



NPTEL ONLINE CERTIFICATION COURSES

Course Name: Embedded System Design with ARM

Faculty Name: Prof. Indranil Sen Gupta

Department : Computer Science and Engineering

Topic

Lecture 12: Digital to Analog Conversion

CONCEPTS COVERED

- ❑ Introduction to digital-to-analog conversion
- ❑ Design of weighted resistor D/A converter
- ❑ Design of resistive ladder D/A converter



Interfacing with the Analog World

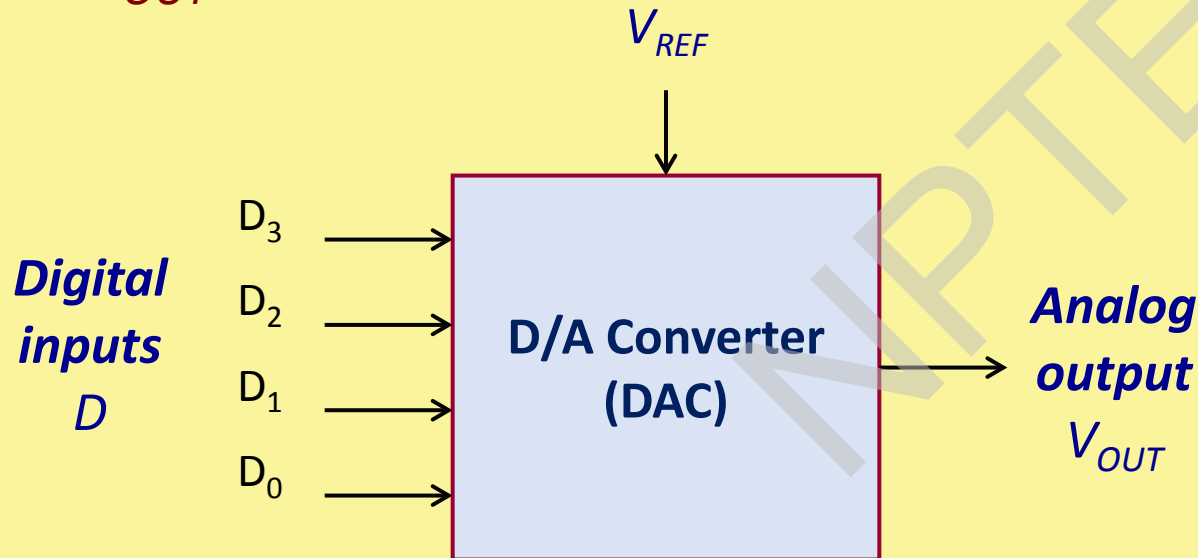
- a) Transducer/Sensor: converts physical variable to electrical variable.
- b) Analog-to-digital converter (ADC)
- c) Digital System (microcontroller)
- d) Digital-to-analog converter (DAC)
- e) Actuator



Digital-to-Analog Converter (DAC)

- Converts a given digital word D to a proportional analog voltage V_{OUT} .

$$V_{OUT} \propto D$$



$$V_{REF} = 15\text{ V}$$

D ₃	D ₂	D ₁	D ₀	V _{OUT}
0	0	0	0	0 V
0	0	0	1	1 V
0	0	1	0	2 V
0	0	1	1	3 V
0	1	0	0	4 V
0	1	0	1	5 V
0	1	1	0	6 V
0	1	1	1	7 V
1	0	0	0	8 V
1	0	0	1	9 V
1	0	1	0	10 V
1	0	1	1	11 V
1	1	0	0	12 V
1	1	0	1	13 V
1	1	1	0	14 V
1	1	1	1	15 V

Resolution or Step Size

- Smallest change that can occur in V_{OUT} as a result of a change in input D .
 - Equal to the weight of the LSB, also called *step size*.
 - Same as the constant of proportionality in $V_{OUT} \propto D$
- Can also be defined as a percentage of the full-scale voltage:

Step-size or resolution $\Delta = V_{REF} / (2^N - 1)$, for an N-bit DAC

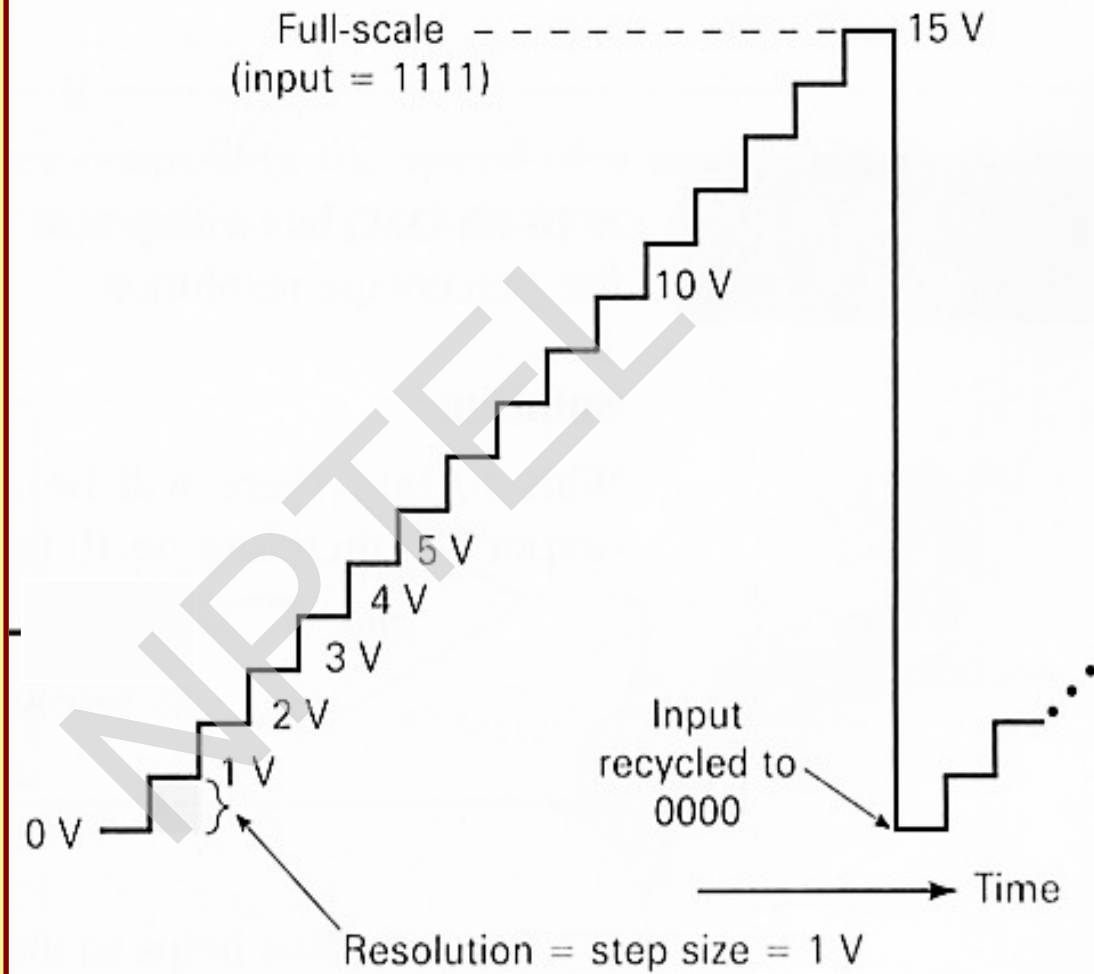
Percentage resolution = $\Delta / (\text{full-scale voltage}) \times 100 \%$

$$= 1 / (2^N - 1) \times 100$$

Clock →

Binary Counter

D/A Converter

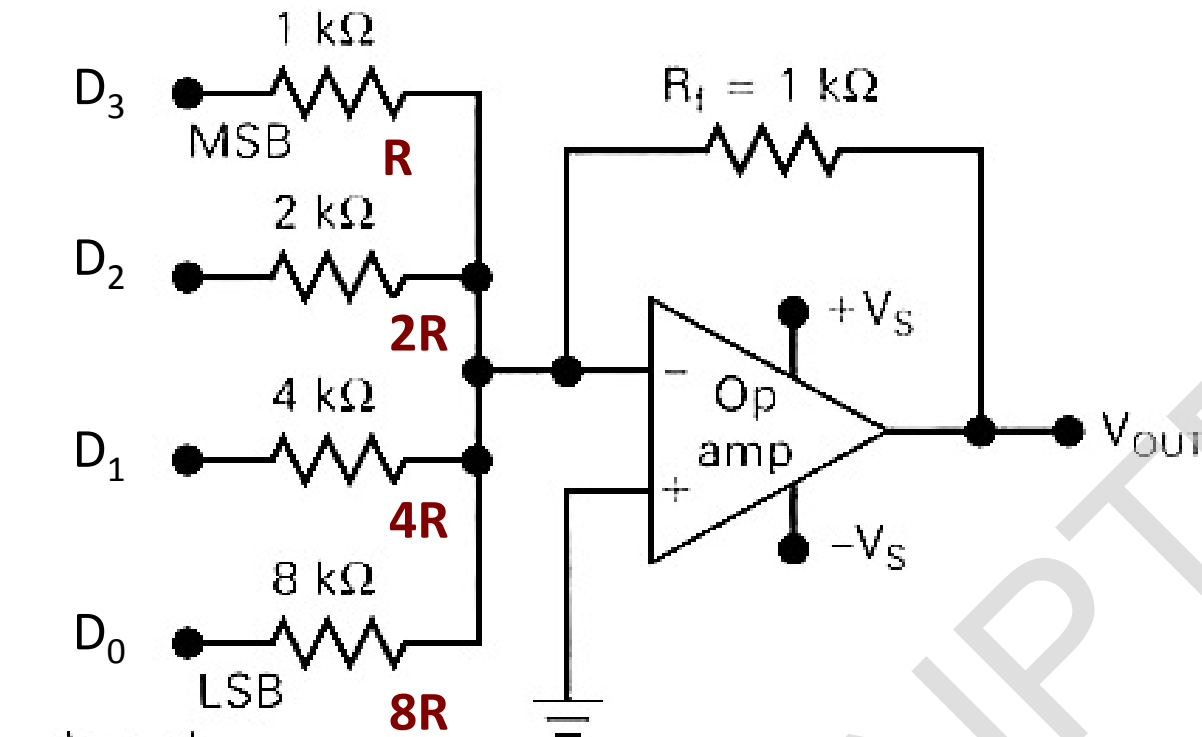


Types of D/A Converter

- We shall discuss two different designs of digital-to-analog converters.
 - a) Weighted resistor type DAC
 - b) Resistive ladder type DAC
- The first type is easier to analyze, while the second type is more practical from the point of view of implementation.

Weighted Resistor Type DAC

- For an n -bit DAC, it consists of n different resistance values of magnitudes $R, 2R, 4R, \dots, 2^{n-1}R$ respectively.
 - The resistances help in generating currents inversely proportional to their magnitudes.
 - The total current is added up by an operational amplifier, and is converted to the voltage output V_{OUT} .
- Main drawback:
 - A different-valued precision resistor must be used for each bit position of the digital input.

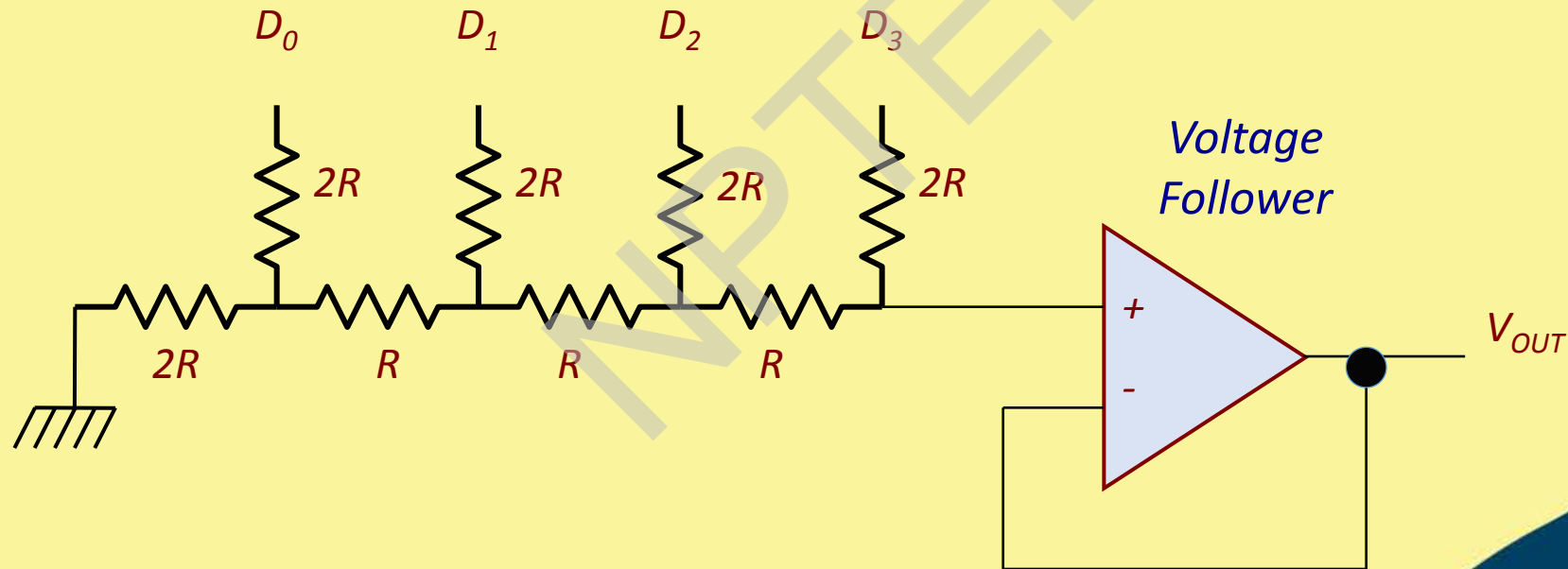


Digital inputs:
0 V or 5 V

$$\begin{aligned}
 V_{OUT} &= -[D_3 + D_2/2 + D_1/4 + D_0/8] R_f / R \\
 &= -[8D_3 + 4D_2 + 2D_1 + D_0] R_f / 8R \\
 &\propto D
 \end{aligned}$$

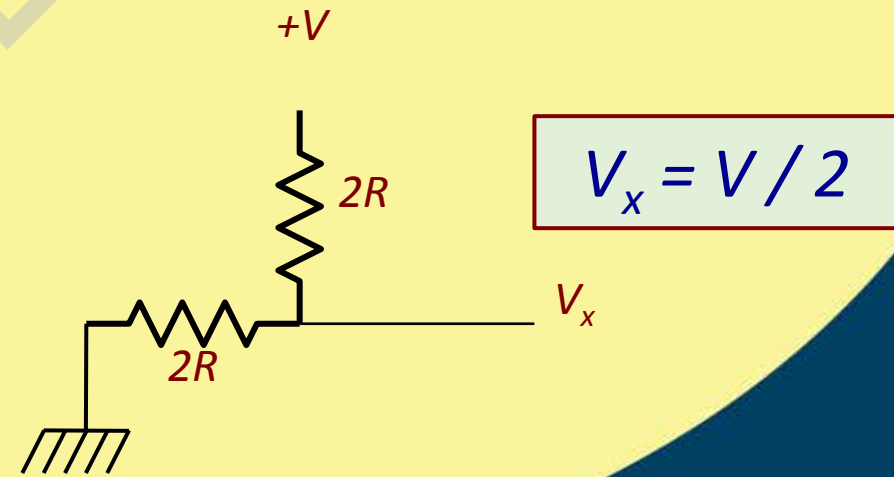
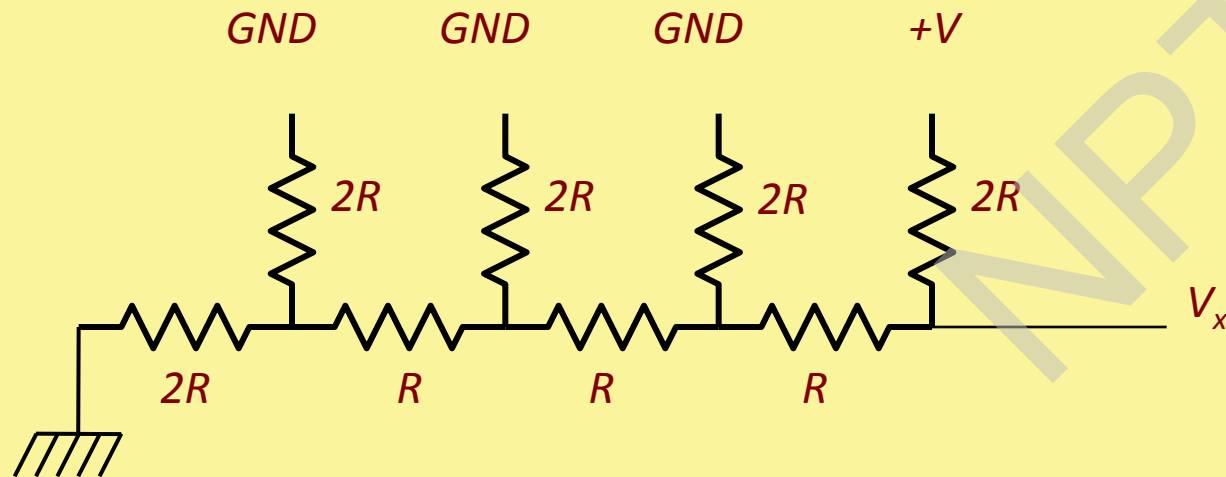
Resistive Ladder Type DAC

- Most widely used, and requires only two different values of precision resistances (R and $2R$).

