Introduction to Embedded System Design
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Lecture 5
Salient Features of Modern Microcontrollers

Hello, welcome to this new session on introduction to Embedded System Design. In the last sessions, we discussed various metrics for selecting the right microcontroller for our embedded applications. Then we looked at six box models with which to visualize various elements that make up an embedded system application. And then we are now here trying to look at more details by which we select a microcontroller for a given application.

So, let us start at, so I am going to discuss what are the salient features of contemporary microcontrollers. What do we want from them? And based on these needs, how to select an appropriate microcontroller while we may be using Texas Instruments, MSP430 microcontroller for our course. As a professional, 1 uses very different metrics for using a given microcontroller. Yes, awareness of a microcontroller is often a significant factor, but there are other professional and economic factors for selecting the right microcontroller.

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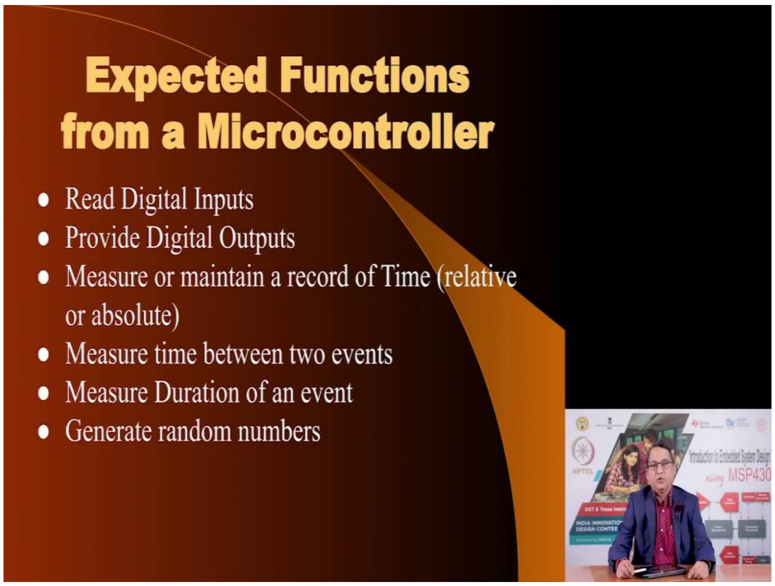

So, in this slide, we are going to look at what are the functions that we as a designer, you as a designer would expect from a microcontroller because the microcontroller is a central piece in this six box model, six block model or six box model it does not mean anything different.

It interacts with the inputs, it interacts with the it provides outputs and so on. So, it has to perform all those functions. So, the first very important function that embedded microcontroller must perform is that it should be able to read digital inputs. The reason is that a microcontroller is a digital integrated circuit. It may also have capabilities of reading analog voltages and so on.

We come to that shortly, but primarily microcontroller is a logic device and therefore it is very natural for a microcontroller to be able to read discrete digital values. These values, even if they are discrete, they must confirm to certain voltage levels. What we call as low voltage and high voltage or oftentimes represented as 0 and 1. So, the microcontroller should be able to read digital inputs.

Then it should be able to once it reads these inputs, it might be processing those inputs and would provide an output. And the natural way for a logic device such as a microcontroller to provide an output would be in a digital form, which means it can produce a logic 1 or a logic 0. Let me show you what are the kind of outputs that may be expected from a microcontroller of the digital input and digital output nature.

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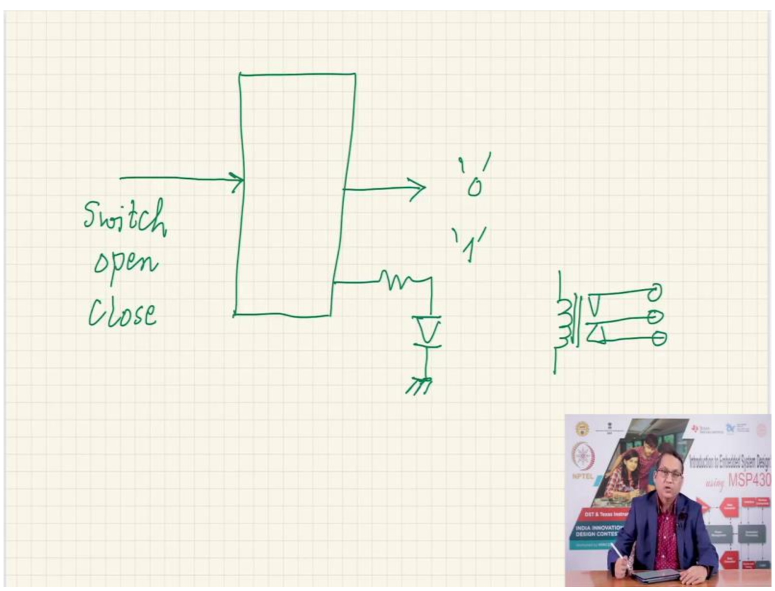

So, if this is my microcontroller, the most common method would be to be able to naturally read inputs which are digital in nature, which are discrete in nature, such as a switch. A switch does not produce a 0 and 1 voltage. Instead, it has two states which we call as open and close, so we will see in the subsequent lecture in a subsequent session how the two states of a switch, open and close, are transformed to 0 and 1.

Similarly. It must produce digital outputs 0 and 1. And the common methods of using these outputs would be to connect to a LED, say in this fashion or to control a relay. Relay has this symbol. And so if it is possible to connect this relay directly to the microcontroller, you would do that. Most often that is not the case. And so some intermediate components, what we have defined as electronic glue would be required to connect such a relay to a microcontroller.

