Introduction to Embedded System Design
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Lecture 20
Physical Interfacing 6

Hello and welcome back to a new session. In the last session, we were talking about exercising control over a DC motor with the idea of controlling the speed and the direction.

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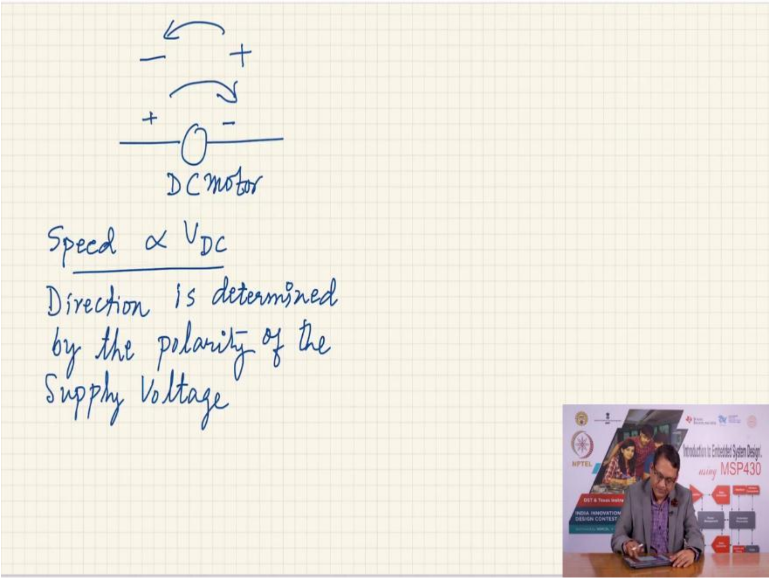

Now, as I mentioned the speed of a DC motor is proportional to the voltage that you apply across the terminals of a DC motor, and the direction is determined by the polarity. Now, how am I able to change the DC voltage across a motor, where my control is in the hand of a microcontroller which is a primarily logic circuit? And so, one concept that we use here is the use of Pulse Width Modulation.

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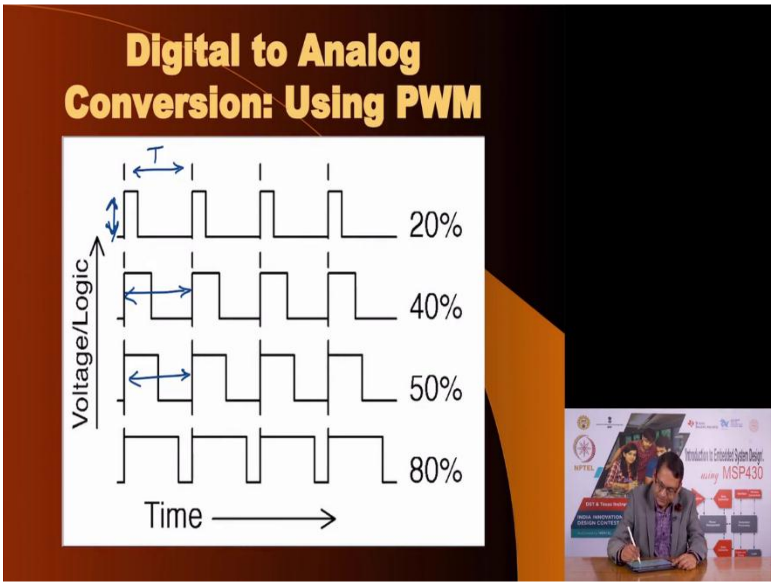

Here is the representation. A pulse width modulation is a rectangular voltage waveform, where the time period of the waveform as we see here is constant, here we see, the time period is constant whether, whether it is for this waveform or for this or for this, but what varies is the duty cycle. This amplitude of the rectangular waveform is also constant. So, we have two constants in this generation of waveform, the time period and the peak amplitude. And what is variable is a duty cycle. Now, let us see how we are able to change the DC voltage in such a situation.