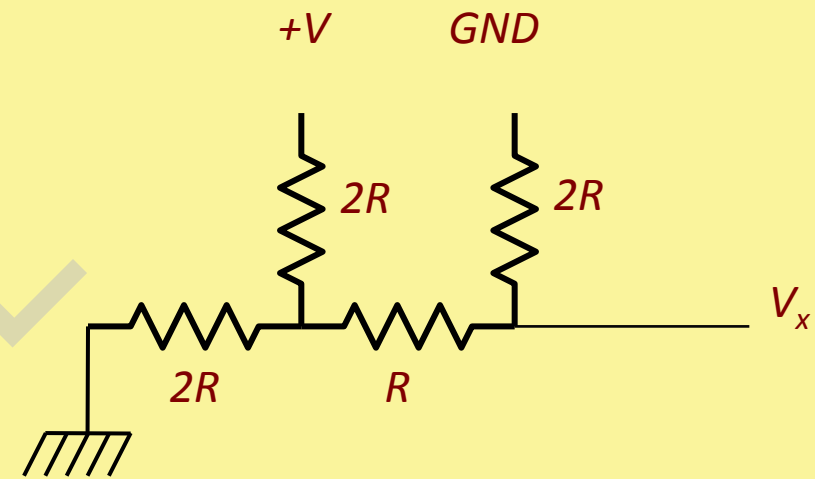
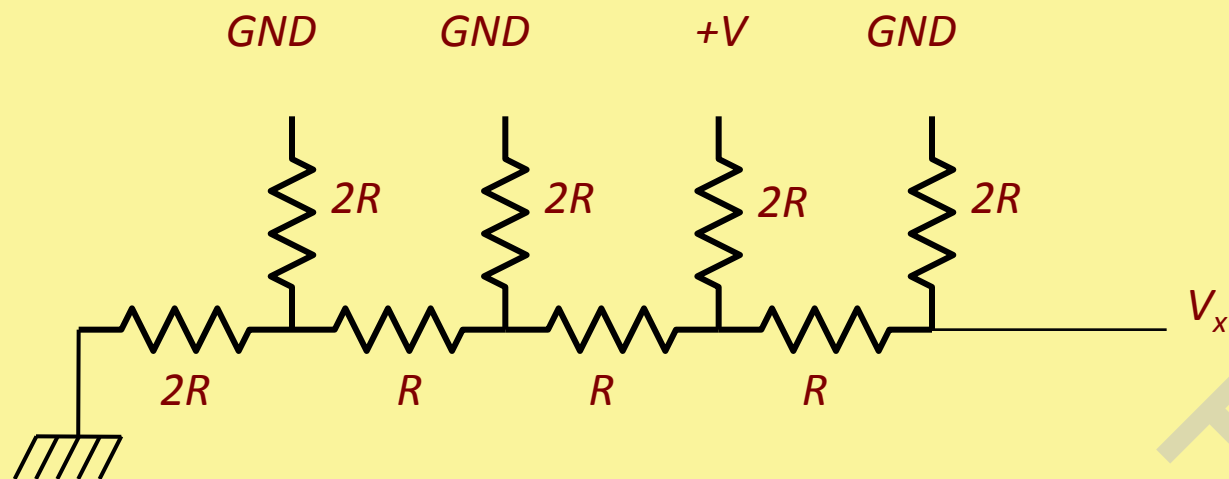


Calculation

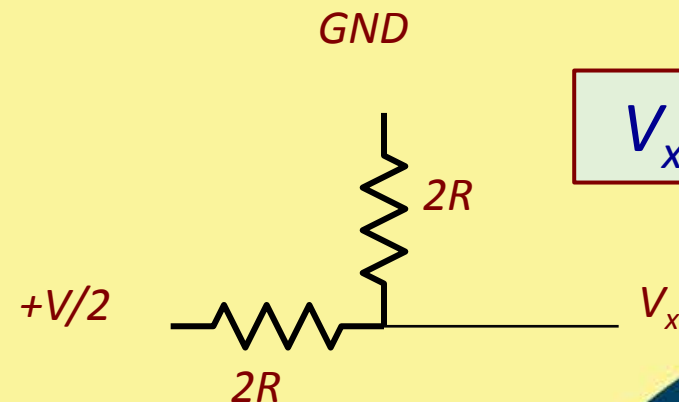
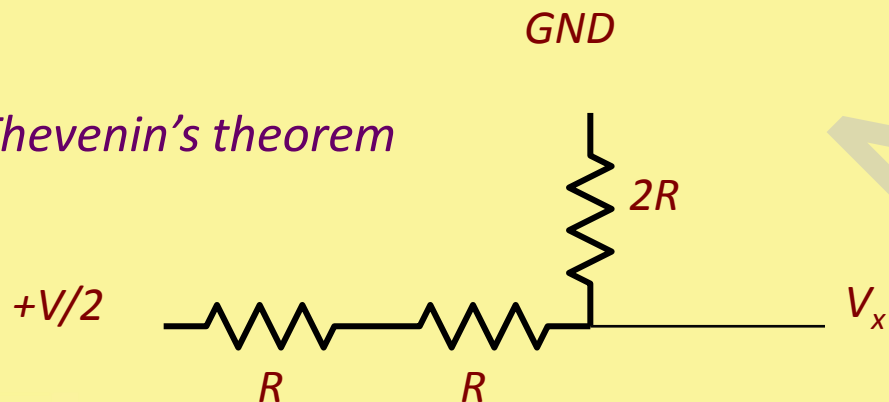
- Let us calculate the voltages at the opamp input when exactly one of the D_i inputs is at 1 (say, $+V$ volts).
- Case 1: Input is 1000.*



- Case 2: Input is 0100.

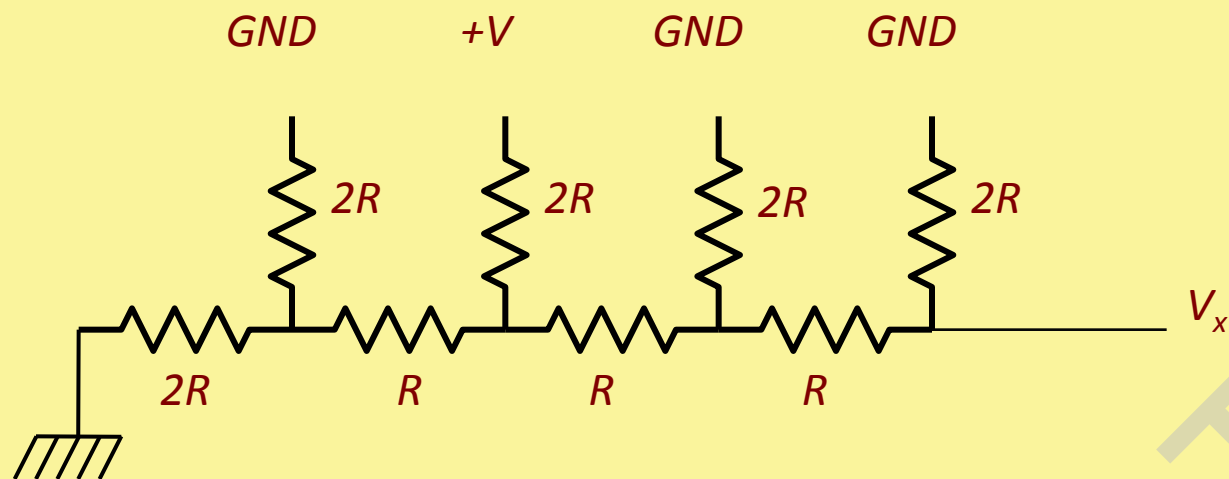


Thevenin's theorem

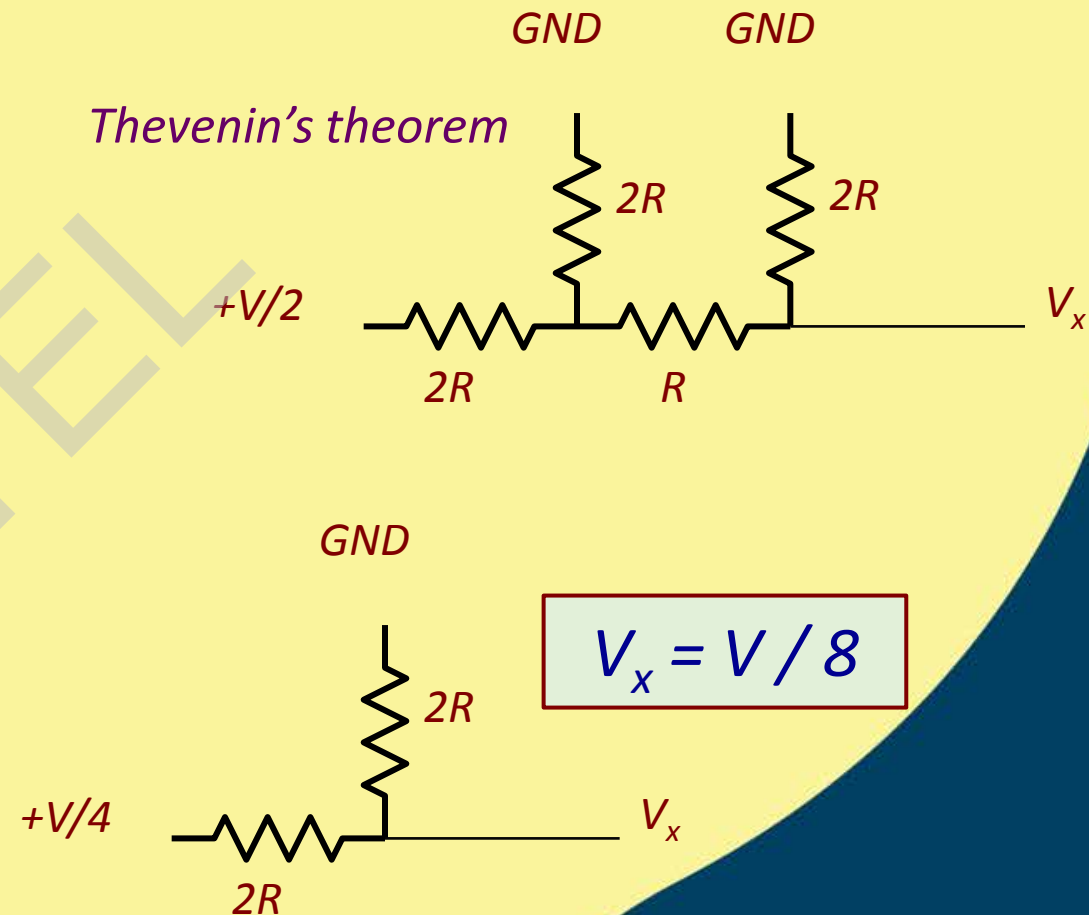


$$V_x = V / 4$$

- Case 3: Input is 0010.

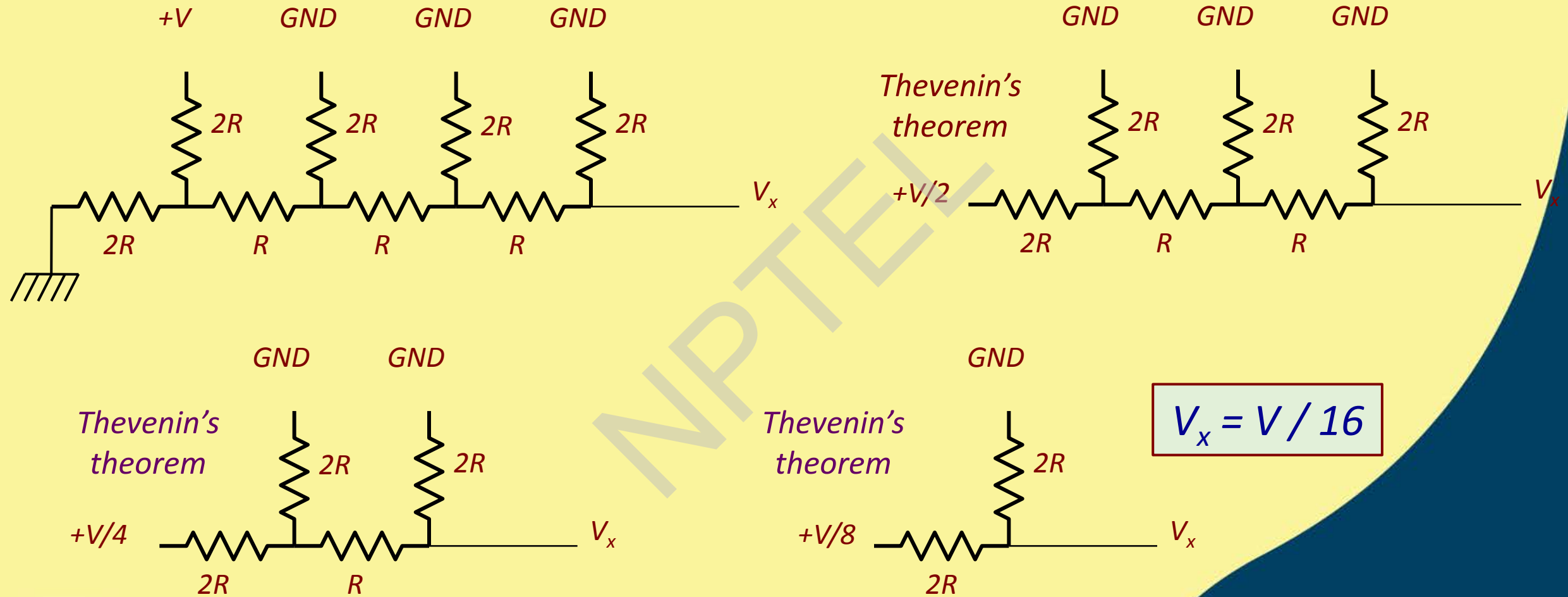


Thevenin's theorem

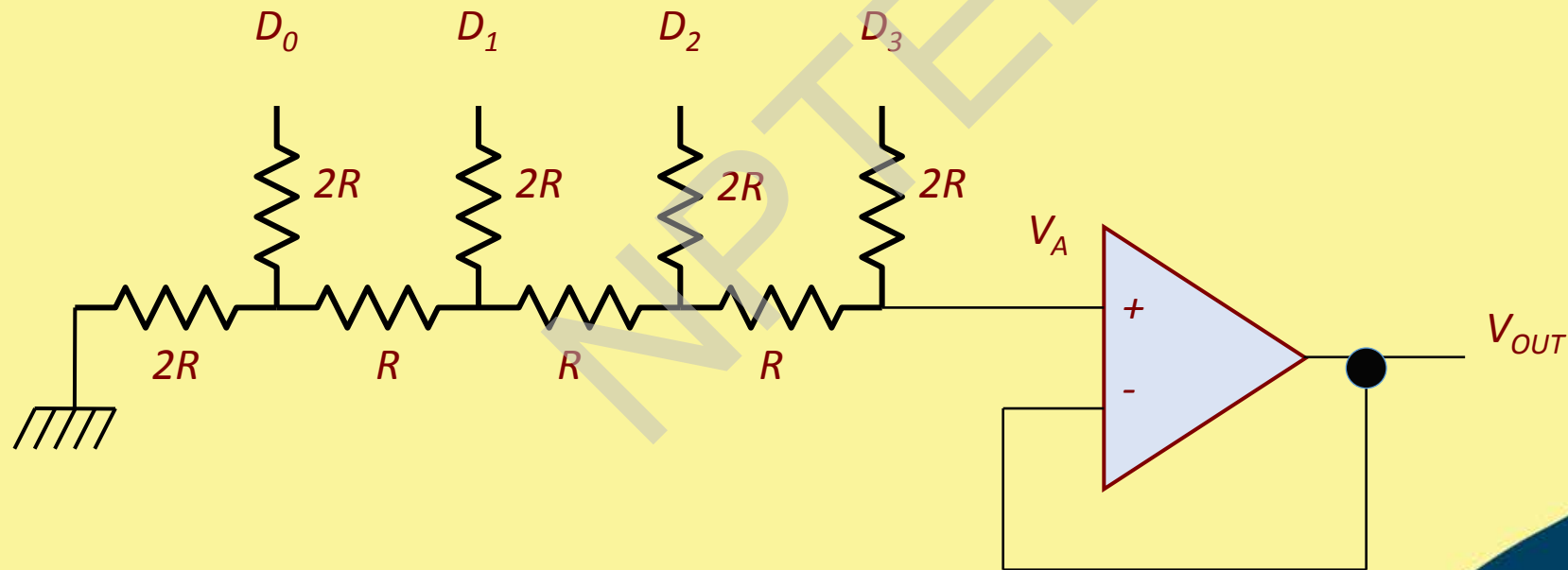


$$V_x = V / 8$$

- Case 4: Input is 0001.



