage divider out of this. I can choose these resistors like that. The voltage here is close to 12 volts so as to if I have 1, I can make this ground and I can saturate this transistor and so it will turn the LED on. Now, instead of 1 if I apply logic 0, this will cut off and therefore it is as good as this resistor is this collector is disconnected.

This lower resistor is floating and therefore the voltage at the base is the same as the supply voltage which means this transistor is not forward biased and this will turn off the LED and therefore whenever you have a situation where the dry voltage of your load is higher than the supply voltage of your driver circuit, microcontroller circuit, the only way to control the high side switch is by incorporating an additional transistor, an npn transistor in this case so that you can turn the LED on and off.

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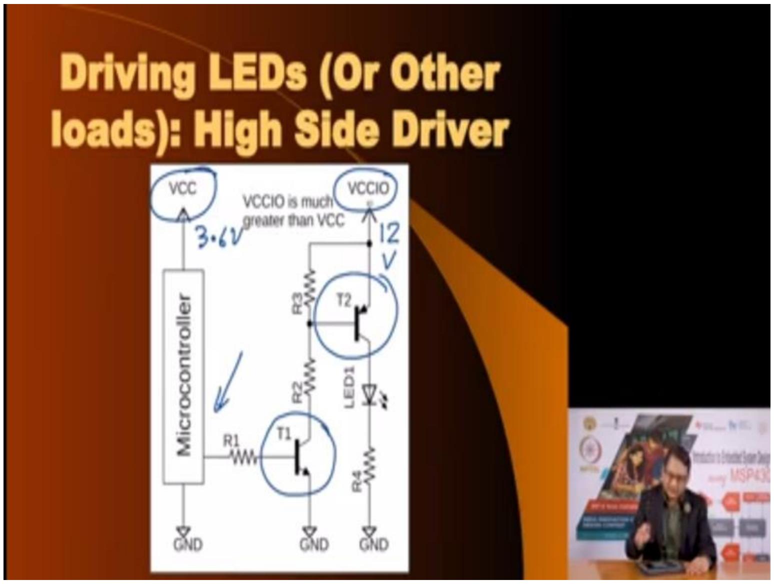

Driving LEDs (Or Other loads): High Side Driver

Similarly, if you want to control the high-power high side switch to provide a constant current source through the LED, we have a similar configuration. Now, we see from the previous configuration, we have moved the currently determining resistor to towards the emitter side. Now, the voltage across this R2 will be equal to one of the LEDs. The other LED will be used to compensate for the VBE drop across the VB of transistor T1 and therefore the current that will flow through R2 IR2 is equal to the voltage drop across diode 1, which is VBE say 0.7 volts divided by R2 that becomes the emitter current of this transistor.

If the beta of this transistor T1 is large enough, the same amount of current will flow through the collector and will be a constant current irrespective of the voltage here. As long as this voltage is above the voltage of some of this plus some of this plus a little bit voltage to keep transistor T1 in active region you will continue to power LED1 using a constant current source. In this case, it is a source why because the current is flowing from the positive supply into the load.

So, this is the way to drive a constant current driver load using constant current source using a high side switch. In fact, this is not a high side switch. It is a high side driver because transistor T1 is not being operated as a switch. It is in the active region.

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Controlling LEDs

- N pins → N LEDs?
- N pins → (N^2)/4 LEDs? (Multiplexing)
- N pins → N*(N-1) LEDs? (Charlieplexing)

Now, we have to consider the situation like we considered for the switch case that when you want to connect a few number of switches, you can 1 switch each to each pin. As the number of switches increase, you have to optimize the number of pins by creating a matrix and if you have N pins output and N pins input that is total number of 2 N pins, you are able to control n square switches. In the same configuration, how about if we want to control large number of LEDs.

We may not have large number of pins to control the LEDs and therefore 1 configuration is that if we have N pins we can control N LEDs. What if N is very large and is more than the number of output pins that a microcontroller has? Then one way is to use a multiplexing technique.