But yes, a relay has discrete states either the relay is on or the relay is off, and therefore it is very natural for device like a microcontroller to control a relay.

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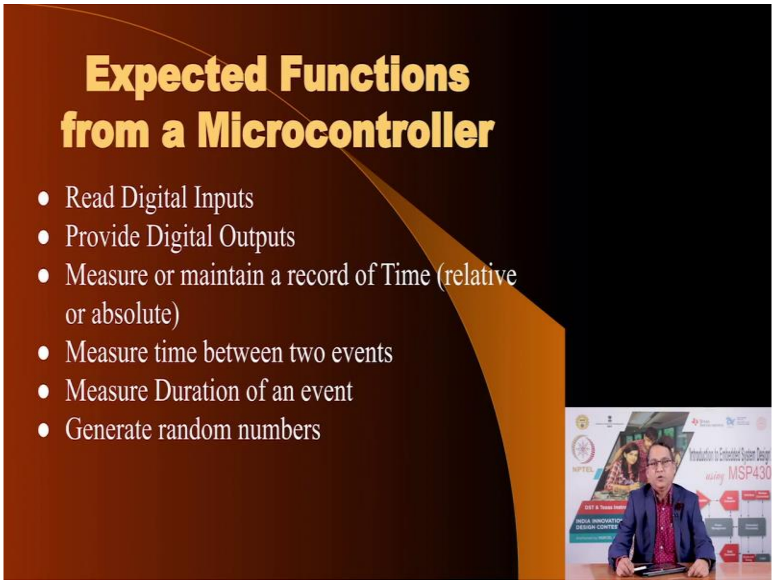

Let us go back to the expected functions out of a microcontroller. Apart from reading digital inputs and outputs, it must be able to measure time or keep a record of time. And why is that? Because the microcontroller part of the embedded system is interacting with the external world. The world is continuously changing, inputs are changing, and therefore the microcontroller must be able to read these inputs, process them in a timely fashion and provide timely outputs, and therefore it must be able to maintain record of time. There are many examples of where this might be used maybe you want to plot the variation of temperature in the room as a function of time. Therefore, you may very well require to measure time.

We will see more examples. It may also be expected to measure time between two events. For example, suppose I am in this room such as this and I open the door and I want to know what is the time between arrivals of two people that would be classified as time between two events, arrival of a person could be classified as an event. I can put a sensor on the gate of this door which provides me a pulse, which provides a logic value, which I can read from the digital inputs.

And after the detection of that signal that a person has entered, I could start counting time till such time that another person enters. So, I would be able to measure time between these two events, events relating to entry of two people in this room. It may also be required to measure duration of a complete event, not just duration between two events, but duration of an entire event.

And again, we can define what we mean by an event, whether the act of a individual passing through the gate is an event or I am holding a program here and the event would be defined as the time and the first person enters the room till the last person exits the room maybe I can define that as a event, what the definition I want to have depends on the application what do you want to define an event and here also you may be able to maybe required to measure the time between events or duration of an event.

I already discussed time between two events. Then a microcontroller would be expected to generate random numbers. We would see applications in subsequent lectures that where do we need random numbers? What are the various methods of generating random numbers?

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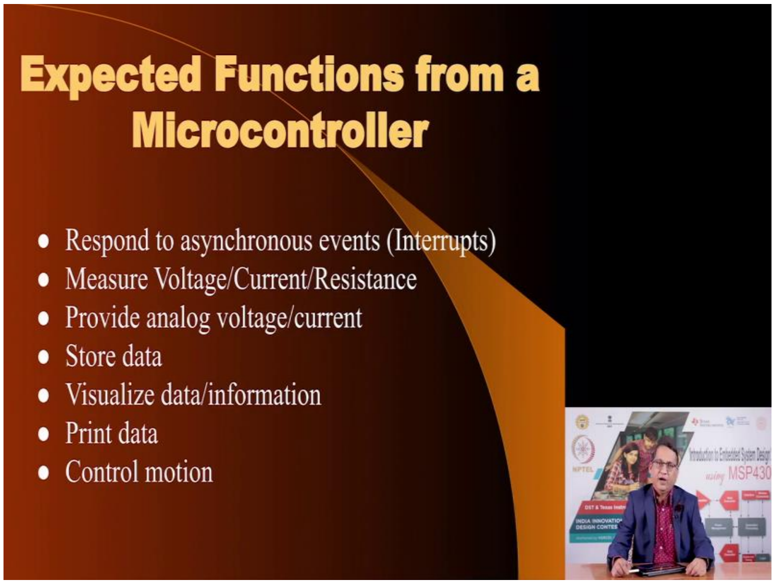

The next function that I may I would expect out of a microcontroller is to respond to what I call as asynchronous events, meaning events that happen without telling, without being synchronized with the clock of the microcontroller. So, all human inputs or all environmental inputs in a way are asynchronous events. And a microcontroller is expected to take cognizance of these events and respond appropriately. And for that, it uses a concept called interrupts. We will see how microcontrollers are able to process such events through the concept of interrupts. Then a microcontroller would be expected to measure voltage or current or resistance.

If it is able to measure voltage by itself and if not, we must add some feature by which we can measure voltage. Then we can easily be able to measure current or resistance and for that matter any other parameter. Let me explain how.