- When all the four inputs $D = D_3D_2D_1D_0$ are applied (where $D_i = GND$ or $+V$ volts), we can apply the principle of superposition to compute the final output voltage V_A .



$$\begin{aligned}
 V_A &= [D_3 \cdot (V/2) + D_2 \cdot (V/4) + D_1 \cdot (V/8) + D_0 \cdot (V/16)] \\
 &= [8D_3 + 4D_2 + 2D_1 + D_0] \cdot (V/16) \\
 &= D \cdot (V/16)
 \end{aligned}$$

Thus, $V_A \propto D$.

For an N -bit DAC, the contribution of the k -th input D_k on the output voltage will be $V / 2^{N-k}$.

D/A Converter in STM32F401

- This development board does not support any DAC channels.
 - We can use the PWM feature for analog control of external devices.
 - Or else we can connect a DAC externally (using resistances or chip).
- Other boards of the family (e.g. STM32F405) supports 12-bit DAC interface.
 - Two channels are supported with DMA capability and triangular wave generator.



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Topic

Lecture 13: Analog to Digital Conversion (Part 1)

CONCEPTS COVERED

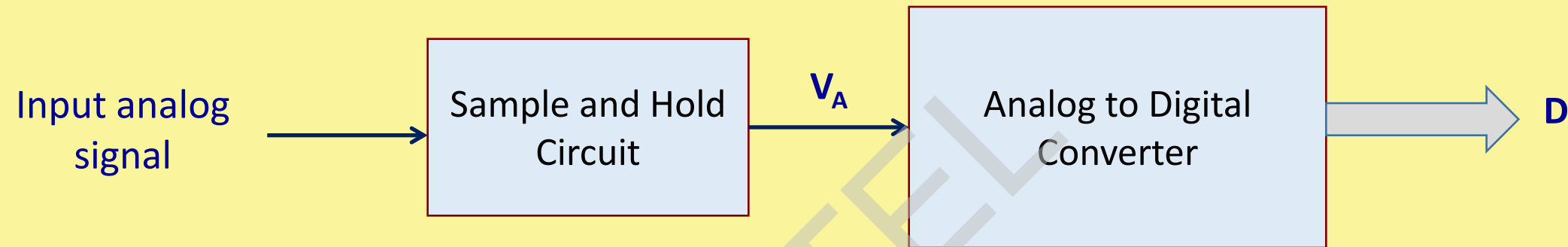
- ❑ Introduction to analog-to-digital conversion
- ❑ Choice of signal sampling rate
- ❑ Flash-type, counter-type and tracking-type ADC



Introduction

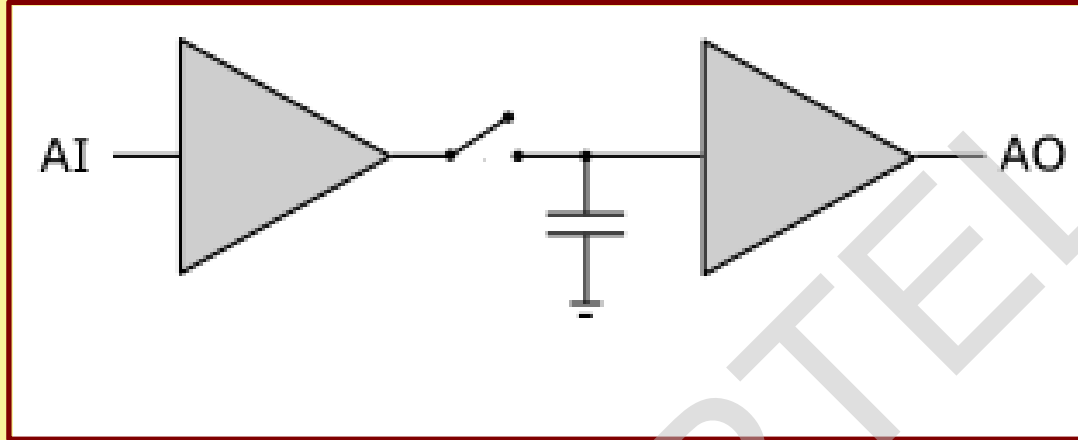
- An analog-to-digital converter (ADC) takes an analog input V_A as input, and generates a digital word D as output, where $D \propto V_A$.
- Various types of ADC are possible:
 - a) Flash-type ADC
 - b) Counter-type ADC
 - c) Tracking-type ADC
 - d) Successive approximation ADC
 - e) Dual-slope ADC

Overall Schematic



- If the input signal changes during the conversion, the final value D may be erroneous.
- We need a *sample-and-hold circuit* to sample the input voltage, and hold it to a constant value while the conversion is in progress.

Sample-and-Hold Circuit



- The input voltage **AI** is sampled by closing the switch; the capacitor charges to the voltage.
- During conversion, the switch is opened again, so that **AO** remains reasonably constant.

How Fast We Must Sample?

- A very important decision.
 - Guided by *Nyquist Theorem*.
- What is Nyquist Theorem?
 - A *band-limited* analog signal that has been sampled can be perfectly reconstructed from an infinite sequence of samples if the sampling rate f_s exceeds $2f_{max}$ samples per second, where f_{max} is the highest frequency in the original signal.
 - If the analog signal does contain frequency components larger than $f_s/2$, then there will be an *aliasing error*.
 - Aliasing is when the digital signal appears to have a different frequency than the original analog signal.

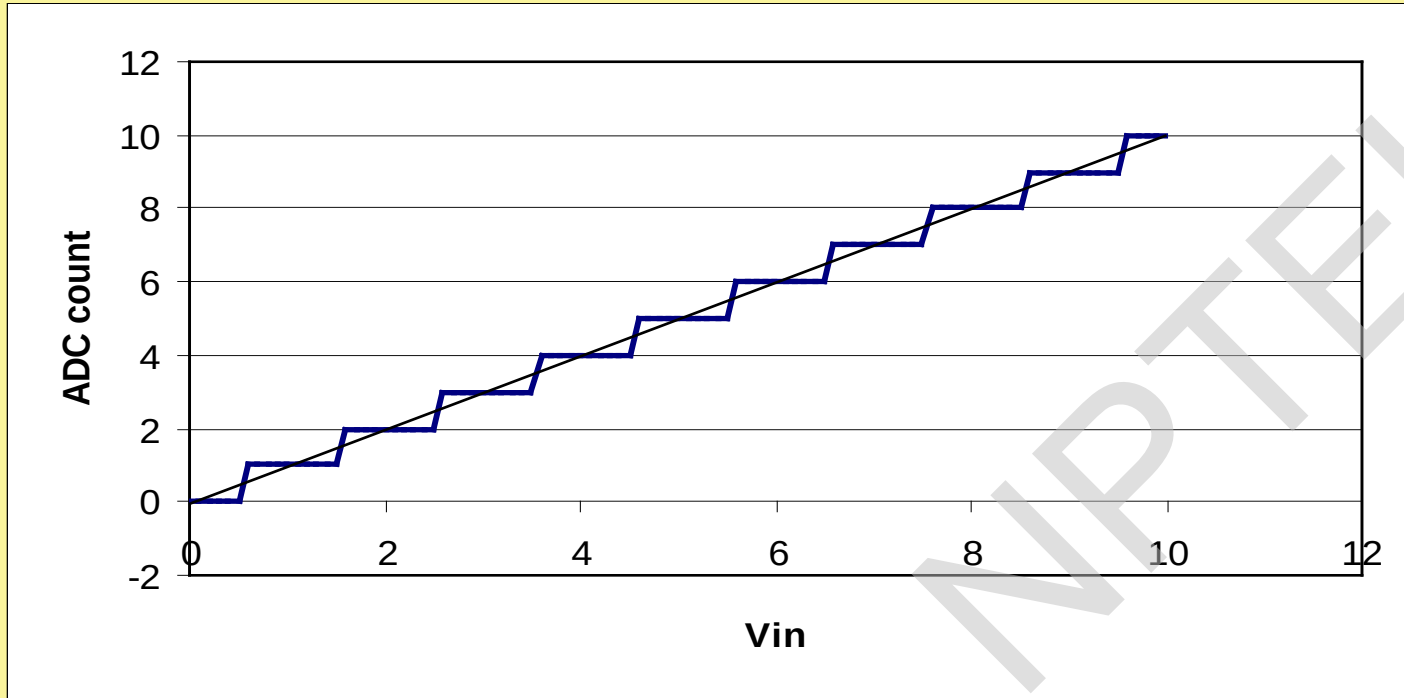
Resolution

- The least significant bit of an analog-to-digital converter (ADC) gives the *resolution*.
- Related to full scale if the ADC is linear.
 - $LSB = A / 2^n$, for an n -bit ADC.
 - For a linear 8-bit ADC with a 1V full scale input,
Resolution = $1.0 / 2^8 = 3.9 \text{ mV}$
Percentage Resolution = Resolution / (Full-scale voltage) x 100 %

Conversion Time and Bandwidth

- How often can a conversion be done?
 - A few ns to a few ms depending on the technology.
- Input bandwidth
 - Maximum input signal bandwidth
 - Sample and hold input circuitry
 - Conversion frequency

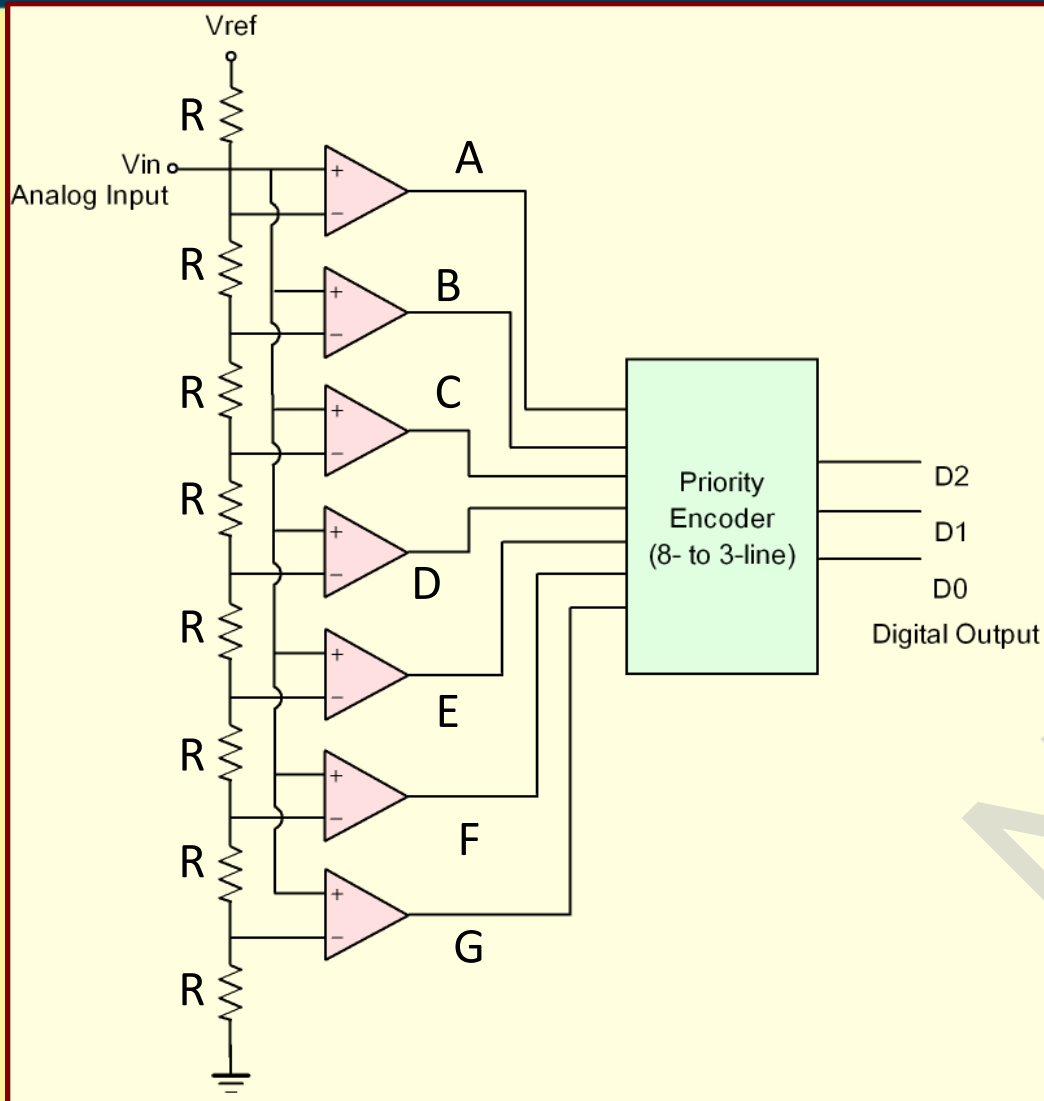
ADC Transfer Characteristics



- This curve is for ideal ADC.
- Possible errors:
 - Offset
 - Non-linearity

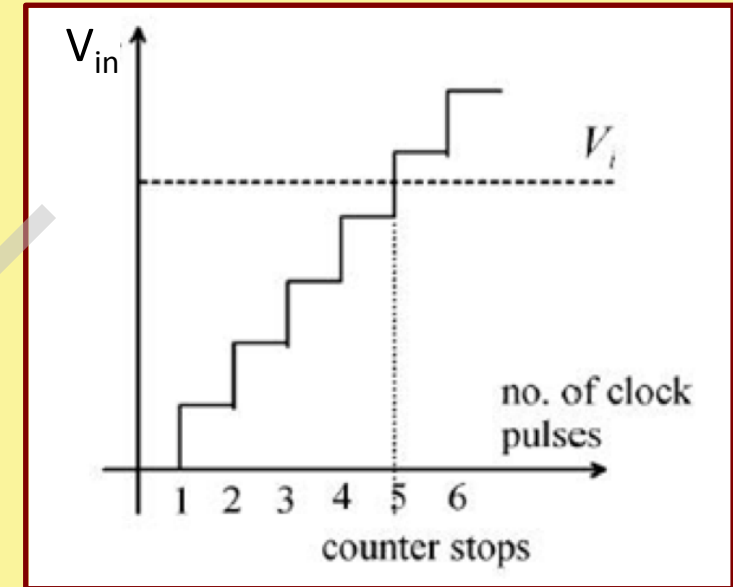
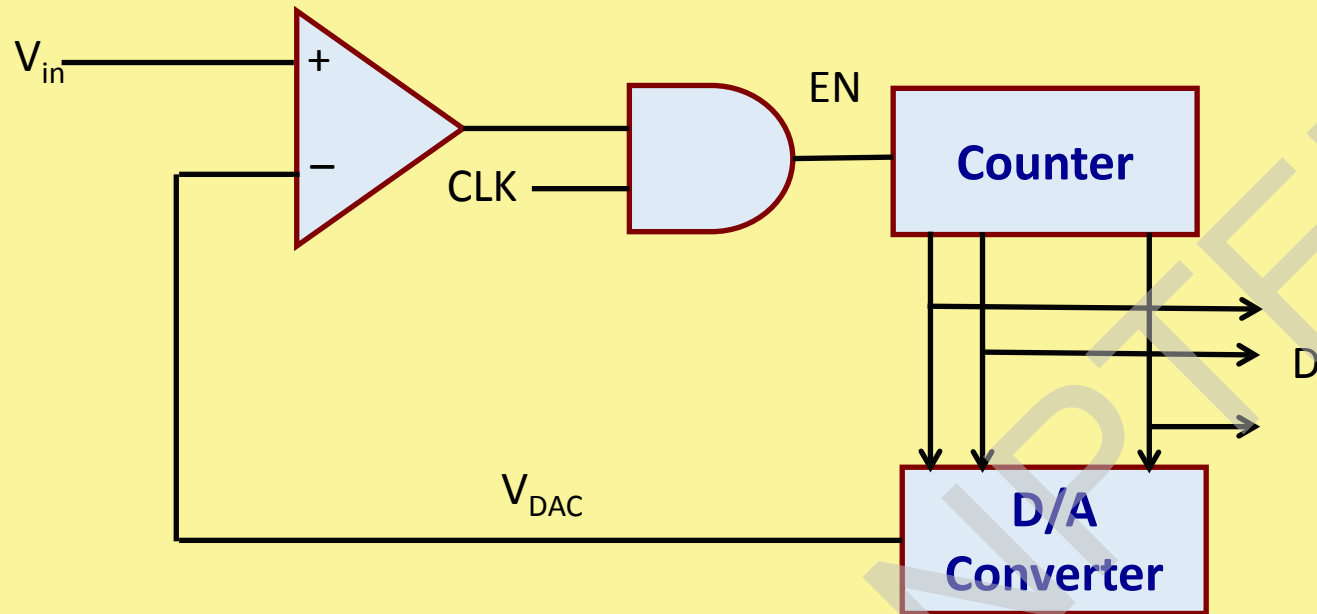
(a) Flash-type ADC

- This type of ADC provides the fastest conversion.
- Requires large amount of hardware.
 - For an n -bit converter, we require $2^n - 1$ comparators, 2^n resistors, and one 2^n -input priority encoder.
- We illustrate the design for a 3-bit ADC.