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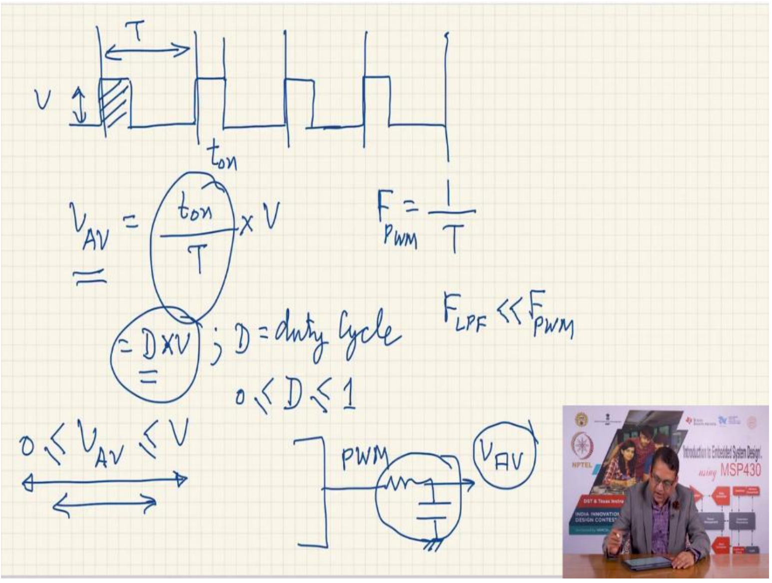

Now, if the time period is constant, if the, that is the frequency of the waveform is constant then if I draw some reference grid here, and if my amplitude of the waveform is this much then I try to generate a similar, here and here. Now, this voltage is let us say, V and this is the area under the curve, this is the time period. The on time is constant in these four waveforms, let us say, this on time is t on and the total time period is T, the average, V average, the average voltage of such a waveform is equal to t on divided by the total time period which is T into the peak voltage which is V.

Now this ratio, we call as the duty cycle, D into V, where D is equal to duty cycle. And what is the range of the, this value? D will always be greater than equal to 0, because when t on is equal to T, you get a value of 1. When t on is 0, 0 by T is 0, so the value of duty cycle is less than, greater than 0, greater than equal to 0 and less than equal to 1. And so, by changing the duty cycle to any arbitrary number between 0 and 1, I can have average voltage, which can be varied from, so, V average can, in this case can vary from 0 to V.

It all depends on my ability to generate this pulse width modulation wave. This waveform is called pulse width modulation, the ability to generate this pulse width modulation waveform, where the duty cycle of that pulse width modulation waveform is in my control, will give me an opportunity, will give me a mechanism to modify the output voltage, the average voltage which can lie in any arbitrary which can be any arbitrary value between 0 and V volts.

Now, the question is, if I am generating a rectangular waveform, how do I get a DC voltage out of this? Well, if you want to measure such a DC voltage using a multimeter, what do you can do is, if any device is capable of generating PWM signal, we know the frequency of this PWM signal is F is equal to 1 by T. The frequency is not changing, we can pass it through a low pass filter such as R and C and this voltage will be equal to VDC, V average.

This will be exactly this provided the cut-off frequency of this low pass filter is much, much lower. So, F low pass filter should have, should be much, much lower than F. So, if this is FPWM, just so that we are able to, if we can ensure this relationship then you will get DC voltage which is determined by this equation to lie in this range. And in fact, in one of the exercises that we are going to have, we will actually show the setup.

Now, I could also utilize such a waveform to drive a DC, DC motor. So, the DC motor behaviour is like a low pass filter. So, as long as I can have the frequency of the pulse width modulated signal to be much higher than the bandwidth of the DC motor then I do not need to put this external filter at all and I can simply apply such a waveform to the to the DC motor which will allow me to change the speed of the DC motor, but I still need to change the.