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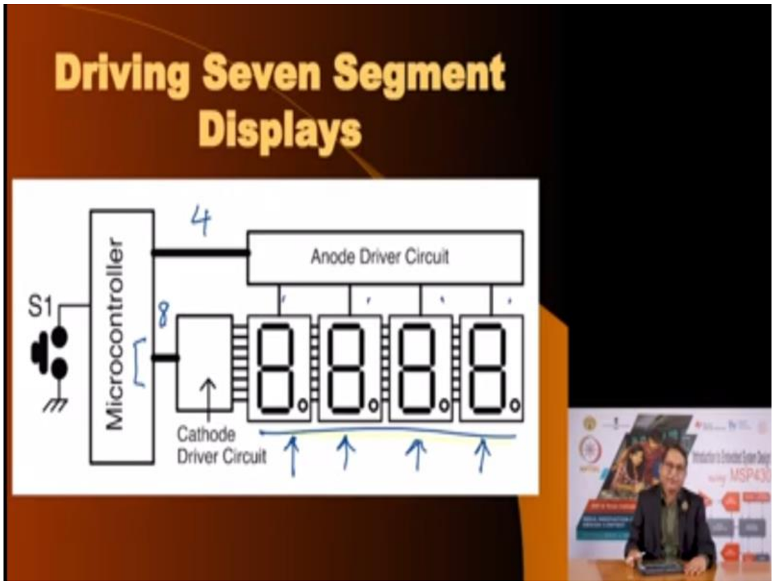

Driving Seven Segment Displays

Let us see what it looks like. Here I have a configuration where we have 4 7 segment displays as I showed here. As we have seen earlier a 7-segment display requires 8 pins. So, if we want to control 4 7 segment displays, it would require that the microcontroller has 32 pins, but what if we do not have 32 pins. Can we control these 4 7 segments displays with less number of pins? It turns out yes using this configuration.

This is a multiplex time multiplexed circuit. Here the number of pins that are required to drive the individual segments is 8 and you need 4 pins to control the common pin of each of the displays and in this case since we have 4 digits we will require 4 pins. So, using 4 plus 8, 12 pins you are able to control 32 LEDs in spread across these 4 7 segment displays.

How does it work? Here at any given time only 1 digit is on but if only 1 digit is on but you want to display all the 4 digits, the way to beat the human eye we have to use a concept called persistence of vision. That is if I display a value here for some time then I turn it off and I display the second digit, then the third digit going to the 4 digit and then I come back to the first digit. If this is repeated at a fast in a frequency, then the I will assume, the I will actually see all the 4 digits simultaneously on and this is what allows multiplexing techniques to use less number of pins and control large number of LEDs.

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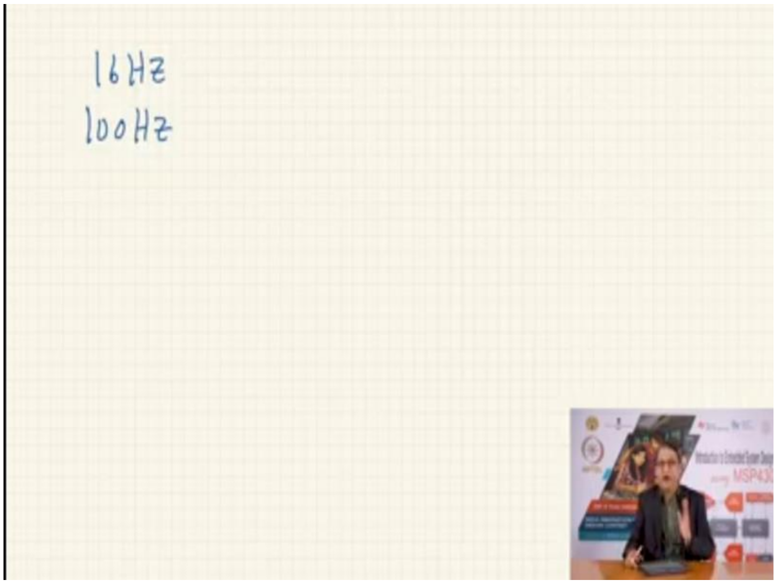

16Hz

100Hz

What is the rate? What is the limitation that persistence of vision happens whenever you turn anything on and off beyond about 16 hertz. In fact, at 16 hertz you may see some flicker. So typically, you go at a much higher frequency say 100 Hertz. So, if I turn each LED each display 7 segment display at a rate greater than 100 Hertz, then my eye will not be able to see individual display on. It will actually see all the displays on at the same time.