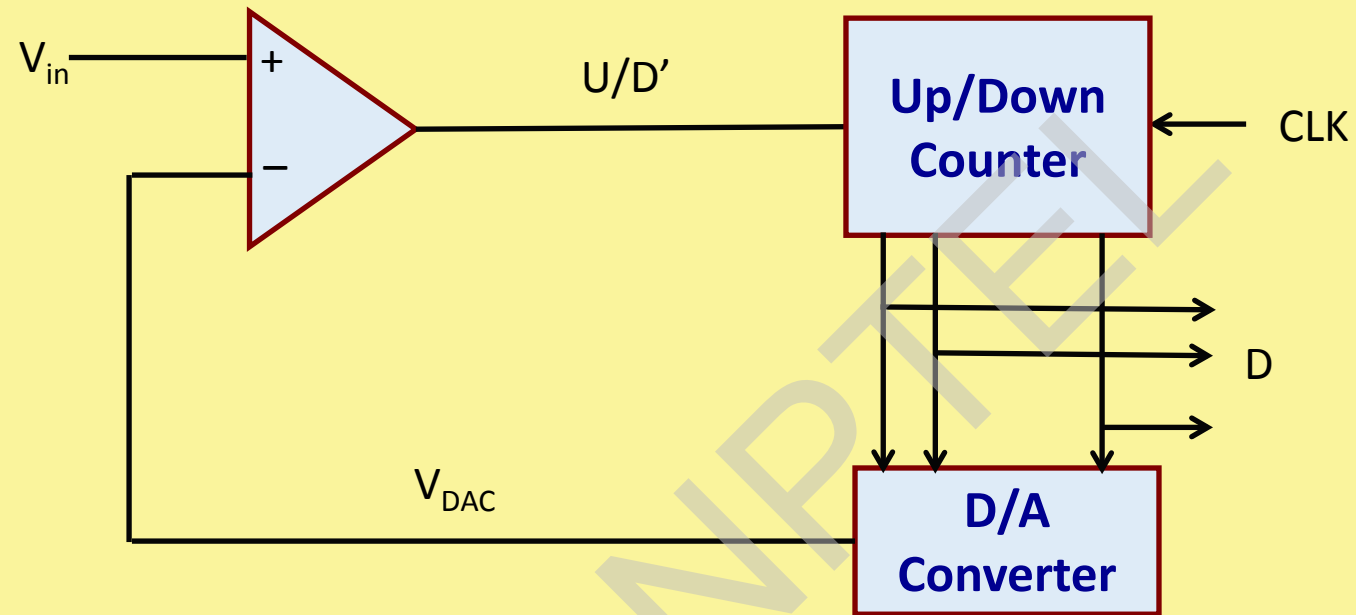
A	B	C	D	E	F	G	D2	D1	D0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	1	0	0	1
0	0	0	0	0	1	X	0	1	0
0	0	0	0	1	X	X	0	1	1
0	0	0	1	X	X	X	1	0	0
0	0	1	X	X	X	X	1	0	1
0	1	X	X	X	X	X	1	1	0
1	X	X	X	X	X	X	1	1	1

(b) Counter-Type ADC

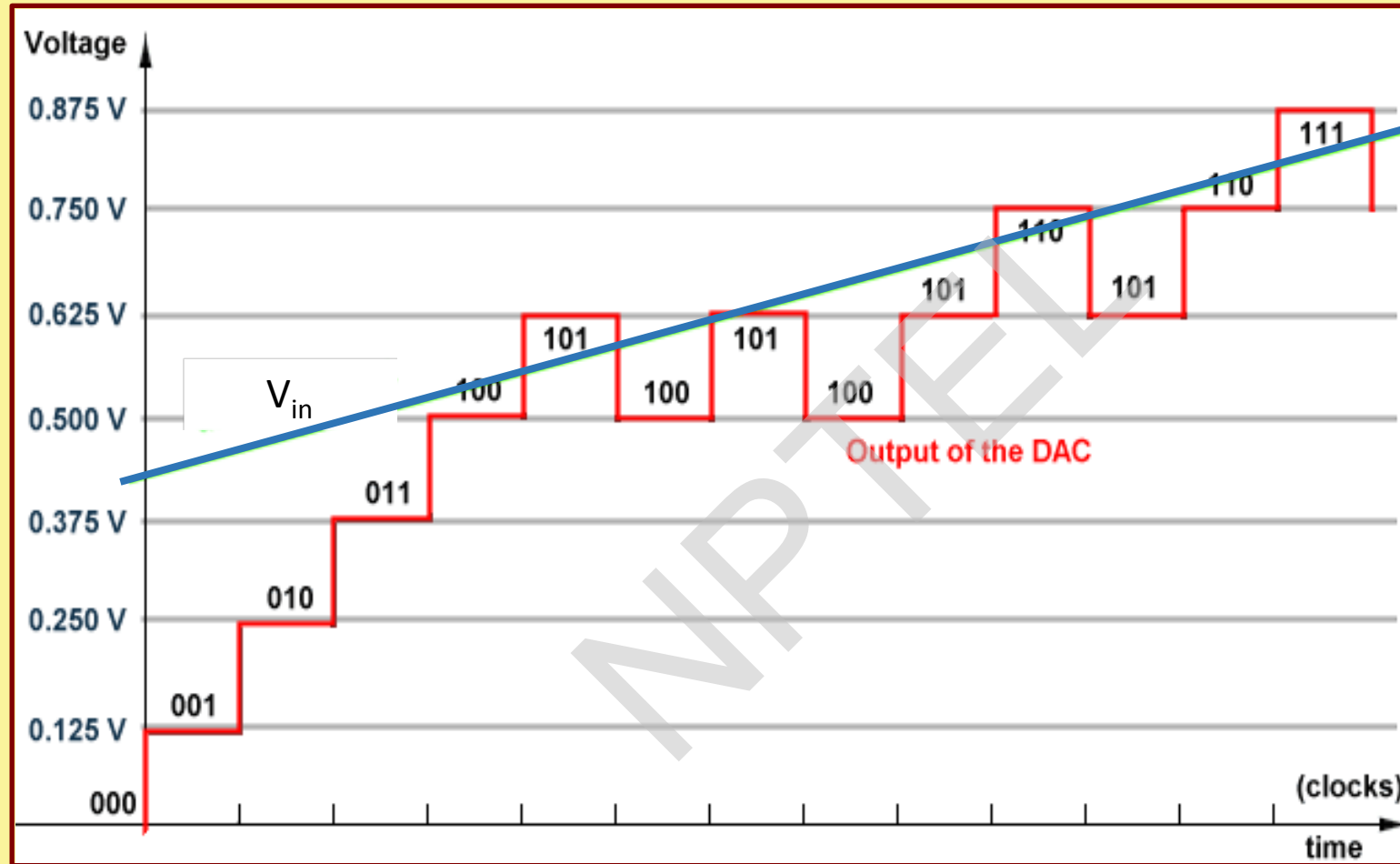


- We use a D/A converter, a counter and a comparator.
 - Before a conversion starts, the counter is reset to zero.
 - The counter output is fed to the input of the DAC.
 - The DAC output V_{DAC} is compared with the input analog voltage V_{in} .
 - If $V_{in} > V_{DAC}$, then the counter is incremented by 1.
 - If $V_{in} < V_{DAC}$, the conversion is complete, and the counter output D gives the required digital output.
- The worst-case conversion time is equal to 2^n .

(c) Tracking-Type ADC



- Here we use a binary up-down counter.
 - If the output of the comparator is 1 ($V_{in} > V_{DAC}$), the counter is incremented by 1.
 - If the output of the comparator is 0 ($V_{in} < V_{DAC}$), the counter is decremented by 1.
 - The counter output D continuously tracks the input analog voltage.
- Suitable for continuous conversion of slowly-varying waveforms.
 - If V_{in} changes too fast, the counter may not be able to track the changes.
 - Here also, the worst-case conversion time is 2^n .





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Topic

Lecture 14: Analog to Digital Conversion (Part 2)

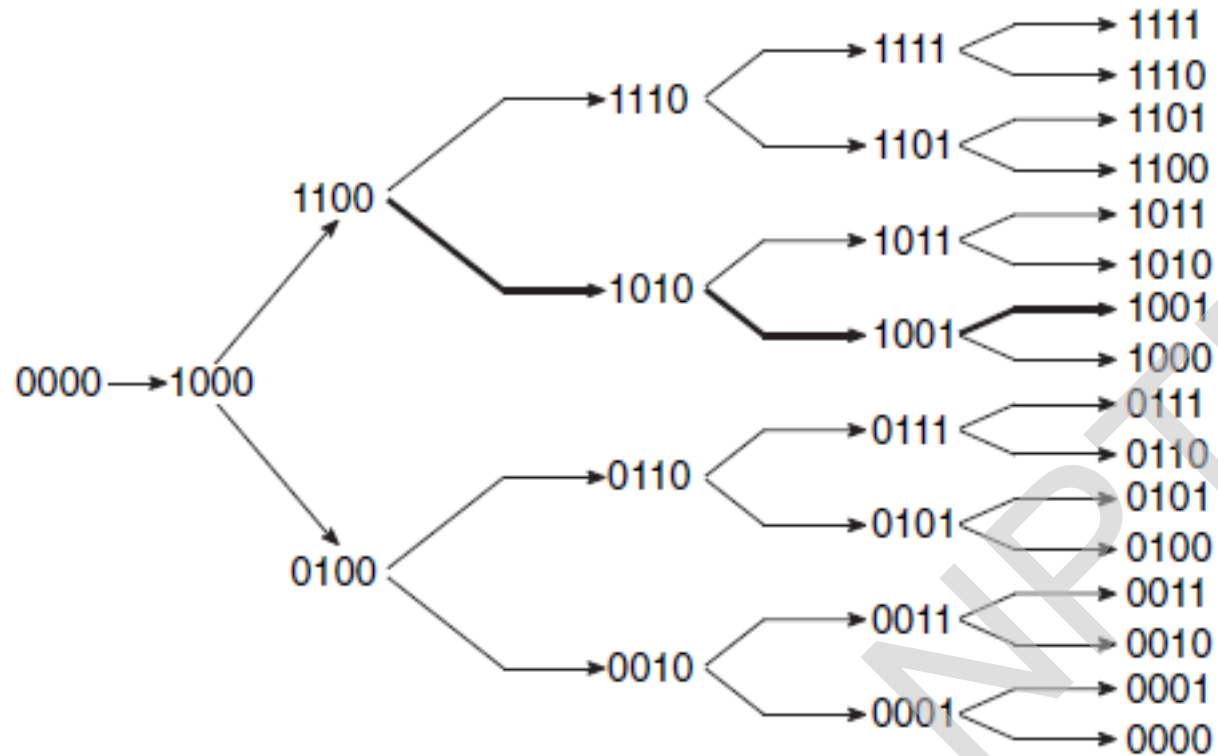
CONCEPTS COVERED

- ❑ Successive-approximation type ADC
- ❑ A/D conversion in ARM microcontrollers



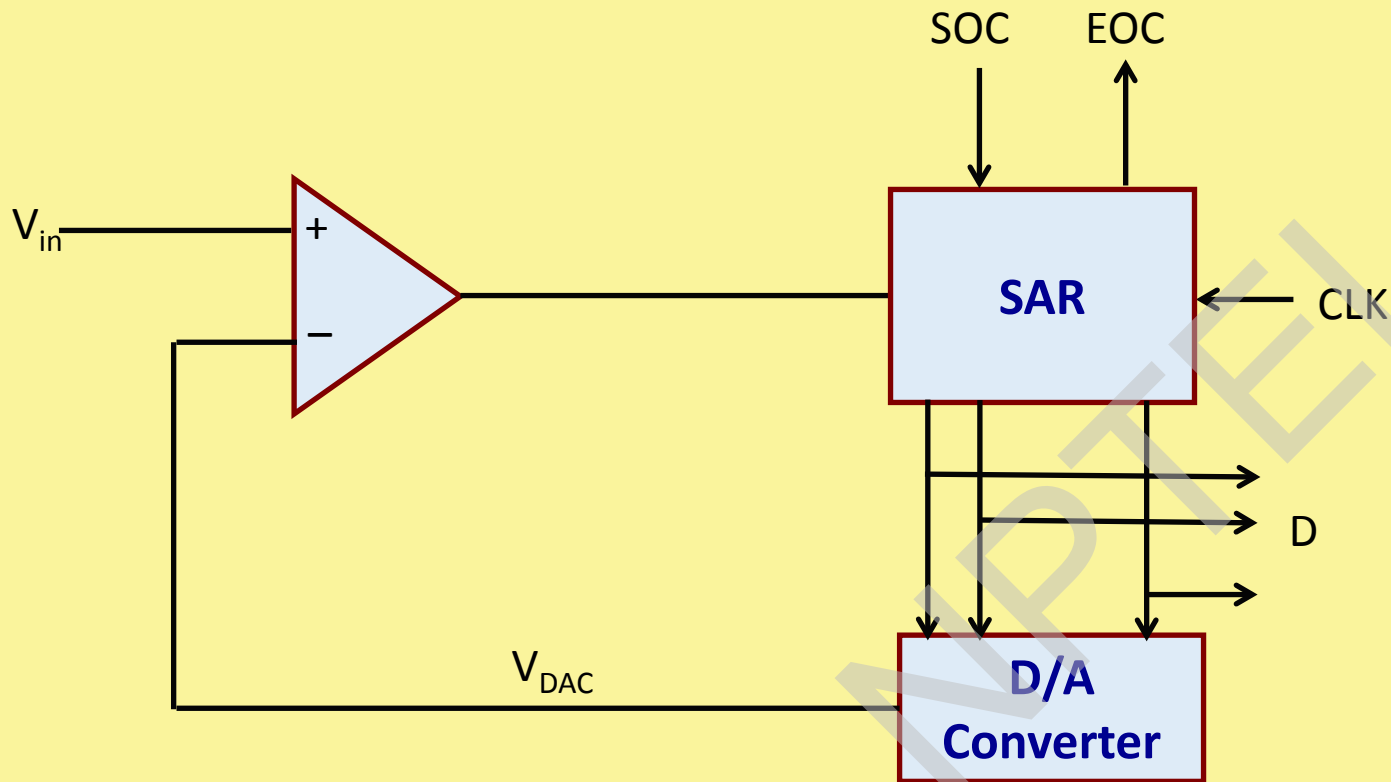
(d) Successive Approximation Type ADC

- The principle of operation is analogous to *binary search*.
 - Suppose we are searching for a number (here V_{in}) in a sorted list.
 - We look into the middle of the list – effectively the size of the list reduces by half.
 - For 2^n steps, the number of steps required is only n .
- What modifications are required?
 - We use a successive approximation register (SAR) instead of a counter.
 - The SAR emulates binary search.
 - For example, in 4 bits, it starts with 1000 (i.e. 8).
 - If the input is smaller, the next value is set as 0100 (i.e. 4).
 - If the input is larger, the next value is set at 1100 (i.e. 12).