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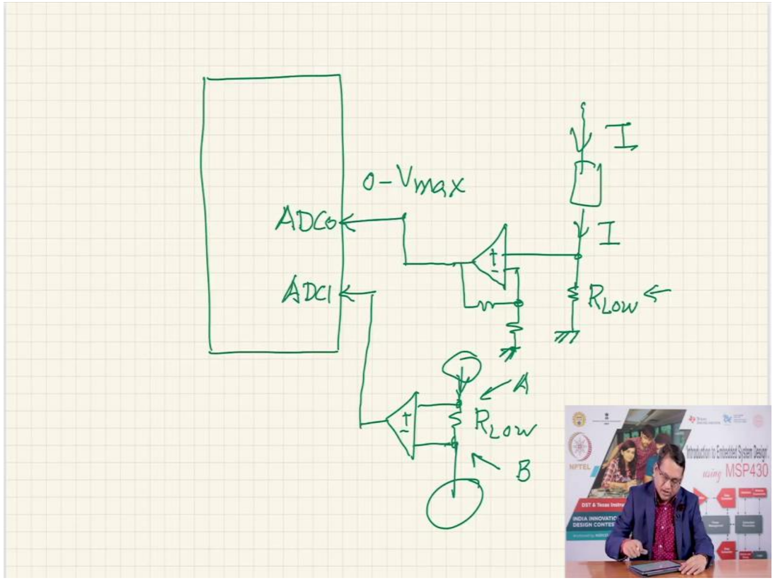

So, let us say that I want I have a microcontroller which is able to read voltage and so that will be called an ADC input where it has a range of say, 0 to Vmax, that is any voltage, any voltage between 0 volts and Vmax volts can be applied to this pin. And now instead of measuring voltage, I want to measure current. Now, current obviously would be passing through some circuit maybe I want to measure this current and I would use the same mechanism that a multimeter and ammeter for example uses to measure current and what I would do is I will introduce a very, very small resistance R very small, so I designate it as R low and I would connect maybe I would need this voltage that is generated is so small that I do not get enough resolution for my ADC.

So, I put it through an amplifier. And say this resistance is grounded and so the current that is passing is also passing through this and then using some gain I can connect it to the ADC input. Now, since I know the value of this low value resistance. Then if I know the voltage, I am able to measure the voltage, if I can divide, if I if my microcontroller can divide that measured voltage by the value of the resistance, my system would be able to measure current.

In case the resistance is not grounded as I am, I have shown, because measuring the current in which it is going into the ground at the point where it just entered the ground is very easy to use. But what if my I want to measure current, which is floating, meaning I have I put a resistance, but n1 of the ends of these resistors, a resistor is grounded, which means I would need to connect. It still has to be a very low value R low.

But now instead of a non-inverting amplifier, as I have shown in this case, I would need to use a differential amplifier, which takes the difference between the two terminals here. And then produces a voltage, so I will connect it to another channel. And so whatever current is going through this, this node need not be grounded but the current flowing through this low resistance value can be converted through a differential amplifier.

This is not the correct circuit for a differential amplifier will come to that. But here I am showing that we will be using a differential amplifier, which takes the difference of the voltage at this point and at this point A B it takes the voltage difference of Va minus Vb that is voltage across R low and then it converts it into a voltage and the DC can read it. And then when we divide that voltage by the value of this resistance, I get the amount of current that is flowing through this resistor. The third expectation would might be to be able to read resistance. Now, there are, again, many methods of measuring the resistance. One is I can create a potential divider.

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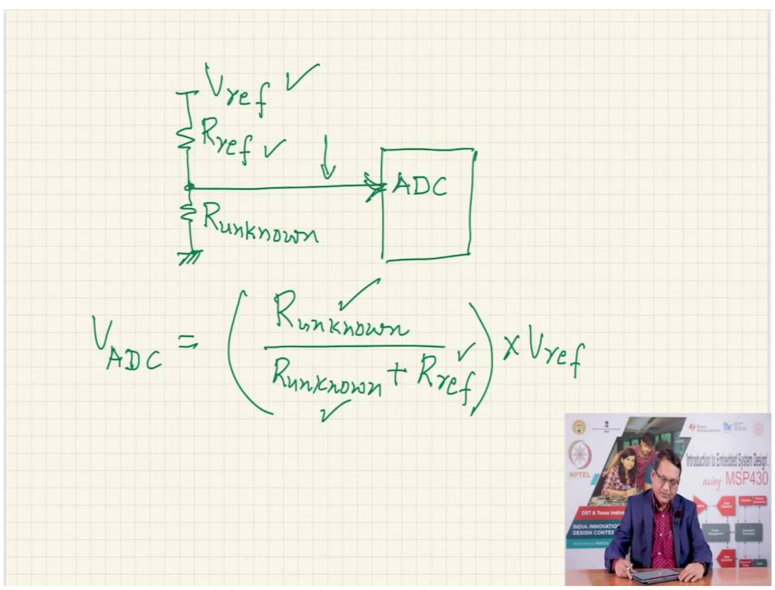

So, say this is R reference, I know the value I connected to a reference voltage Vref. And then I connect an unknown resistance and I ground it so this is R unknown. And then I connect it to my microcontroller the same ADC input. Now, since the system knows the value of Vref, the system knows the value of reference, therefore the voltage that is produced at this point is equal to R unknown divided by R unknown plus Rref into Eref. This is the VADC the voltage at the ADC input is this volt. Here I know the value of this. I do not know these values. And from this equation, I can calculate the value of the unknown resistance.

So, I once I have the ability to measure DC voltage then I can be I can measure any other parameters such as current or resistance and for that matter any other physical parameter also, as long as I have a appropriate mechanism to convert that parameter into voltage.