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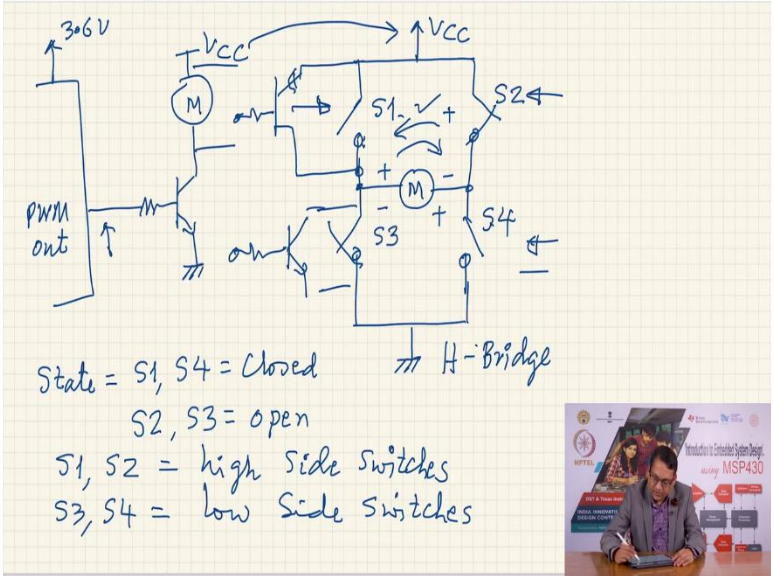

So which means if I were to extend this and I, if I, if my requirement is just to change the speed and not the direction, then I can do very much like this, here is my microcontroller which is a powered at 3.6 volts. I need a mechanism to generate a PWM signal, so I will say PWM out, and we will see how PWM signal can be generated out of MSP430. I will take NPN transistor in the similar way that we used earlier. And I will put a DC motor here and this is VCC which can be any value, 3 6, 3.6 volts or even higher.

And I, this is my motor, and by changing the PWM duty cycle here, I can change the average voltage that appears across this motor and it can change the speed. Now, my question is I have to be able to change the direction also at will. Now what do I do? I have an interesting topology, and we will see what is the name of this topology. Imagine that I have 4 switches. Right now, I am showing these switches to be mechanical in nature.

And now, here is my supply voltage VCC. This is the same as this. And I apply my motor in the centre here. Now, so, let me name this, this is S1, S2, S3 and S4. Now, let us look at the condition state of S1 and S4 is equal to closed that is the switch I had turned on and S2 and S3 is equal to open. So, if I close this and I close this, this applies plus voltage here and this becomes grounded. It perhaps moves in this direction. Right?

Now, I open this switch S1, and instead I close this and this, it applies a voltage here in this polarity. So, the polarity of the voltage has been changed to the opposite of the earlier one and because of this, this motor is going to go in this direction. So, by using 4 switches and closing 2 of them at any given time, yes, you have to ensure that S1 and S3 are never turned on at the, are never closed at the same time. Similarly, S2 and S4 should never be engaged together, if that happens, basically, you are going to short the supply voltage.

So, as long as you can ensure that by engaging S1 and S4 or S2 and S3, I am able to change the polarity of the voltage applied across the motor and therefore I can change the direction of rotation. Now, how do I control the speed? Now, do you recognize, do you recognize that this switch S1 and S2, if these were implemented using electronic components such as BJTs and MOSFETs, then S1 and S2 become high side switches. Why? Because they are connected to the high side of the circuit, high side switches.

And S3 and S4, S3 and S4 are connected towards the ground side. So, these are low side switches. And we have already seen that when you need a high side switch, what do you use? You use a PNP transistor. When you need a low side switch, what do you use? You use a NPN transistor. And this configuration of using 4 switches implemented through electronic components such as BJTs or MOSFETs for that matter has a name and this is called H-Bridge.

And you do not have to build such a H-Bridge using discrete transistors, H-Bridge integrated circuits are available where the high side and low side switches are implemented in a common package and you get 4 controls, a control, so S3 will be implemented, this part will be collector, this part will be the emitter and you will get a base. Similarly, for S1 and S2, you will get a PNP transistor, where this side will be the emitter, this side will be the collector and you will get a base control.

So, you get base controls for the switches and internally the emitters and collectors are appropriately connected, so that all you do is apply, control waveforms. Now, what would be the control waveform? Instead of not keeping the switch on or off, if I apply a PWM signal appropriately, so if I apply, if I want to have the motor move in the direction of this one where it had to have a plus here and minus here, I will keep S1 and S4 open and maybe keep S2 closed, but I will apply a PWM signal on S3, it will give a proportional voltage across the motor equal to the supply voltage into the duty cycle of the waveform applied to S3 and it will allow me a speed control.