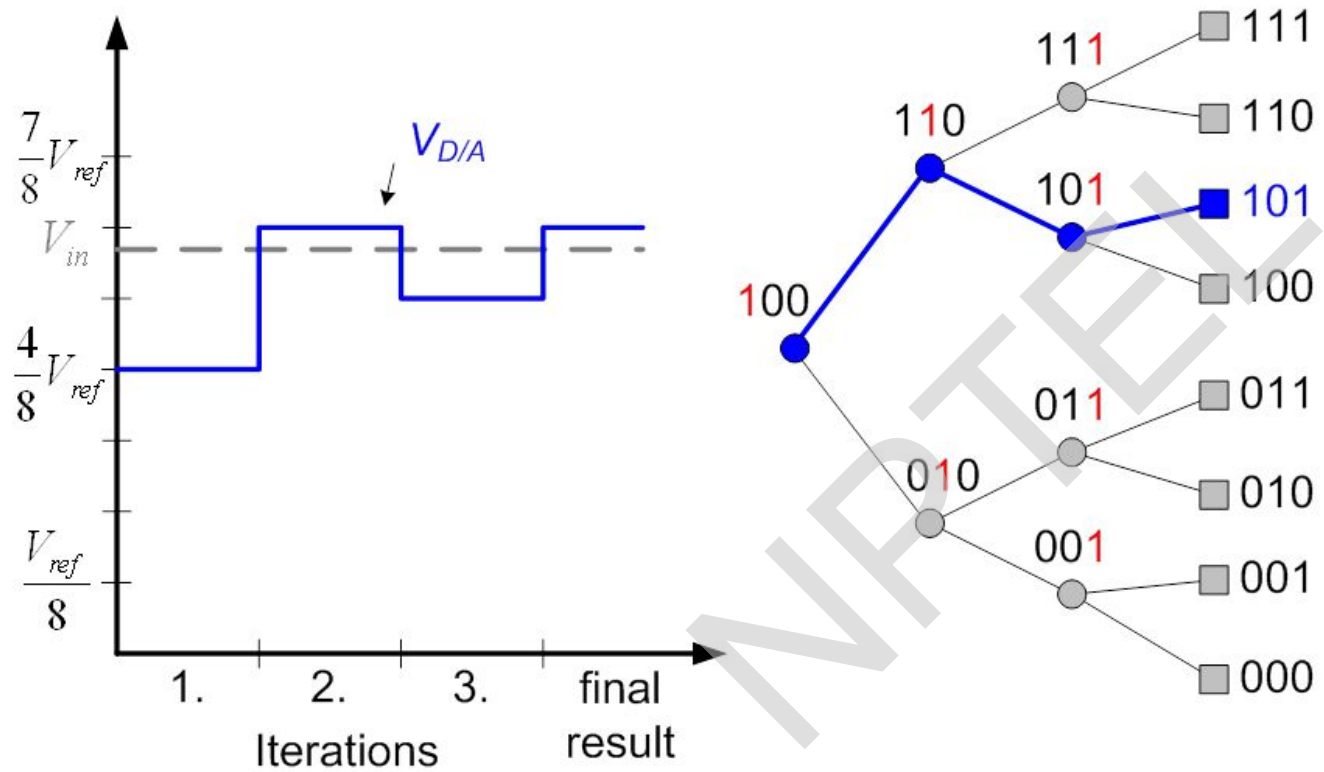


Conversion process in a successive approximation type A/D converter.

- An example for a 4-bit ADC, where the expected digital output is 1001.
- Only 4 comparison steps are required, once per bit position.



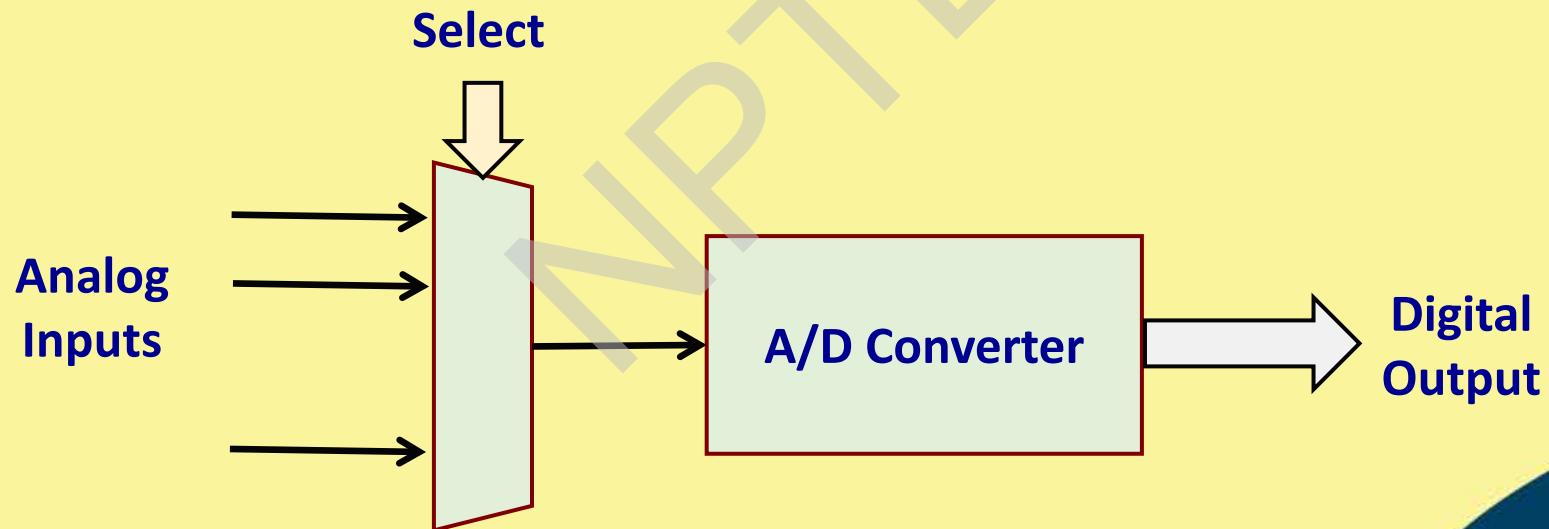
- SOC: Start of Conversion
- EOC: End of Conversion



A/D Conversion in ARM Microcontrollers

- **ADC in LPC2148 ARM7 Microcontroller**
 - Built-in 10-bit successive-approximation ADC.
 - With $V_{REF} = 3.3V$, step size = $3.3 / (2^{10} - 1) = 3.23 \text{ mV}$
 - This determines the accuracy of the measurement.
- Some specific details:
 - Two built-in ADC modules, ADC0 and ADC1.
 - ADC0 has 6 channels, and ADC1 has 8 channels.
 - ADC operating frequency is 4.5 MHz (maximum).

- There is a Control Register that must be written into to determine the operating mode.
- Interrupt is generated after A/D conversion is complete.
- An analog multiplexer is used to select one of the input analog channels at the input of an ADC.



• ADC in ARM Cortex-M4

- STM32F4xxx microcontrollers have up to 3 in-built 12-bit A/D converters, each of which has 19 channels.
- With $V_{REF} = 3.3V$, step size = $3.3 / (2^{12} - 1) = 0.806 \text{ mV}$
- There are 16 external channels, connected to I/O pins.
- 6 of these are connected to dedicated Arduino connector pins, A0 to A5.
- There are 3 internal channels:
 - V_{bat} : voltage on battery pin.
 - Temp sensor: used to measure difference in temperature.
 - V_{ref} : voltage reference for the A/D converter.

User Button

Red LED
(power)

Green LED
(test)

Arduino Connector
and Analog input

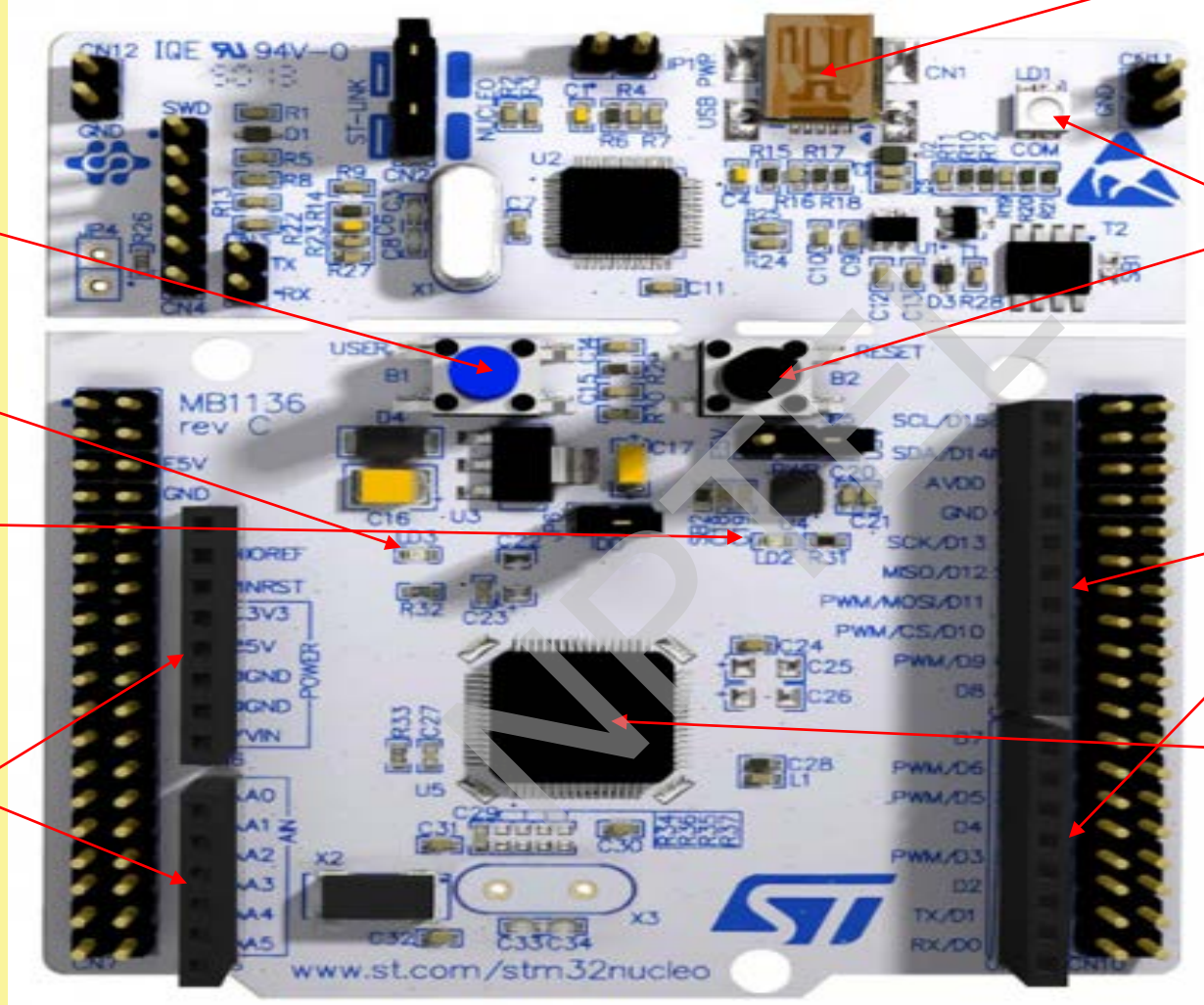
ST Link USB Type A to
mini B

Reset Button

Red/Green LED
(com)

Arduino Connector
and Digital output

STM32
Microcontroller





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**Lecture 15: Output Devices, Sensors and Actuators
(Part 1)**

CONCEPTS COVERED

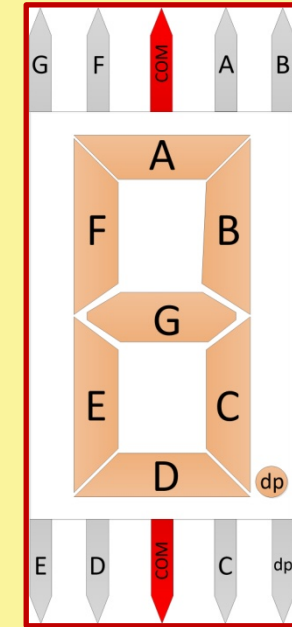
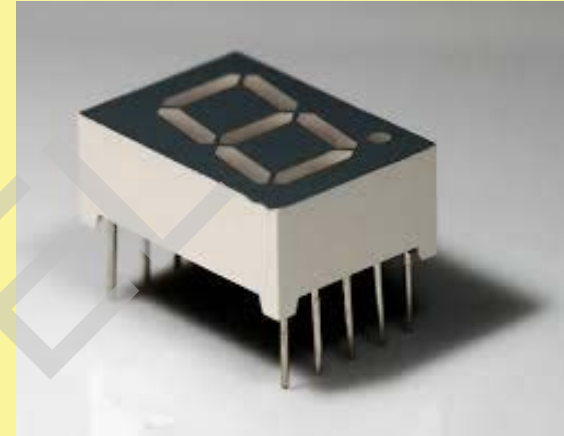
- ❑ Seven-segment LED unit and interfacing
- ❑ LCD display unit and interfacing



Output Device: Seven Segment LED Display

What is 7-Segment LED Display?

- It is a display device consisting of 8 LEDs used for number display purpose.
 - Seven line segments and a dot point.
- It can display 0-9 for Decimal and 0-F in Hexadecimal.



Two Types of 7-segment Display Units

- **Common Anode**

- The common point (COM) connects to a positive voltage source, and a segment pin should connect with ground to glow the LED.

- **Common Cathode**

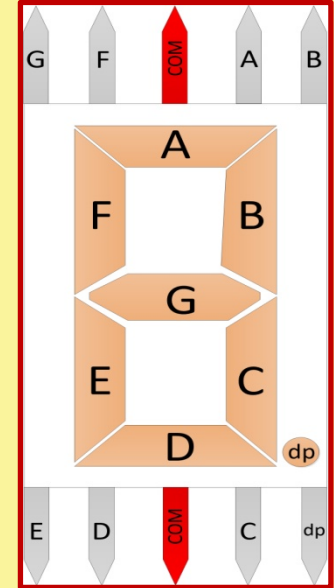
- The common point (COM) connects to ground, and a segment pin should connect with positive voltage source to glow the LED.

- **Point to note:**

- To glow a LED, about 5-10 mA current should be made to flow.
- Current limiting resistance is used (1 for common, or individual for segments).
- Drop across LED is typically 1.2 V.

A Typical Interface

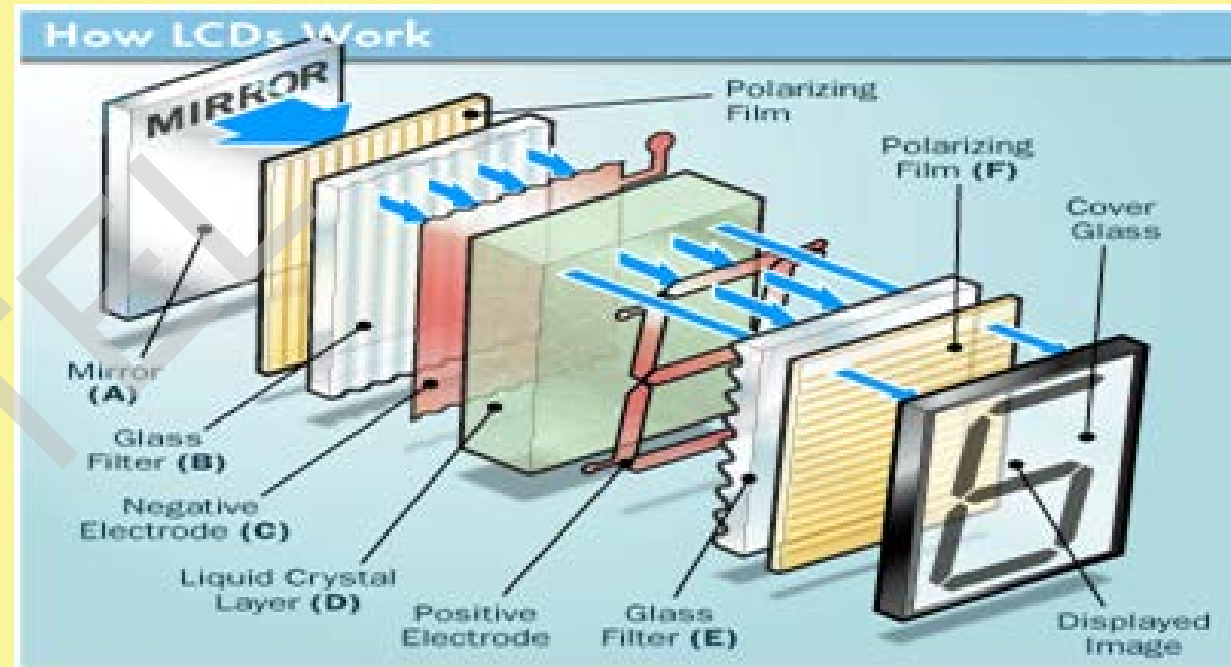
- Consider a *common anode* display unit.
- If a segment line is set to GND, it will glow.
 - To display 0, we apply $A = B = C = D = E = F = \text{GND}$, and $G = V_{cc}$.
 - To display 5, we apply, $A = C = D = F = G = \text{GND}$, and $B = E = V_{cc}$.
 - To display F, we apply $A = E = F = G = \text{GND}$, and $B = C = D = V_{cc}$.
- To display arbitrary characters, the seven segment lines can be driven from microcontroller port lines.
- For common cathode display, the convention will be just the reverse.
 - GND for OFF, V_{cc} for ON.