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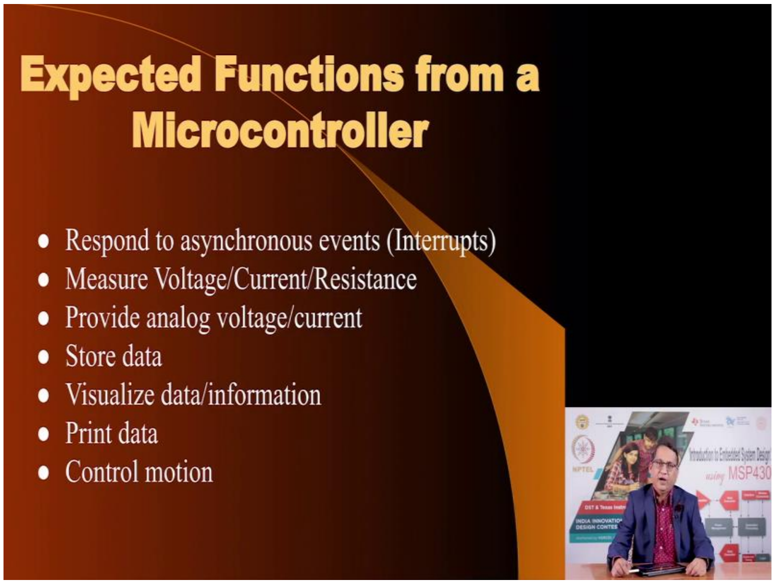

Similarly, beyond being able to measure voltage, current and resistance, a microcontroller would be expected to create or generate varying voltages, not just discrete voltages that discrete voltage is also varying voltages or digital output is a varying voltage 0 and 1 is varying. But it is not continuously varying. I may want to create voltage which is continuously varying and a microcontroller can do that in two ways. One, it could have a device such as an ADC for reading analog voltage. It can have a device called a DAC, a digital to analog converter in most cases, in many cases, in lot of cases microcontroller does not have an explicit digital to analog converter.

But there are other methods of converting digital voltages or digital numbers into analog voltages or current and then so on, using a method called pulse rate modulation. And why would I need to do that? Let me take an example that we considered in a previous lecture that is the speed of a DC motor in the Gillette razor that we considered. The speed of a DC motor depends on the applied voltage.

The voltage that is applied to the terminals of a DC motor determines the speed. If I want to increase the speed of the DC motor, I would increase the voltage. If I want to reduce it, I will have to reduce the voltage and therefore in such application I may require to be able to produce analog voltages and therefore a microcontroller must be able to do that. Later in this lecture, we will see how a microcontroller is able to achieve that requirement.

Then another application that another function that a microcontroller would be expected to perform is to be able to store data. Now, while the program executes a microcontroller, uses RAM, or it uses the internal registers to store data temporarily. But sometimes you may want to store data in a more permanent medium so that you can inspect it later. You can transport it when you do not have the mechanism or a communication channel to transport it right away. So, you store it.

And so you may require large amounts of capacity to store that data more than the internal registers, more than the RAM that your system may have. And so this function will be performed by connecting to external devices which have larger, higher storage, such as a hard disk drive or serial E square PROM devices or serial flash memories. Another function that is expected out of a microcontroller is to be able to visualize data.

Imagine that you want to plot how the temperature in this room is varying as a function of time over 24 hours or continuously. What would you want to do? You would want to have a display which can create a graph and then fulfill this requirement. Another function that is expected is to be able to print data, print data in a portable fashion or print data whenever you want it.

An example is these days in India, there are a lot of these parking lots and the parking lot attendant is carrying a portable device. As you enter the parking lot, they will enter the car registration number and quickly punch a button and a printout is produced. So, you may want your device to be able to print information. And last but not the least, an embedded microcontroller would be expected to control motion.

As we saw, whether it is the speed of a DC motor or the position of a certain device, maybe you are designing a printer then the print head needs to be located appropriately. And so we are talking of being able to control motion. So, these are all the common functions that 1 expects that microcontroller should be able to perform. Now, let us see how it does that or what all features are available on microcontrollers to be able to satisfy these requirements.

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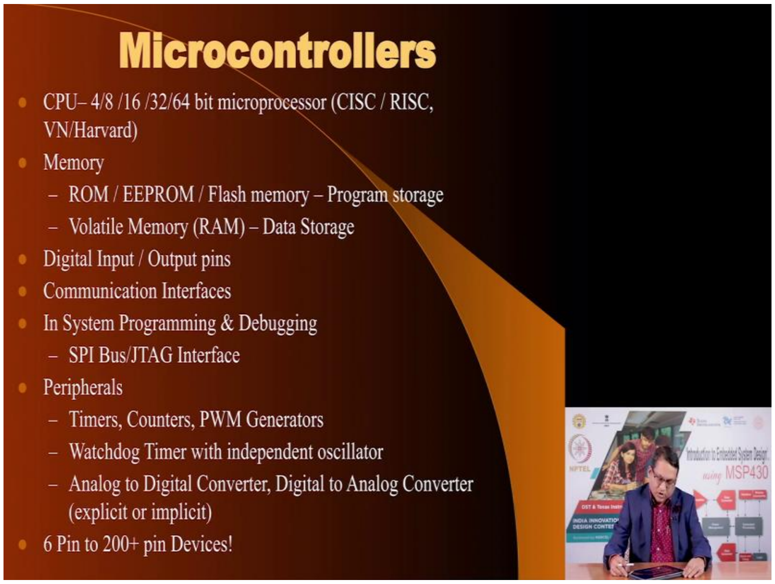

Now, before that, let us see what does our contemporary microcontrollers have to offer. This is not related to a single microcontroller, but in general, a survey of the features that modern contemporary microcontrollers offer. So, all microcontrollers are as we have seen nothing but a complete computer on a single chip and therefore the CPU part of the microcontroller would be able to handle certain amount of data bits at a time and that is the bit handling capacity of that device and it can range from 4 bits or 8 bits or 16 up to 64 maybe even more.