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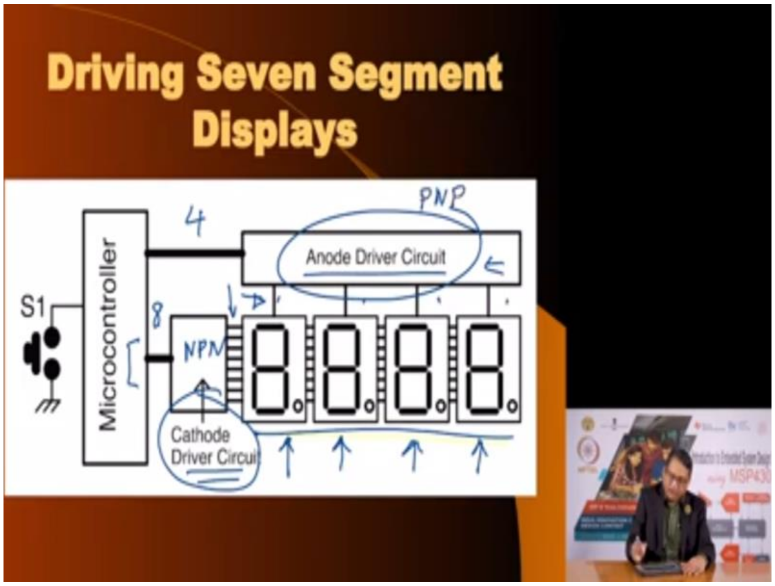

Driving Seven Segment Displays

So, this is a very effective method of controlling large number of displays using less number of pins, but at the cost of additional circuitry. In this case what we call as anode driver circuit, and we have a cathode driver circuit. We will see what kind of electronic components are used for creating the anode driver circuit and creating the cathode driver circuit. Now if the way this led 7-segment displays on can you guess what sort of 7 segment displays being used here.

This one is a common anode 7 segment display which means to enable a display to display a value this voltage must be close to VCC and the individual segments here must be at a lower potential and therefore we need a anode driver circuit, which is a nothing but a high side switch and the cathode driver circuit will be a low side switch and by now, you know that a high side switch is made using PNP transistors and the cathode driver circuit could be used using in configured would be implemented using a low side switch using NPN transistors.

So, by using 4 PNP transistors here and 8 NPN transistors here and 4 PNP transistors here, you would be able to create a high driver circuit and low driver circuit to control 4 7 segment displays and this can be scaled. You can go from 4 to 8 or maybe 10 but not too much and we will see what is the limitation here but let me show you the circuit diagram.

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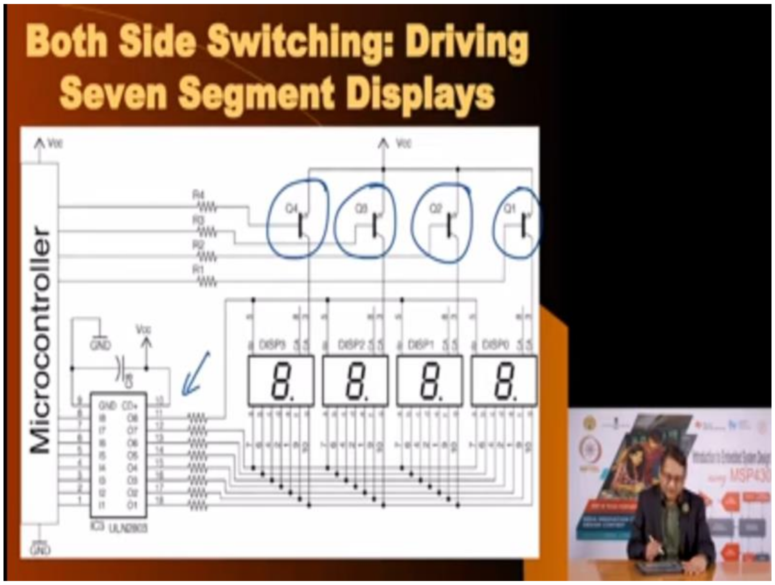

Both Side Switching: Driving Seven Segment Displays

For such a configuration here, I have created a schematic for you which shows 4 7 segment displays common anode type and as you see here, we have 4 PNP transistors and instead of individual 8 NPN transistor we have used a IC which consists of 8 NPN transistors that IC is a low side driver.

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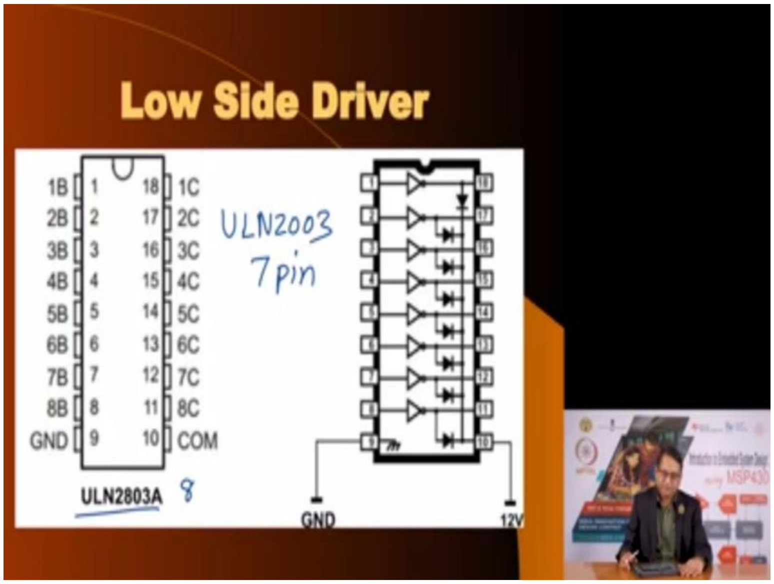