Output Device: LCD Display Unit

What is Liquid Crystal Display (LCD)?

- It is a type of display screen used in numerous applications.
 - Very low power consumption as compared to LED.
- LCD units are very thin and is composed of several layers.
 - Two polarized panels, with a liquid crystal solution sandwiched between them.
 - Light is projected through the layers and is colorized as it passes, thereby producing the visual image.



Working Principle

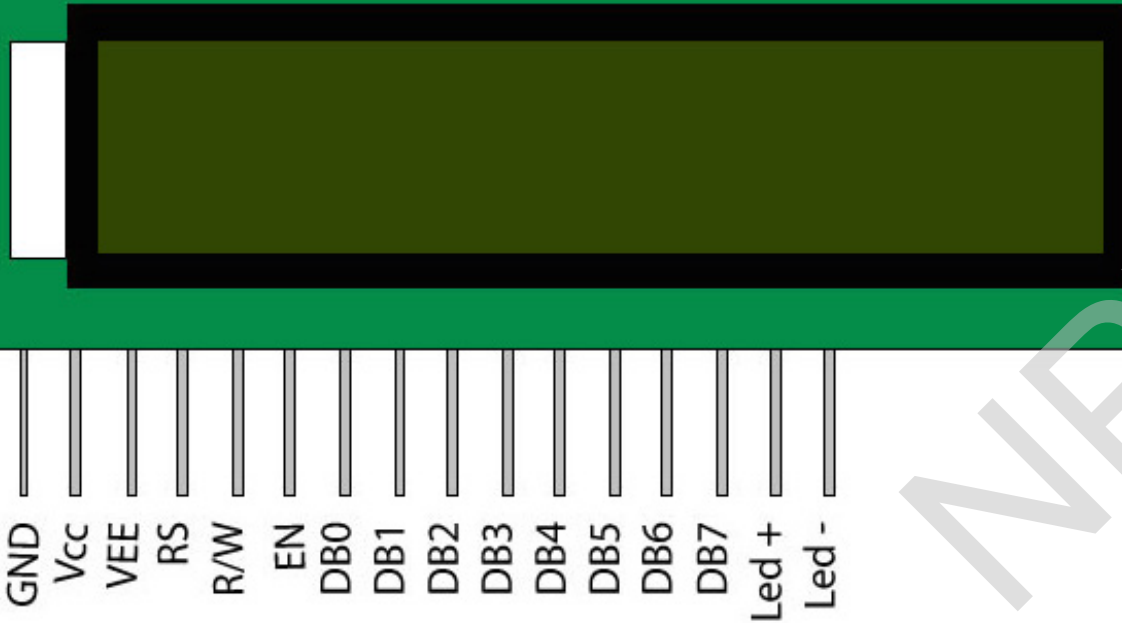
- When an electric current is applied to the liquid crystal molecules, they untwist.
 - Results in a change in the angle of light.
 - The polarized layers are responsible for either blocking the light or allowing it to pass.
- A reflecting mirror is arranged at the back of the unit.
- An electrode plane is used to allow the current to flow in selected areas.
- The entire arrangement is placed inside a sealed casing, with necessary electronics for controlling the device.

The JHD162A LCD Display Unit

- The JHD162A LCD display unit consists of 16 pins and can display 16 x 2 monochrome characters.
 - Two lines of display, where each line can hold 16 characters.
 - Can be interfaced in 4-bit mode or 8-bit mode.



JHD162A Pin Description



PIN NO.	SYMBOL	DESCRIPTION	FUNCTION
1	VSS	GROUND	0V (GND)
2	VCC	POWER SUPPLY FOR LOGIC CIRCUIT	+5V
3	VEE	LCD CONTRAST ADJUSTMENT	
4	RS	INSTRUCTION/DATA REGISTER SELECTION	RS = 0 : INSTRUCTION REGISTER RS = 1 : DATA REGISTER
5	R/W	READ/WRITE SELECTION	R/W = 0 : REGISTER WRITE R/W = 1 : REGISTER READ
6	E	ENABLE SIGNAL	
7	DB0	DATA INPUT/OUTPUT LINES	8 BIT: DB0-DB7
8	DB1		
9	DB2		
10	DB3		
11	DB4		
12	DB5		
13	DB6		
14	DB7		
15	LED+	SUPPLY VOLTAGE FOR LED+	+5V
16	LED-	SUPPLY VOLTAGE FOR LED-	0V

How to Display Characters using 4-bit Interface?

- Data are sent out as nibbles and not as bytes.
 - D3-D0 are not connected in this mode.
 - D7-D4 are used to transfer the nibbles.
- The commands and data are still 8-bits long, but are transferred as mentioned.
 - The most significant nibble is transferred first, followed by the least significant nibble.
- The detailed command codes are available in the LCD module data sheet.
 - The Mbed interface automatically takes care of the codes.

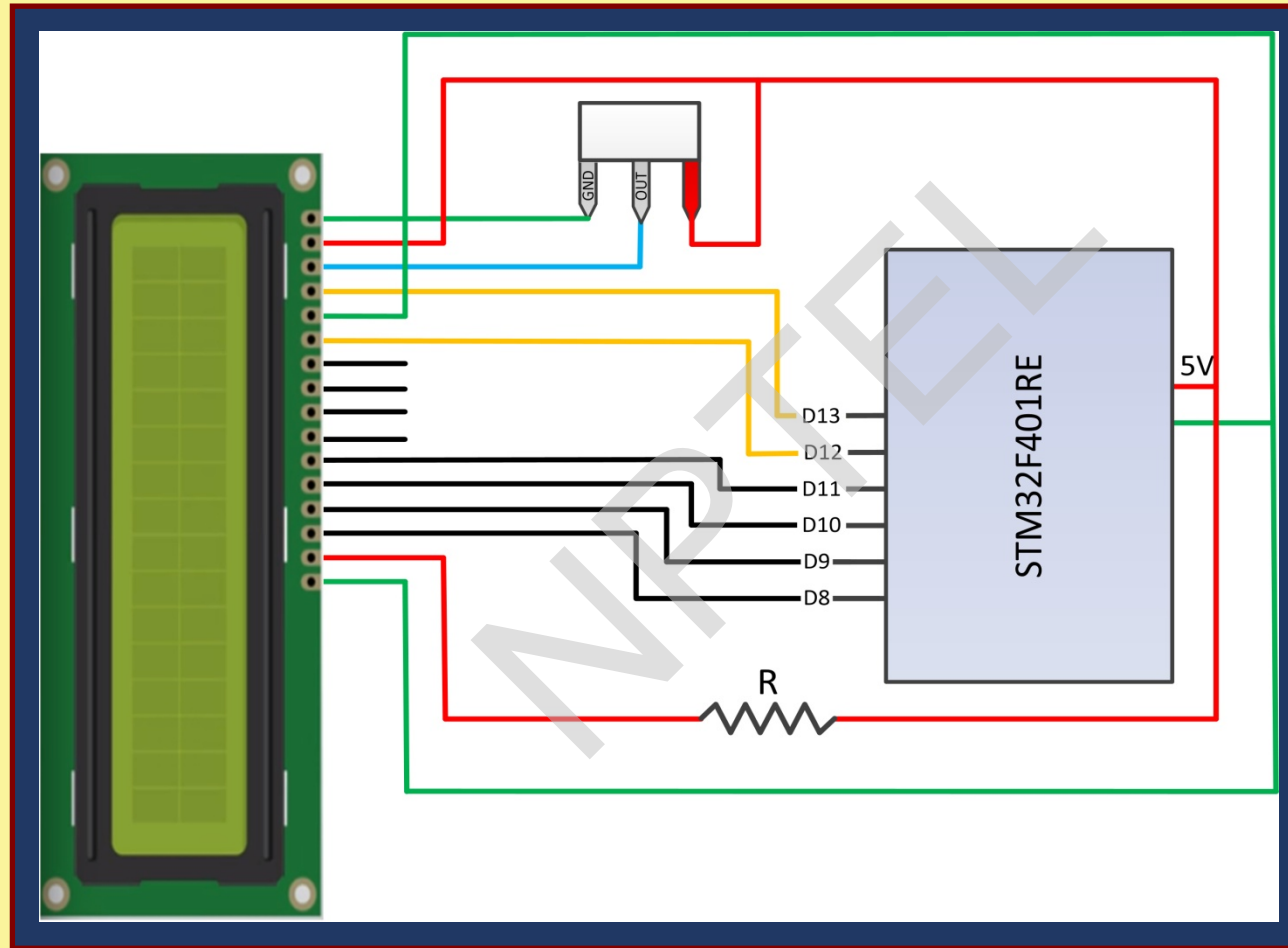
Mbed Code Requirement for 4-bit LCD Interfacing

- Include the libraries “*TextLCD.h*” and “*TextLCDScroll.h*”
 - First one acts as the LCD driver.
 - Second one allows various functionalities like display, scroll, etc.
 - The required control and data words are sent to the display unit in proper sequence.
- An object of *TextLCDScroll* class is first created, which takes 7 arguments:
 - Register Select pin RS in STM32
 - Data Enable pin EN in STM32
 - 4 data pins in STM32
 - LCD type – here we give “TextLCD::LCD16x2”

Basic Functions in the TextLCDScroll Class

- **cls()**
 - Used to clear the screen.
- **setSpeed (n)**, where $n \geq 1$
 - Used to set the scrolling speed of the text (text scroll per second).
- **setLine (line_number, "Text")**
 - Here line_number can be 0 or 1, and indicates first and second line respectively.
- If the number of characters displayed in each line exceeds 16, then the text will scroll through the screen.

Connection Diagram with STM32



An Example Mbed Code for STM32

```
#include "mbed.h"
#include "TextLCD.h"
#include "TextLCDScroll.h"
TextLCDScroll lcd(D13, D12, D11, D10, D9, D8, TextLCD::LCD16x2);
int main() {
    lcd.cls();
    lcd.setSpeed(1);
    while(1)
    {
        lcd.setLine(0, "EMBEDDED SYSTEM DESIGN");
        lcd.setLine(1, "NPTEL - 2018");
        wait(25);
    }
}
```



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**Lecture 16: Output Devices, Sensors and Actuators
(Part 2)**

CONCEPTS COVERED

- ☐ Working principle of speaker
- ☐ Working principle of LM35 temperature sensor
- ☐ Working principle of LDR
- ☐ Working principle of microphone

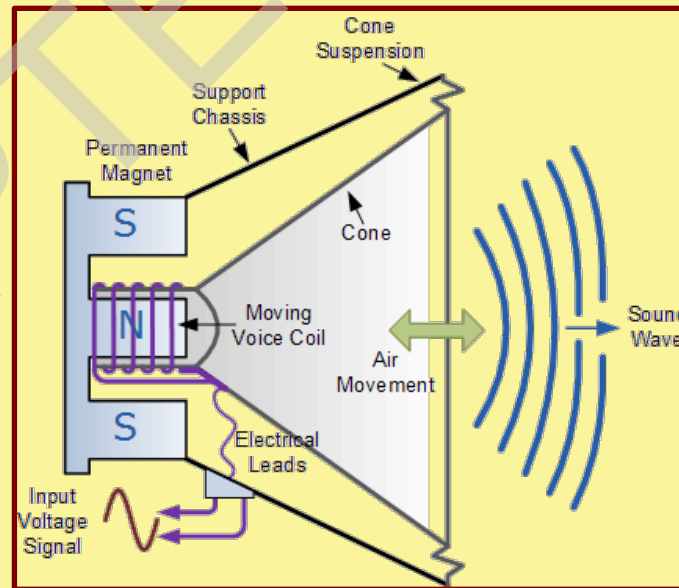
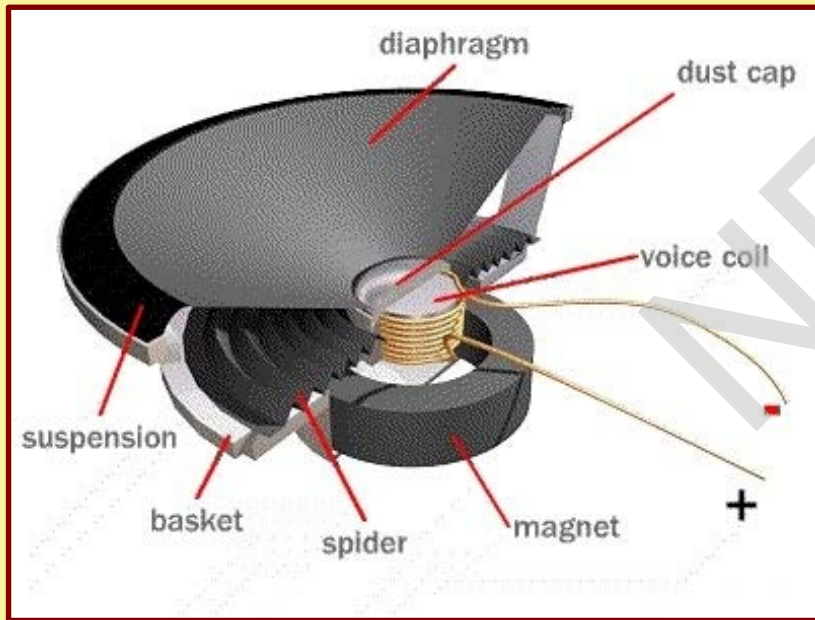


Output Device: Speaker

What is a Speaker?

- It is an electro-acoustic transducer, which converts an electrical audio signal into a corresponding sound.
- It consists of the following:
 - A permanent magnet that is fixed.
 - A movable electromagnet attached to a diaphragm.
- How it works?
 - When a current flows through the coil of the electromagnet, a magnetic field is produced in the direction determined by the polarity of the input signal.
 - The two magnets either attract or repel.

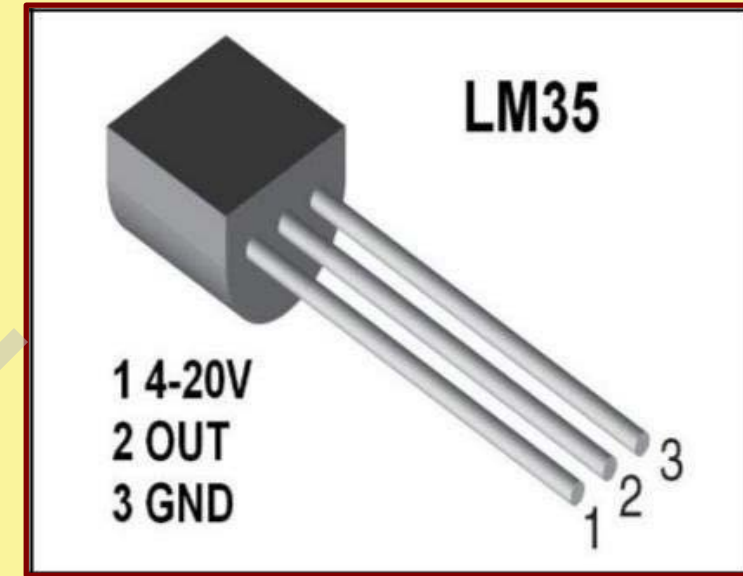
- Changes in the input audio signal.
 - The electromagnet experiences attractive and repulsive forces.
 - Causes the electromagnet (and diaphragm) to vibrate back and forth.
 - The frequency of the vibrations determine the pitch of the output sound produced.
 - An amplifier circuit can magnify the magnitude of vibrations.