The instruction set architecture of such microcontrollers could be of RISC or could be of CISC types. Now, we have observed over time that there are no very strict boundaries between RISC and CISC. Good ideas from one architecture are often borrowed and implemented in another architecture. We see traditional RISC or manufacturer defined architecture if the manufacturer says there is a RISC architecture you might find certain features which actually belong to the CISC category and vice versa.

But yes, these are two dominant architecture that are available and then from a memory access point of view, we have two architecture that are available von Newman or Harvard. And therefore, when you look at the microcontroller, essentially it would it could be that it is a 16 bit microcontroller, which is of a RISC nature and it has a von Neumann or it has a Harvard method of connecting to the memory that would be the complete description of the microcontroller in those aspects.

Apart from that, it may be able to it is able to connect. It has on chip memory. The question is how many types of memory it has usually it would require two types of memories. One is permanent to store the program and the other being volatile to store data or to store pass parameters to a subroutine or to store the return address when you are calling a subroutine.

We will go get into the details of all these things that I am mentioning here once we start talking about the actual microcontroller. But these are the requirements that these memory devices have to perform and therefore you would require a permanent memory for the E square PROM or it is more common these days to find such permanent memory of the type of flash and for volatile memory, it is usually SRAM for the data storage.

Microcontrollers offer pins, general purpose pins, which can be programmed to behave as a digital inputs or as digital outputs, they often have several communication interfaces what we menti1d intra devices or inter device. It may have (())(22:55) it may have LIN it may have CAN, it may even have USB and we will see our microcontroller that we are going to use. What all does it have.

To be able to program download the program from your development platform into the memory there would be pins, which support these days what is called as In system programming and through some pins you may also be able to debug the program after you have downloaded it into the memory of the microcontroller in case your application is not working in the way that you expect it to.

And for that it uses a SPI bus as well as another interface specialized for debugging called JTAG. Our MSP430 microcontroller has another format called SWD which is Serial Wire Debug. And so these are all the programming and debugging options that you would find on these microcontrollers. Then it would have peripherals, peripherals with which you can measure time, you can count events, you can generate pulse width modulation signals.

And I want to add here that pulse width modulation signals are primarily used by microcontrollers to convert digital numbers into analog voltages and we will see how then it most modern microcontroller often have a specialized timer. It has a dedicated function and it is called a watchdog timer. And just like a watch dog at home, when there is a burglary or when there is an unusual event happening at home, the dog is expected to bark and alert the owner, the residence of the house.

In a similar fashion the watch dog timer, if it appears to the watchdog timer that things are not going well, things are not in the way not going in the way they are expected to on the embedded system. It will do something to alert the system. And usually it is in the form of resetting the microcontroller. To do that, it has an independent oscillator so that one if one enters a low power mode and in low power mode usually you fiddle with the value of this clock signal.

You do not want to affect the operation of the or the function of the watchdog timer. So, usually these watchdog timers are equipped with independent oscillators. They also have analog to digital converters and in some cases, they may also have digital to analog converters and all these functions, all these functions that we have listed here are available in packages which vary between 6 pins to 200 pins.

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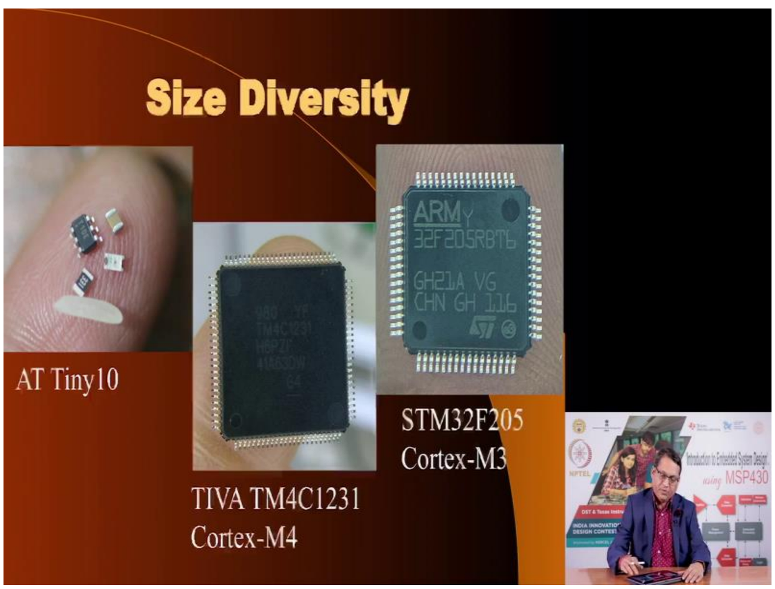

Here again, I am repeating the same picture I showed in the earlier lecture that we have a great diversity of size, a microcontroller which is smaller than a grain of rice in fact it is comparable to the rest of the components that you can see on my thumb and in the middle we have one of the larger microcontrollers. This is a cortex M4 from Texas Instruments. And on the extreme right is another arm cortex M3 microcontroller from ST microelectronics.

These are the kind of varieties that are available. Obviously, the one with bigger package would be more expensive, would have more features and would be used in such applications that have higher demands. Then, for example, the one on the left, which is a 6 pin microcontroller. Okay, now we are here looking at what are the features of modern microcontrollers.

Previously we have just we have listed what we expect these microcontrollers, what functions we expect these microcontrollers to perform to be able to perform those functions, what features it has. I have called out information from contemporary microcontrollers and sort of made a list of good features, desirable features of all these microcontrollers put together.