Low Side Driver

This is the IC. In the electronic components that we expect you to have, you may recall that we have an IC called ULN2003. It is exactly like 2803 except ULN2803 has 8 control pins, but ULN2003 has 7 pins that is you can control 7 switches.

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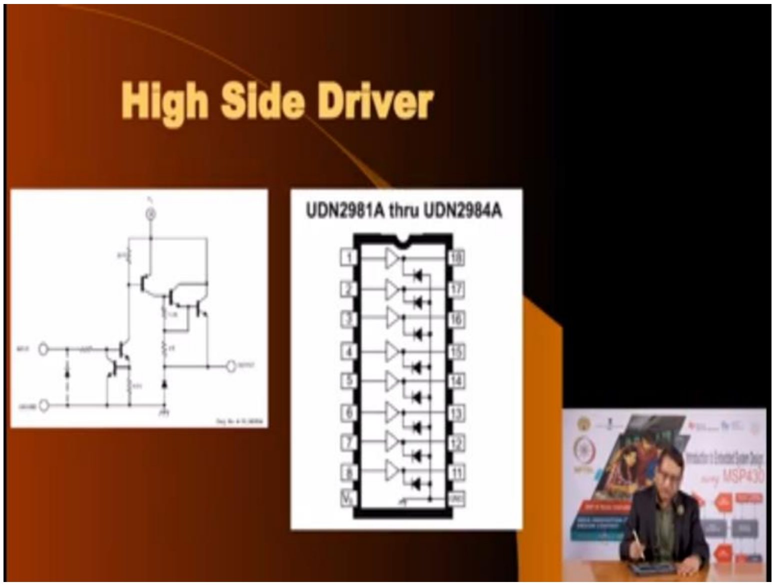

High Side Driver

Similarly, for P and B, either you can use individual PNP transistors or you could also use this driver IC called UDN2981.

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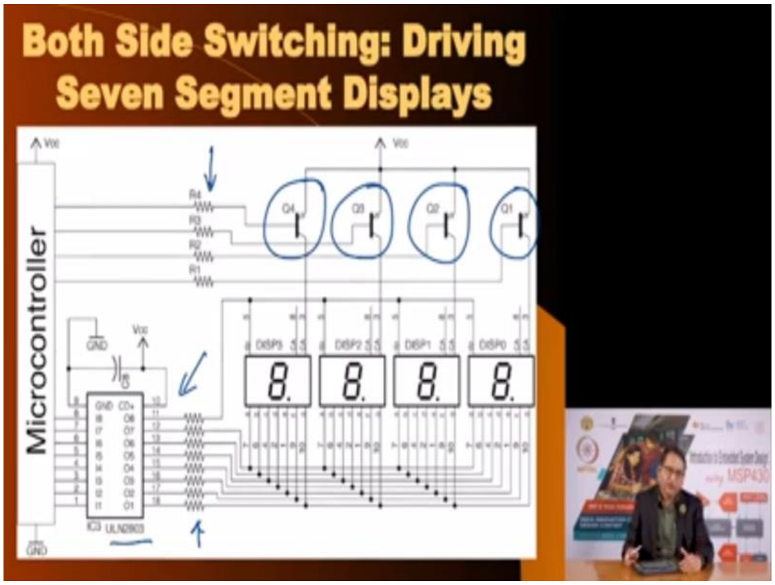

Both Side Switching: Driving Seven Segment Displays

In this in this circuit. I have actually used individual PNP transistors and on this side, I have used a ULN2803. In the next lecture, I will go through how this circuit operates, what are the limitations, how to calculate the values of these current limiting resistors, how to calculate the values of these base resistors for the PNP transistors and since we are using an integrated circuit for the low sides, which we do not really need to register to control these switches. They can be directly driven from the logic output of a microcontroller. We will consider all these questions in our next lecture. Thank you very much. I will see you soon.