Sensor: LM35 (Temperature)

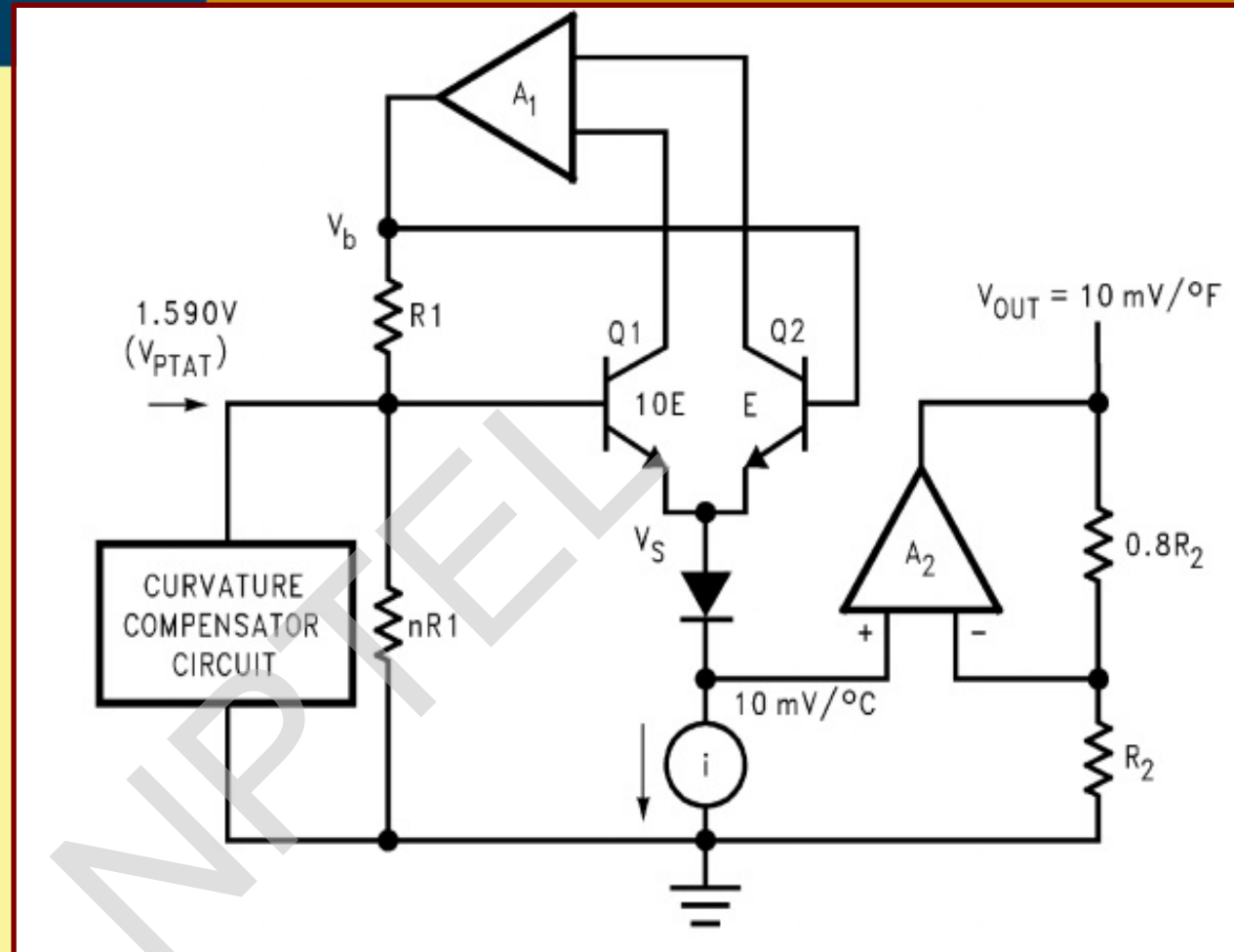
What is LM35?

- The LM35 series are precision integrated-circuit temperature sensors with an output voltage linearly proportional to the centigrade temperature.
 - Does not require any external calibration and provides accuracy of $\pm 0.25^{\circ}\text{C}$ at room temperature.
 - It is a low-power device, and draws only $60\mu\text{A}$ current from the power supply.
 - It can operate over the range -55°C to 150°C .
 - Operates for supply voltages from 4V to 20V.



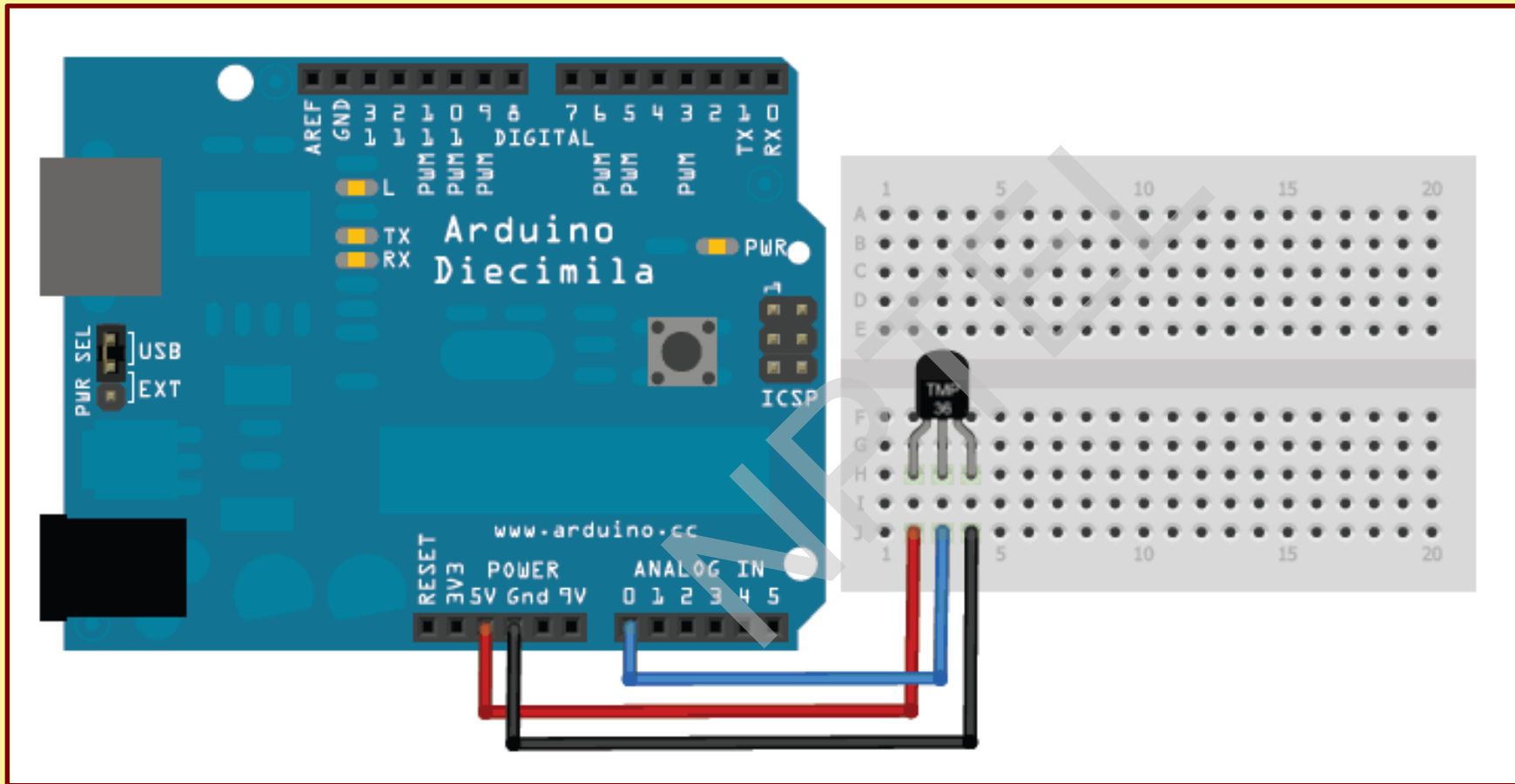
The analog output increases by 10mV for every degree rise in temperature

- There are two transistors, one with an emitter 10 times the area of the other.
- The voltage generated across $R1$ is proportional to the absolute temperature.
- The amplifier at the top ensures that the voltage at the base of the transistor $Q1$ is proportional to the absolute temperature.
- The amplifier on the right converts absolute temperature into Celsius.



Inside the LM35

Typical Interfacing to Ardiono UNO



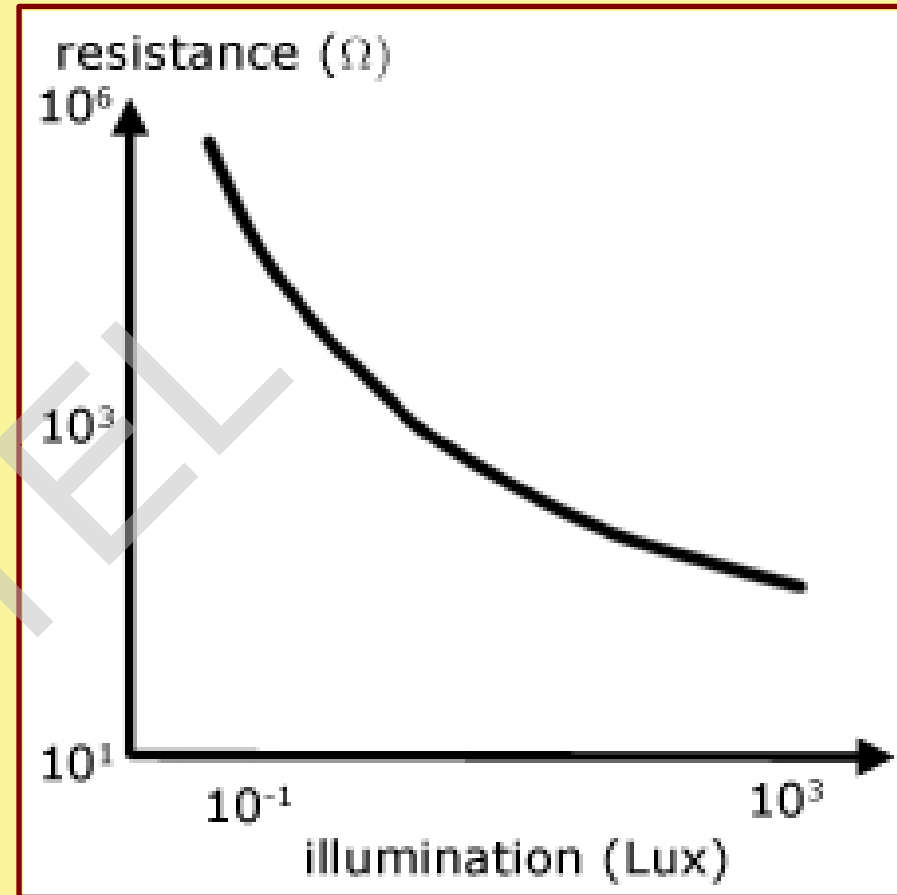
Sensor: LDR (Light)

What is Light Dependent Resistor (LDR)?



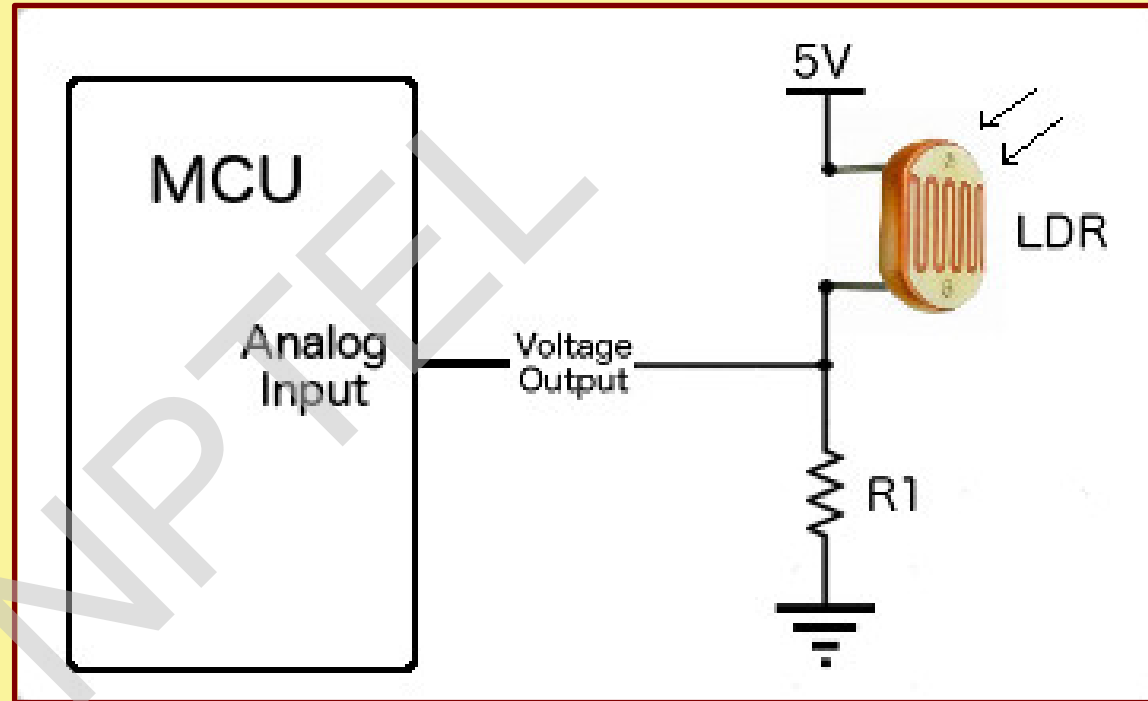
- A LDR or a photo-resistor is a device whose resistance is a function of the incident electromagnetic radiation.
- It is made up of semiconductor material having high resistance.
 - When light (photons) fall on the device, the electrons in the valence band of the semiconductor material are excited to the conduction band.
 - This results in an increase in the number of charge carriers.
 - Thus, the flow of current is increased, resulting in a decrease of resistance.

- The variation of resistance with incident light is non-linear.
 - May therefore require calibration.
- The change in resistance can be by an order of magnitude.
- When light is incident on a LDR, it usually takes 8-12 ms for the change in resistance to take place, while it takes one or more seconds for the resistance to rise back again to its initial value after removal of light.



How to Convert LDR Resistance to a Voltage?

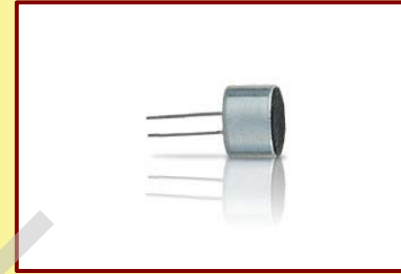
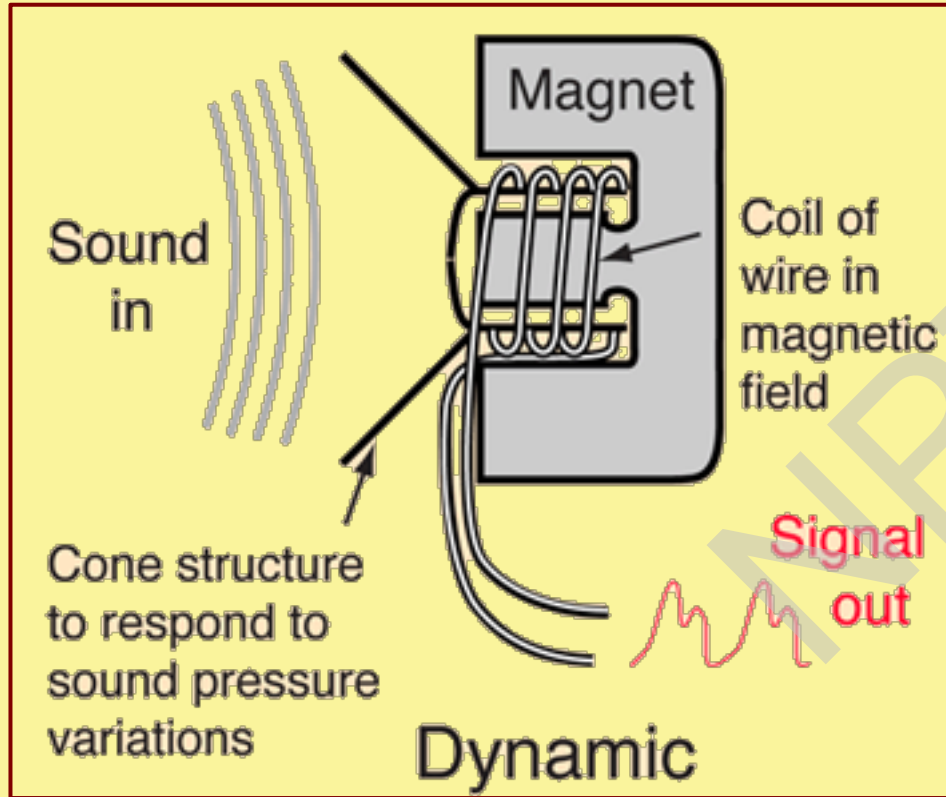
- The resistance $R1$ can be chosen suitably.
- The range of analog output voltages over the expected variation in light intensity must be estimated a priori.