Obviously, when you are going to consider a particular microcontroller for your application, you have to check the datasheet whether the features that you are looking for are available in those microcontrollers or not. But this is the current state of the art. And we as a designer, we as practitioners of this engineering realm should be aware of the possibilities.

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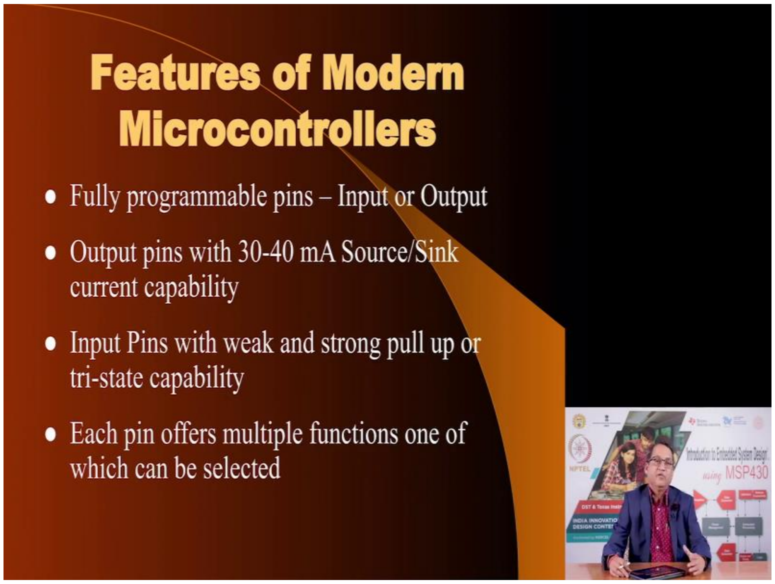

The first important feature that modern microcontrollers offer are programmable pins. These pins can be programmed to either behave as input or output. Now, why is it important? Is that when we are talking of a microcontroller, we are talking of a single integrated circuit and a single integrated circuit, whether it is small or big, would have a limited number of fixed number of pins. Let us say we have a 20 pin IC.

Now, any 20 minutes or any IC for that matter, electronic circuit would require power supply, pins and so we would have to discount 2 pins for power supply application that would leave us with 18 pins. Now, you could use all this if this 20 pin device that I am talking of here is a microcontroller. You are left with 18 pins and you could decide that, oh let us do a equitable partition. Let us say 9 of the pins are digital inputs and 9 of the pins are digital output.

So obviously, any application which requires less than 9 inputs or less than 9 outputs could possibly utilize this IC. What if I still need total number of input pins and output pins to be 12, but I want 10 input and 2 outputs or 10 outputs and 2 inputs. Now, in principle, these 18 pins or 20 pins IC is quite capable of satisfying the requirement. But if the inputs and outputs are equally partiti1d and fixed, then this specific application where I need 10 input pins and two output pins will not be able to use such a microcontroller.

Thankfully, that is not the case that all the pins, general-purpose pins that are available apart from the specialized function pins such as power supply and there maybe other specialized function pins, rest of the pins are programmable, and by writing an appropriate program, the user can decide which of the pins will function as inputs and which of the pins will function as outputs.

So, we have seen how the pins on the microcontroller are programmable and you can program them to be of input or output types. Now, let us see the next point. And it says that the output pins, if you define a pin to be of output type, then it has the capability to provide about 30 or 40, 30 to 40 million amperes of source or sync current. Now, what is the meaning of source and sync current let us look at a sketch.

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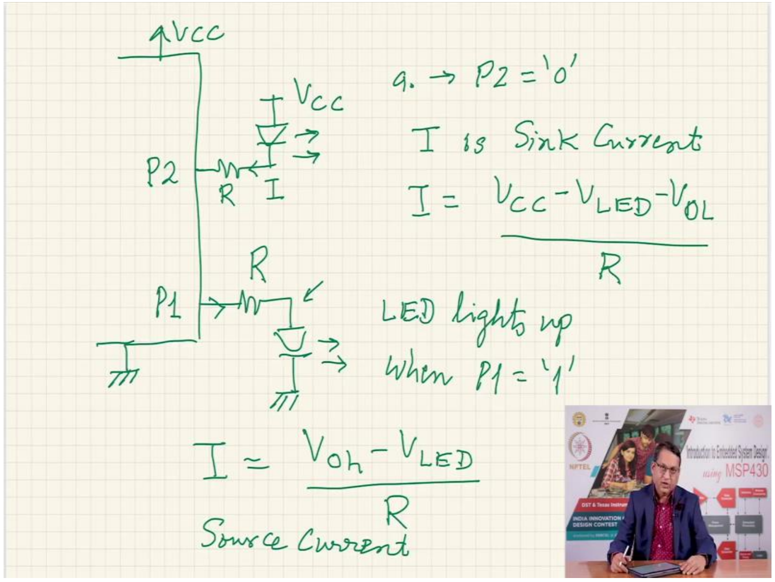

Now, when I have a microcontroller, I can connect LEDs which we saw earlier. I can connect LEDs in two ways I can connect LEDs in this fashion. In this case, the LED this is a pin let us say P1. This LED will light when the P1 voltage, even logic is 1. So, it is going to LED lights up when P1 is equal to logic 1.

When the logic voltage level on P1 is 1, the LED lights up, the question is how much current flows through the LED and it will depend on the resistor R and the nature of this LED. The voltage across the LED depends on the color of the LED and therefore you need to find out from the datasheet what is the voltage drop across that LED.

And you can involve these numbers parameters in an equation and estimate the amount of current and the current will be the voltage output of at P1, which would be called as VOH that is the voltage when the output is high minus the voltage across the LED divided by the resistance R. So, if this current that you want pass through the LED is less than 30 milli ampere that means you can easily connect this resistor and LED combination to the pin without needing any current amplifiers.