By varying the duty cycle I can increase or decrease the speed of the DC motor. If I want to reverse the direction, I am going to open S, S2 and S3, close S1 and apply a PWM signal on

S4. This will reverse the direction and the speed will be determined by the duty cycle of the PWM waveform connected to S4. And so, such packages are called H-Bridge driver ICS.

And they come in different ratings that is the amount of current that they can handle, the 4 switches can handle and the maximum voltage that they can handle and using such a driver IC, you can easily control a device like a DC motor. While we are on the topic of controlling such external loads with microcontrollers, it is impertinent to note here that suppose you wanted to control relay, a relay is a electromechanical device.

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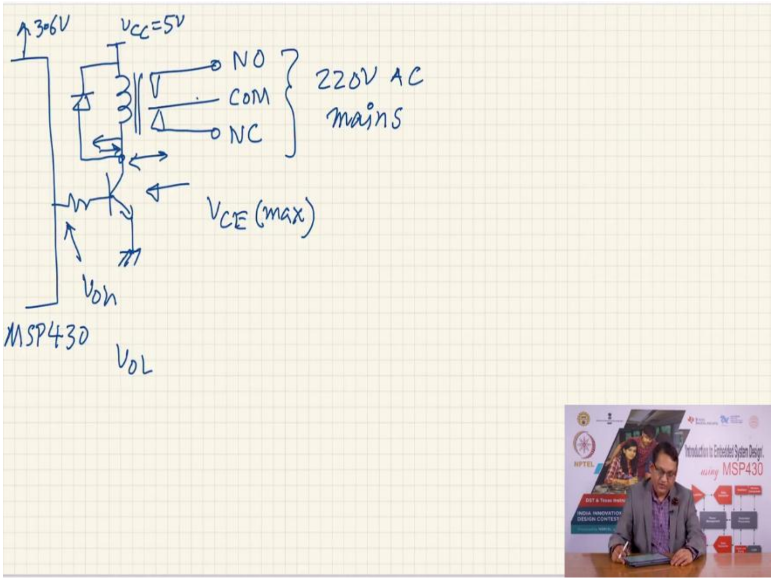

Let me draw the symbol of a relay, a relay has a coil and it is electromagnetically controlling 3 contacts and they have, this is called normally open, this is common and another contact which is called normally closed, which means this contact normally closed is normally connected to the common pin when the coil is not energized. When it is energized, the common, the normally closed pin gets disconnected from the common pin and the common pin goes and connects itself to the normally open pin.

And with you, since this is electrically isolated from the coil, you can use a higher voltage or AC voltage, you can use this with 220 volts means 220 volts AC means to control external load, such as what we discussed if you remember, in the very first lecture of controlling air conditioners and motors for washing machine or a bulb, you could connect on this side. And on this side, you can exercise the, you can control this relay with the help of our low voltage DC, which can be controlled by a microcontroller.

So, imagine that we want to control a 220 volts load, say a bulb or a higher power device. And we want our microcontroller to do it. So, I am going to take a microcontroller. This is my MSP430. These relays come in various ratings, the primary coil ratings, say 5 volts or 9 volts or 12 volts and obviously since my microcontroller cannot drive 5 volt supply voltage load, I am going to connect my VCC, say, VCC equal to 5 volt, and I will have to use a NPN transistor as an external switch, using the same calculations that we saw earlier.

The only problem here is now because this is a coil, when the coil is energized there is no problem, when the, when this, when the input here, the output of the microcontroller is VOH, it will saturate the transistor which will bring the voltage to the collector to VCE sat which will apply almost all the supply voltage of 5 volts across the coil, the coil will, the relay will energize and will connect the common pin to normally open pin.

When you make the microcontroller output equal to VOL, it will cut off this transistor and the relay will de-energize and the common pin will come back to the normally closed position. However, when that happens this terminal, the collector terminal of the relay of the coil since you want to suddenly stop current flowing through that coil, it reacts in a very violent way and it produces a very high voltage here, and this high voltage is capable of killing this transistor. Why?