What are current amplifiers, if you need more than this current will see subsequently. But right now, suffice it to say that this current which goes through the LED, goes out of the pin is called source current. So, in this case, it is a source current. And modern microcontrollers offer up to 30 or 40 milli amperes of source current. There is another way to connect this LED and this is the method, let us say I have another PIN P2.

I connect the resistor exactly like that, but now reverse the LED instead of the anode of the LED connected to this register here, I connect the cathode. And on the anode side I connect it to VCC which incidentally is also the VCC and there is a ground also of this microcontroller. Now, the first thing is a, that the LED lights up when P2 is equal to 0, this is called active low. In this first case, the LED lights when P1 is high is active high, that is that activity happens when the signal is logic 1 logic high, here it is active low.

The current now is I, is flowing into the pin. I have this resistor the current is flowing into this pin, this current is called sink current because it is sinking into the microcontroller pin and the amount of current is now Vcc minus V LED minus VOL that is the voltage at pin 2 when the logic is 0, when it is low logic, it does not mean 0 volts. It may be some nominal voltage. You have to refer to the datasheet of the microcontroller to know what is the value of VOL.

This is the voltage across the resistor and therefore divided by the value of the resistor would be the current that flows through this LED. The intensity of light that is coming out of the LED is proportional to the current flowing through the LED. And so if the intense if the intensity that you are going to get for this current, which if is less than 30 or 40 milli amperes, you would be able to connect it directly to the microcontroller.

In case you want more intensity, you want higher intensity, and you have to have much more than 40 milli amperes of current. We will have to resort to some other circuit configuration. But 30-40 milli amperes is a significant amount of current with which to control small LEDs. And so they do not need any other driver circuit to handle them. Also, you can probably turn on small relays with this amount of current.

And so having a capability to drive 30-40 milli amperes of source or sink current is a good feature that these modern microcontrollers offer. In case you choose to have these pin, these pins as input pins, then sometimes we need these pins to offer a feature called a pull up resistor. Let me explain.

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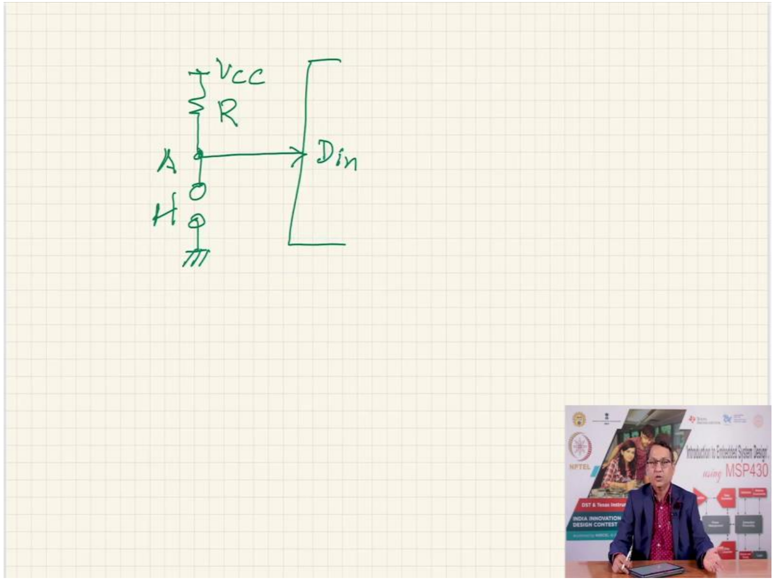

So, if I have a microcontroller and I want to connect a switch, as I mentioned earlier, a switch does not produce any voltage. It has two states and the two states of the switch are open and close. And these two states have to be then translated to logic levels. And 1 way to do that is to connect a resistor. And this point, this junction of the resistor and the switch I can connect it to a Din pin of the microcontroller. Now, when the switch is not pressed because of this resistor R and this resistor is called pull up resistor, it will be able to provide logic 1 to the input pin.

When the switch is pressed, it will ground the, this terminal A and therefore the logic voltage applied to the Din pin will be 0 and so the open and close state of a switch have been converted to logic 1 and logic 0 with the help of this resistor. This is called a pull up resistor. If the value of resistor is small, it is called a strong pull up. If the value of the resistor is large, that is the amount of current going through it is small, it is called a weak pull up.

Modern microcontrollers often times give you options to 1 have a pull up to select the amount of select the nature of the pull up to be either of strong nature or weak nature. And in some cases, if you do not want to have the pull up, it would function with what is called tri state capability. Also, we in the previous slide, we saw that a microcontroller is supposed to measure time, measure analog voltages, maybe even produce analog voltages, it is expected to measure time between events.

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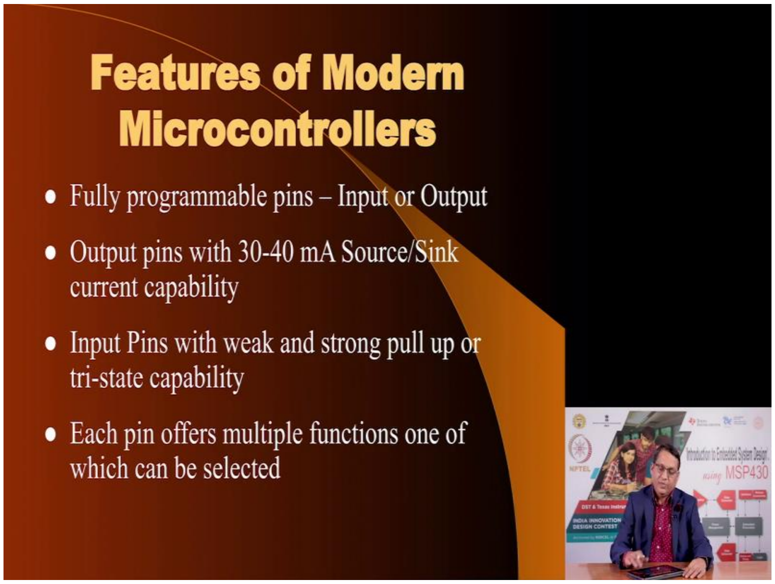