Because that voltage will often exceed the VCE max that we saw earlier easily, and so this transistor will be destroyed the first time you turn this relay off, and therefore, there are there is a good method that you apply a diode like this. So, this diode is called freewheeling diode that is when this voltage, collector voltage tries to exceed the supply voltage of 5 volts, this diode is turned on and it recirculates the energy through that coil and it protects the transistor.

So, one must take care of using such diodes, so that the transit, the driver circuits are not destroyed. So, this is one way of controlling external loads such as a relay. We have already seen that instead of relay if you want to control LEDs, we have seen that configuration. If you want to exercise a high side control, this is the low side control over the relay. If you want to exercise the high side control over the, this relay for some reason, then you know what topology to use.

If the supply voltage is more than the supply voltage of the microcontroller, you will have to use 2 transistors, so as to isolate the higher supply voltage of the load from the low supply voltage of the microcontroller. So, with this we have seen how you can control external loads, which may require higher current and higher voltage to be handled and controlled through a microcontroller. We have seen various topologies. One point we were at last time was when we were looking at various methods of controlling large number of LEDs through a microcontroller.

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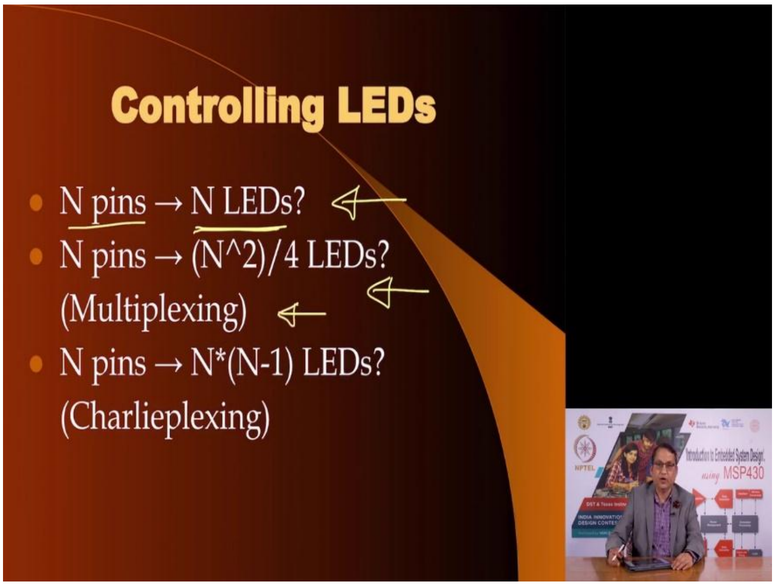

And we have seen that there are, these are the options we have that we could have, if we want to control n LEDs, we could dedicate n pins. If you do not have n pins, then you go to a Charlie technique called multiplexing.

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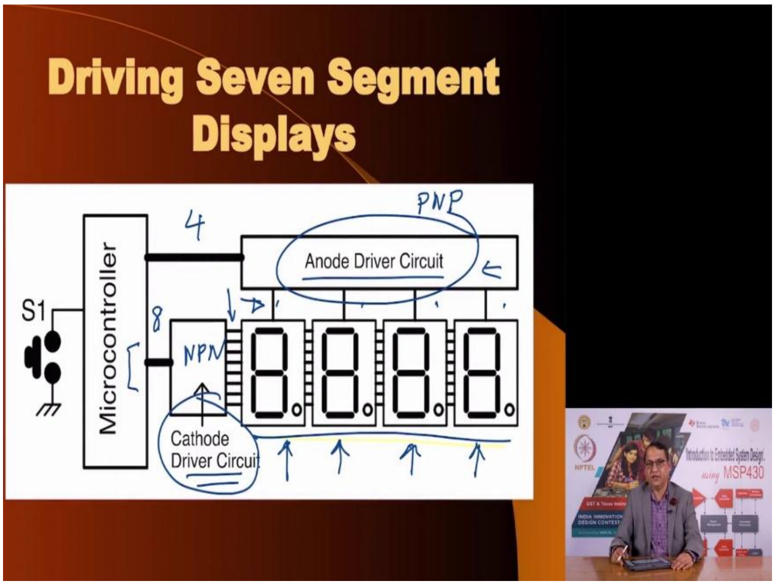