How is it possible to fit all these functions on a limited number of pins of a microcontroller other than to share the functionality of these things, and that is the meaning of fourth point, that each PIN offers multiple functions. One of the important functions is that the PIN is digital input or output fine, but besides that it will also offer additional functionalities and the user must write an appropriate program to select which of these offered functions on a given pin would they like to use in that application.

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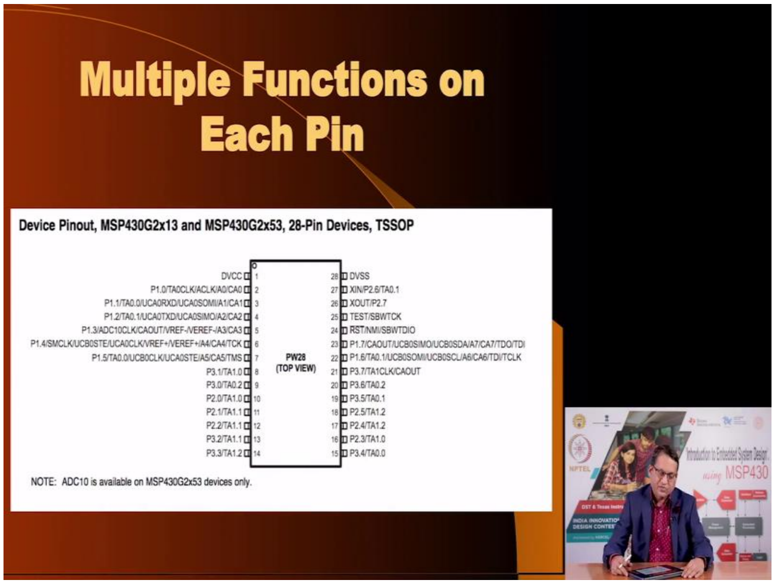

Let us see what is the meaning of this inner pin diagram from 1 of the MSP430 microcontrollers here. As you see, this is a 28 PIN device, pin number 1 and 28 are VCC pins. They do not have any other function and rightly so. They are used to connect power supply voltages to this microcontroller. Other than that, almost every pin, if I look at PIN number 14, it has two functions listed P3.3 slash PA 1.2.

These are two functions let me let us look at another pin, for example this is pin number 26 is X out slash P2.7. Now, in case you want to use PIN 26 for X out, then you will have to forego the other function that is listed there such as which is P2.7 that is port 2 pin number seven. And I 1 hopes that you could use other pins for that function, which P2.7 is was otherwise going to provide you.

Because you want to use pin number 26 for X out functions. This is the way multiple functions can be shared on a small on a chip with limited number of pins, and this is the meaning of each PIN offers multiple functions.

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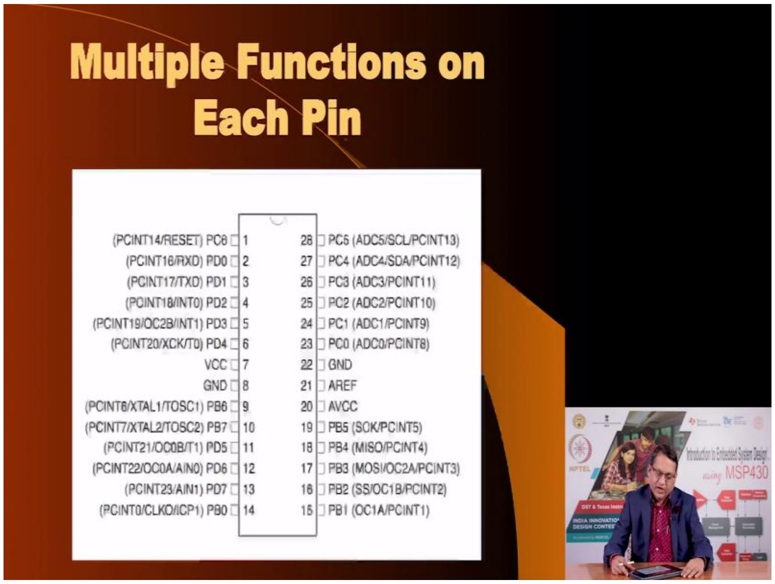

Let us take another example. This is from 1 of the AVR microcontrollers. In fact, this is the microcontroller that is used in Arduino platform. And you see here also in the middle, we have four pins, pin number 7, 8, 21 and 22, even 20, which are of single functions. And these are related to the power supply as well as the reference voltage.

Other than that, almost every pin has two or three functions. For example, PIN number 1 is PC in 14 that means it is pin change interrupt number 14. It is also a reset pin and it is also Port C bit six. And you can see that let us take another example PIN number 23, it is PC0 that is, it can be programmed as port C bit 0 or it is ADC channel 0 or it is pin change interrupt number 18.

So, this is the meaning of fitting multiple functions on each pin and leaving it to the judicial judiciousness and the knowledge of the user to decide which exact function they would like to select of all the multiple functions that a particular PIN offers. We will finish this lecture here and we will continue with the rest of the important features that modern microcontrollers offer. Thank you.