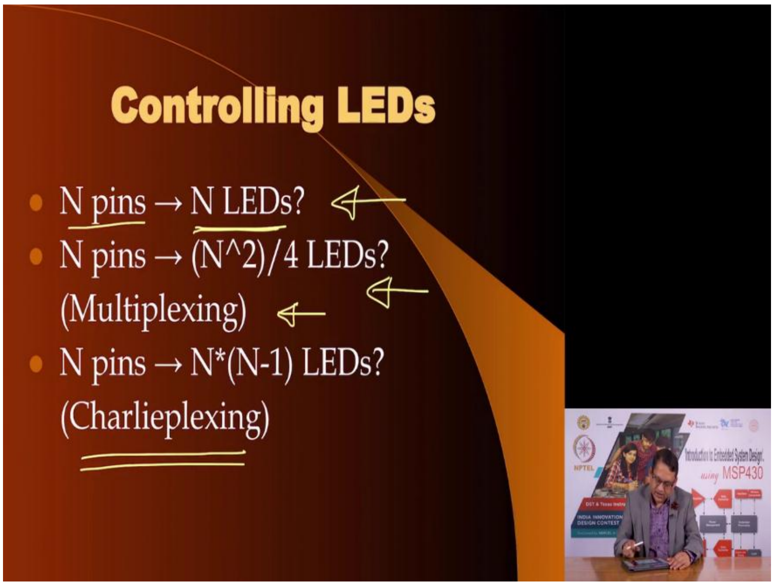

And this was in fact a normal multiplexing technique. There is an interesting extension of that technique. And it has a interesting name it is called Charlieplexing. And I would like to illustrate the concept of Charlieplexing to you through this lecture. And here is a topology of a Charlieplexed LED display.

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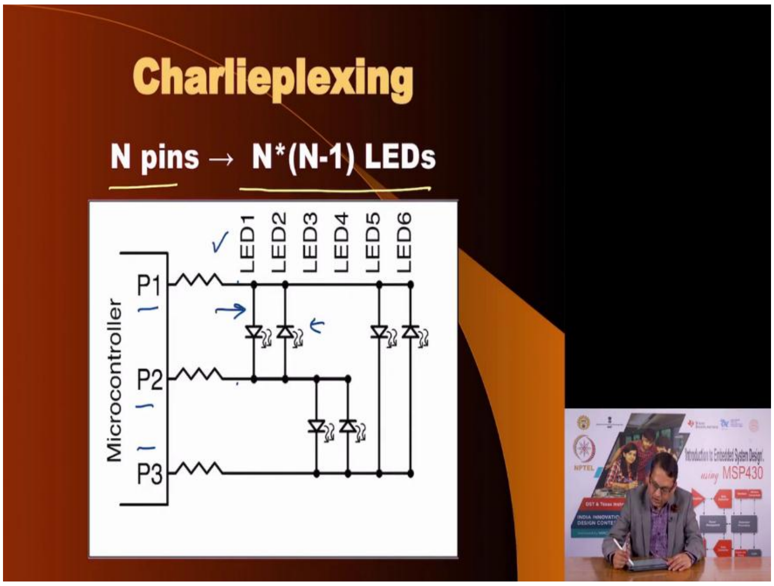

Now, you see here is a microcontroller, it could be MSP430. In fact, we will rig up an experiment to show you how you can have Charlieplexed LED displays. Here, we have only three pins as you see here P1, P2 and P3. In the normal configuration, you would, you could have only connected 3 LEDs to the 3 pins, but now with this configuration, we are able to control 6 LEDs. And the normal rule of thumb is that for n pins, you can control n into n minus one LEDS.

However, this formula should not tempt you into believing that, let us say I can have n equal to 10. It is easy, easily possible to have 10 control pins on a microcontroller, 10 output pins on the microcontroller. And using this technique, you can control 90 LCDs. Well, in principle you can, but those 90 LEDs will not grow, glow as brightly as you would like them to grow, glow for the reasons that I am going to explain. But first, let us see how these LEDs are going to work, how you are able to turn them on and off using this technique.

And so, if you notice I have 6 LEDs and between any 2 pins, I have 2 LEDs in reverse direction. LED 1, if you see is connected with anode on the P1 and cathode on P2 and LED 2 is reversed. So, we have two LEDs between any 2 pins and therefore because there are 3 pins, the total number of combination is 6, we have total number of 6 LEDs. Now when you want to turn LED 1 on, what should be the, what should be the, the state of the 3 pins. I am going to redraw it and show, show, discuss it here.

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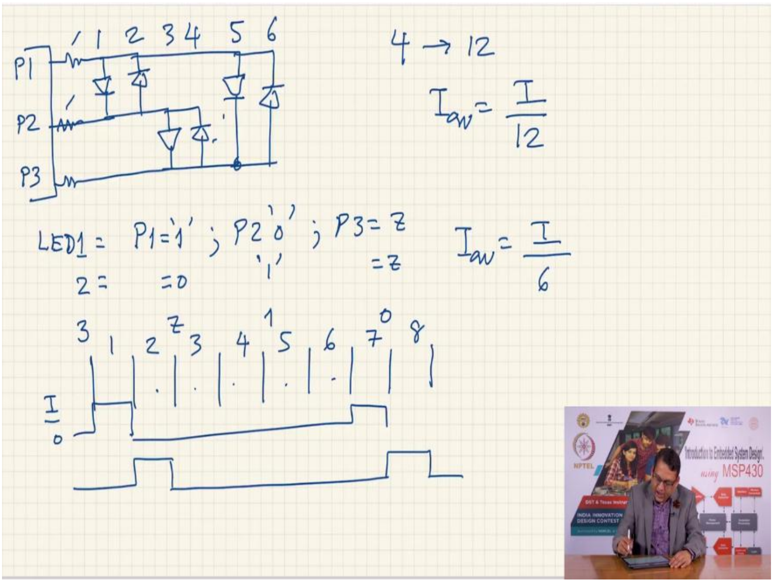

So, we have my microcontroller. Here is my resistor. So, this is all these 6 LEDs. This is LED number 1 2 3 4 5 and 6. This is P1, P2 and P3. When I want to control LED 1 on, LED 1 then P1 should be equal to 1, P2 should be equal to 0, but what about P3? If P3 is 1, it will turn LED number 4 on, which may, we may not want. If we make P3 equal to 0, then it will turn LED 5 on, and so, again this is not what we wanted. And so, this is to bring out the fact that microcontroller pins, modern microcontroller pins can have not just 2 states, it can have 3 states, a 1 or a 0 as well as you can convert the pin into an input pin and it becomes a high, high impedance state

So, the third pin P3, I will program it to be Z. This will ensure that only LED 1 is turned on. When you want to control LED 2, the state of P1 becomes 0, P2 becomes 1 and P3 is still Z. When I want to turn LED 3 on, then P1 becomes Z. P2 becomes 1 and P3 becomes 0, and so on as you can see. Now at any given time, in this configuration, only 1 LED is turned on. And so, if there are 6 LEDs, they are going to start with 1 2 3 4 5 6, back to 1 2 3 4 5 6.

If you want any number of LEDs to be on, the turn on and turn off of these LEDs is done at a much higher rate, higher than the persistence of vision of a human eye, which is roughly 16 hertz. So, if you go much more than that, let us say we turn on and off each LED at 100 hertz and since these are 6 LEDS, if I have a mechanism to turn on and off things from a microcontroller point of view at 600 times a second then each LED can be turned on and off 100 times a second, it will give me a comfortable display.

Now what is happening is at any given time, since only one LED is on therefore, you have 1 2 3 4 5 6. So, this is time slot 1 2 3 4 5 6 and the time slot 7 8 and so on. Now, in time slot 1, I can turn LED 1 on and then it will have to be off for the next 1 2 3 4 5 and it can only be on here. Similarly, LED 2 can be turned on in second time slot and it will have to be off for the next and then it can have an opportunity to be turned on here and so on.

Each of the LEDs has 1 slot out of 6 slots. Now, if this waveform represents the current through that LED that means this is 0 current, this is some current I, which will be determined by both these resistor at any given time, 2 resistors come in the path of the LED. Therefore, the current will be determined by some of these two resistors in series with the LED. Let us say that current is I, so you have either a current I flowing for 1 time minute and for 5 time minutes no current is flowing. Therefore, the average current, if this I, the I average through the LED becomes I by 6.

Now, if the current becomes one sixth, the intensity of the LED in the Charlieplex configuration in this case become one sixth. And there is not much you can do by trying to increase the current through the LED is because the microcontroller pins are limited in the maximum current they can allow. MSP430, as we saw is the limited to 6 milliamperes, other microcontrollers can go up to 30 40 milliamperes and yet the average current will start falling rapidly, if I, instead of 3 if I go to 4 pins, I will be able to control 12 LEDs.

So, my I average current will become I by 12. So, it becomes, quickly, it starts reducing, and therefore, using a Charlieplexing technique, this is what I meant that this is not a very scalable opportunity, this is not a very scalable technique, that if you try to increase the number of LEDs by using slightly more number of pins, it does not work very well because the intensity of the LEDs goes by this.

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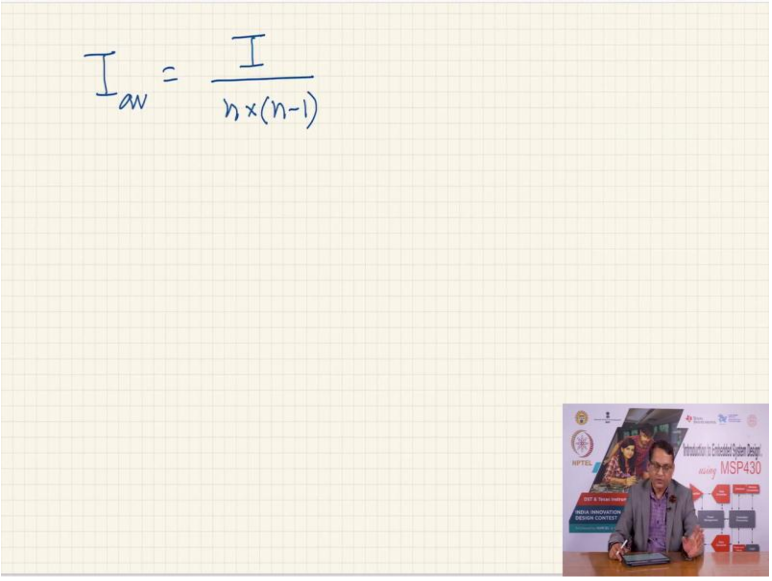

So, I, the average current through the LED in a Charlieplexed fashion I average is become, will be equal to the maximum current that you can allow divided by n into n minus 1 that is the for n pins that you have, you can control n into n minus 1 LEDs. You see, this factor grows up by a factor of a, by square. And so, the average currently is quickly going to drop. And may, we will make this topology quite useless for value of n more than 4 or 5.

But still, it is a very interesting mechanism, it allows you to control relatively large number of LEDs using few pins, if you are stuck in an application where the number of pins is very less, and you want to control a few LEDs, few 4 5, maybe 10. This is a good technique because this allows you to control relatively large number of LEDs for using less number of pins without involving additional hardware expansion technique.

For example, you could use a shift register, you do not have to involve any extra, extra hardware and yet you are able to control these LEDs, so this is very good for such a configuration. And so, in this lecture we have seen how you can control external LEDS in multiplex fashion, using Charlieplex fashion, how you can control large amount of currents through these loads such as the LEDs or the relays using low side switch or a high side switch, how you can also have a combination of high side switching and low side switching using the topology called H- Bridge which is used to control DC motor and such loads.

We complete our discussion here. We still have to talk about creating digital to analogue converters and controlling LCD displays and so on and so forth which we will take up at appropriate opportunity. I thank you for listening to me. I will see you in the next lecture very soon. Bye-bye.