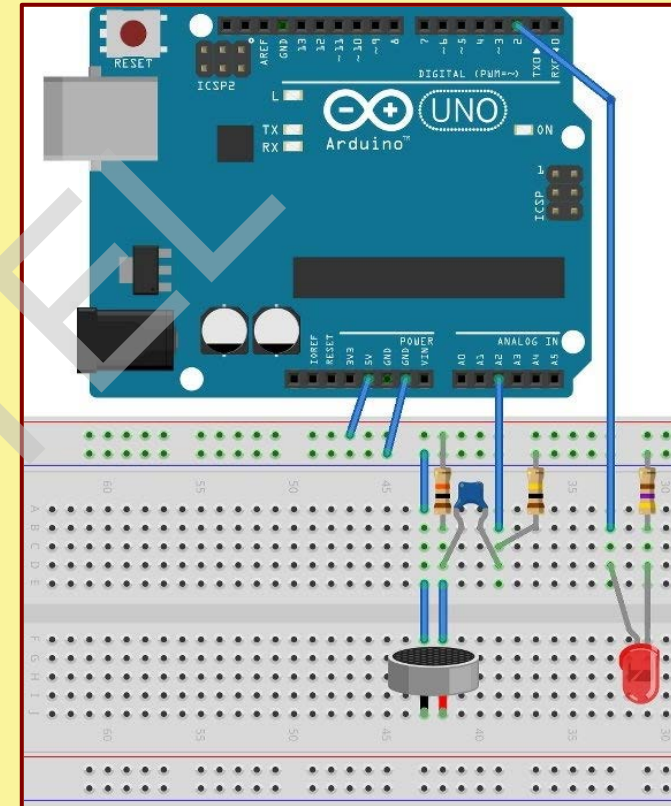
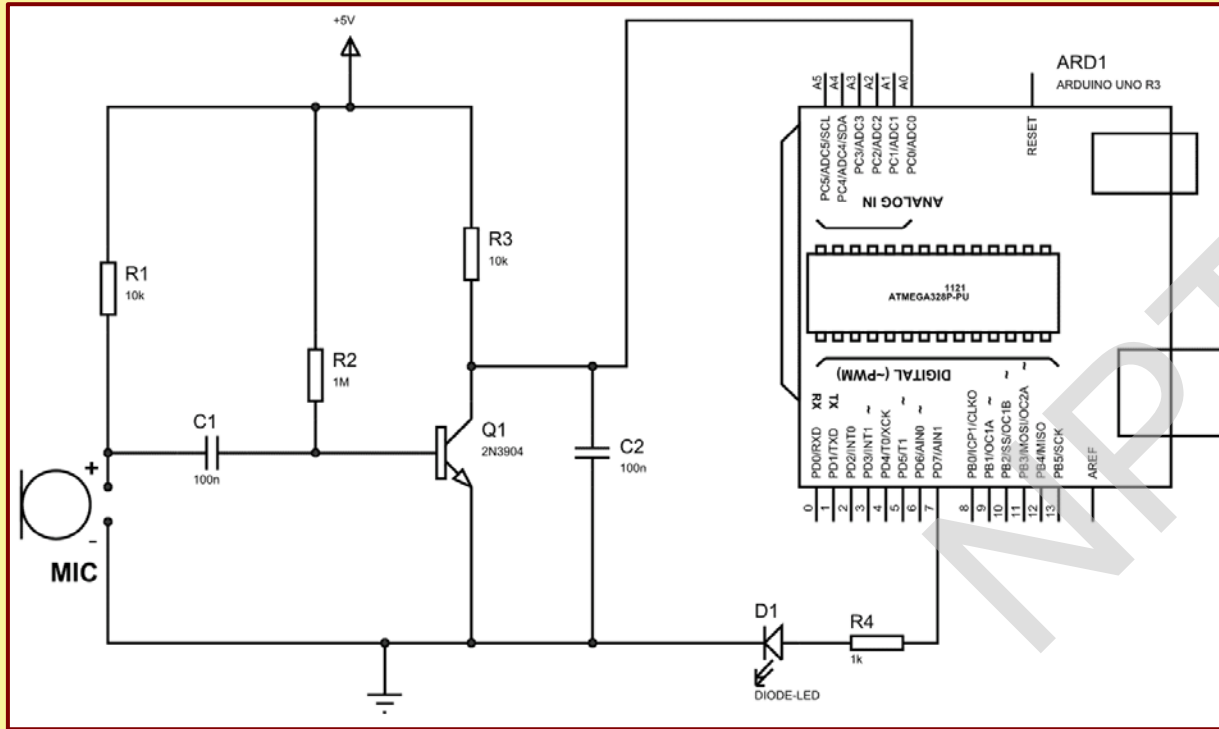
Sensor: Microphone (Sound)

What is a Microphone?

- A microphone is functionally the opposite of a speaker.
 - Converts sound waves into electrical signals.
 - Very similar in design to a speaker.
- How does a microphone work?
 - The diaphragm (much smaller as compared to a speaker) moves back and forth when the sound waves hit it.
 - The coil, attached to the diaphragm, also moves back and forth.
 - The permanent magnet produces a magnetic field that cuts through the coil. As the coil moves, an electric current flows through it.
 - Sound energy gets converted into electricity.



Interfacing a Microphone to Arduino UNO





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**Thank
you!**



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Course Name: Embedded System Design with ARM

Faculty Name: Prof. Indranil Sen Gupta

Department : Computer Science and Engineering

Topic

**Lecture 17: Output Devices, Sensors and Actuators
(Part 3)**

CONCEPTS COVERED

- ☐ Working principle of capacitive touch sensor
- ☐ Working principle of smoke sensor
- ☐ Working principle of electro-mechanical and solid-state relays



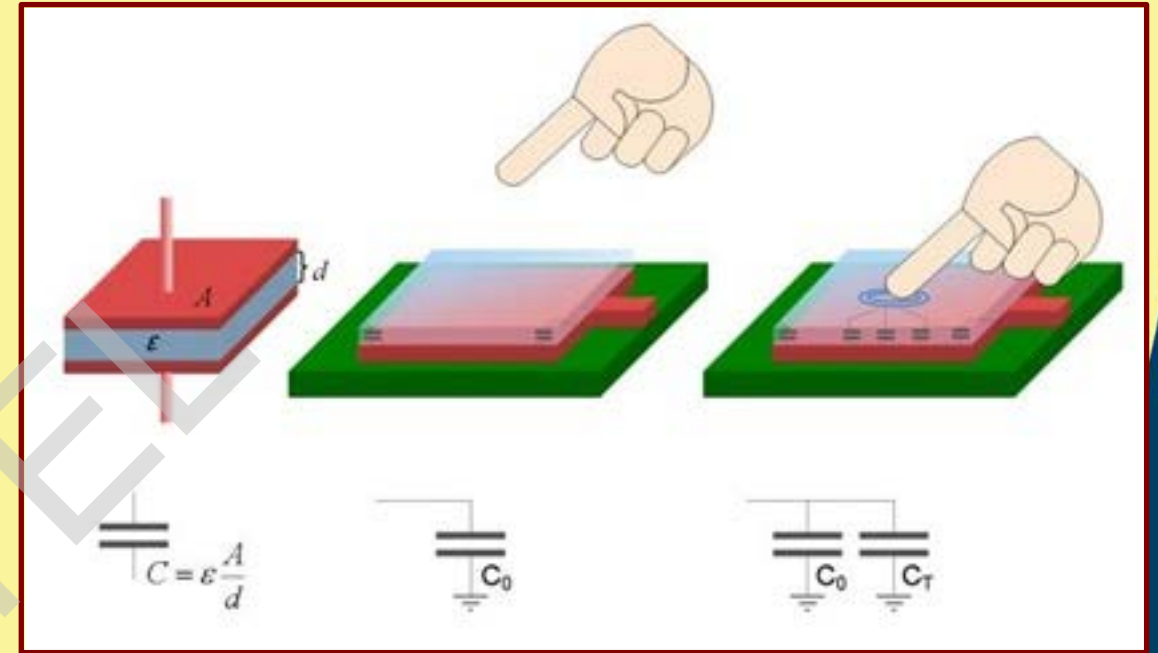
Sensor: Capacitive (Touch)

What is Capacitive Sensing?

- Capacitive sensing is a technology based on capacitive coupling, that can detect and measure anything that is conductive or has a dielectric different from air.
- The working of a touch sensor is similar to that of a simple switch.
 - When there is contact with the surface of the touch sensor, the circuit is closed inside the sensor and there is a flow of current.
 - When the contact is released, the circuit is opened and no current flows.
 - Two types: *capacitive* and *resistive*.
- Many applications in human interface devices:
 - Trackpads, touchscreens, touch switches, etc.

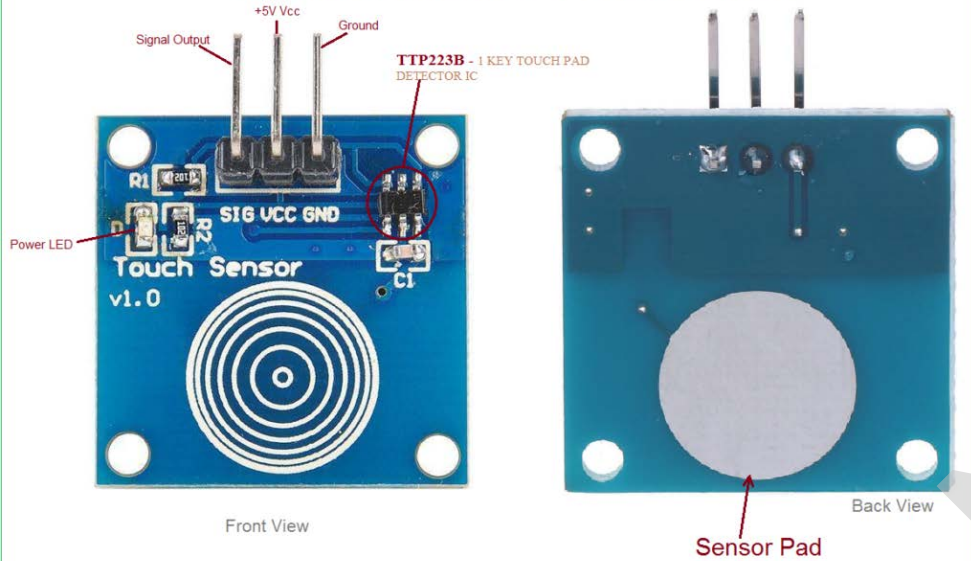
Principle of Operation

- The capacitance of a parallel plate capacitor = $\epsilon_0 * \epsilon_r * A / d$, where ϵ_0 is the permittivity of free space, ϵ_r is the relative permittivity of the dielectric material, A is the area of the plates, and d is the distance between them.
- The capacitance will increase if a conductive object touches or approaches the sensor electrode.



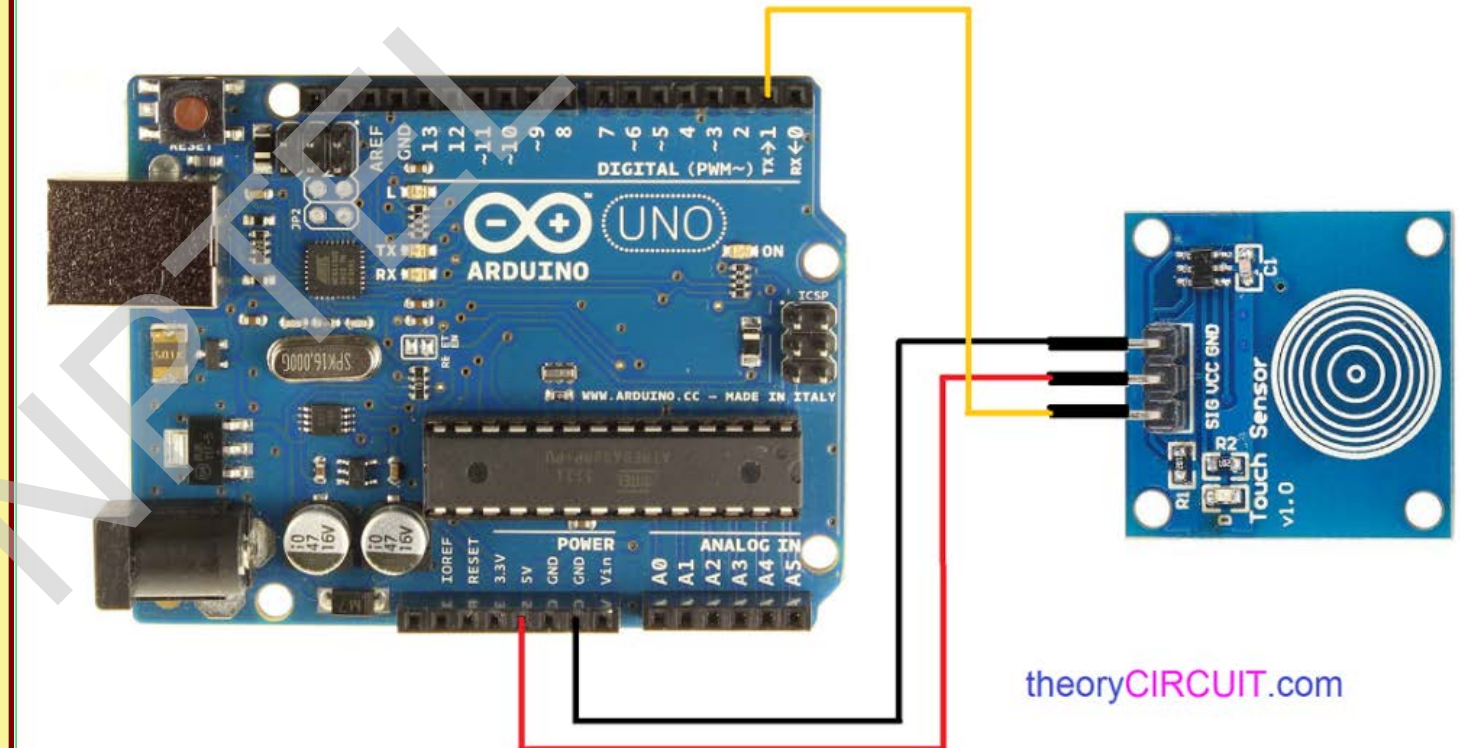
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Digital Capacitive Touch Sensor



Operating voltage: 2.0V – 5.5V
Response time: 60 – 220 ms

Digital Capacitive Touch Sensor arduino Interface



theoryCIRCUIT.com

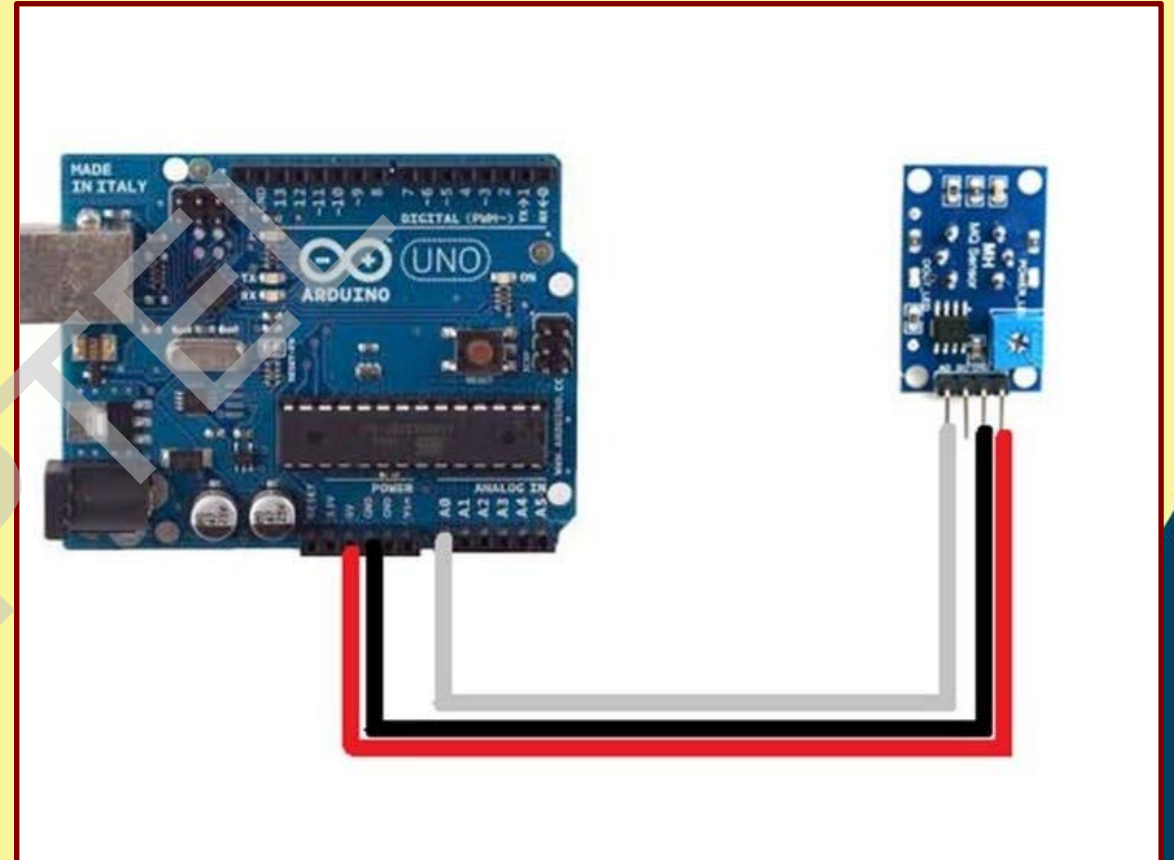
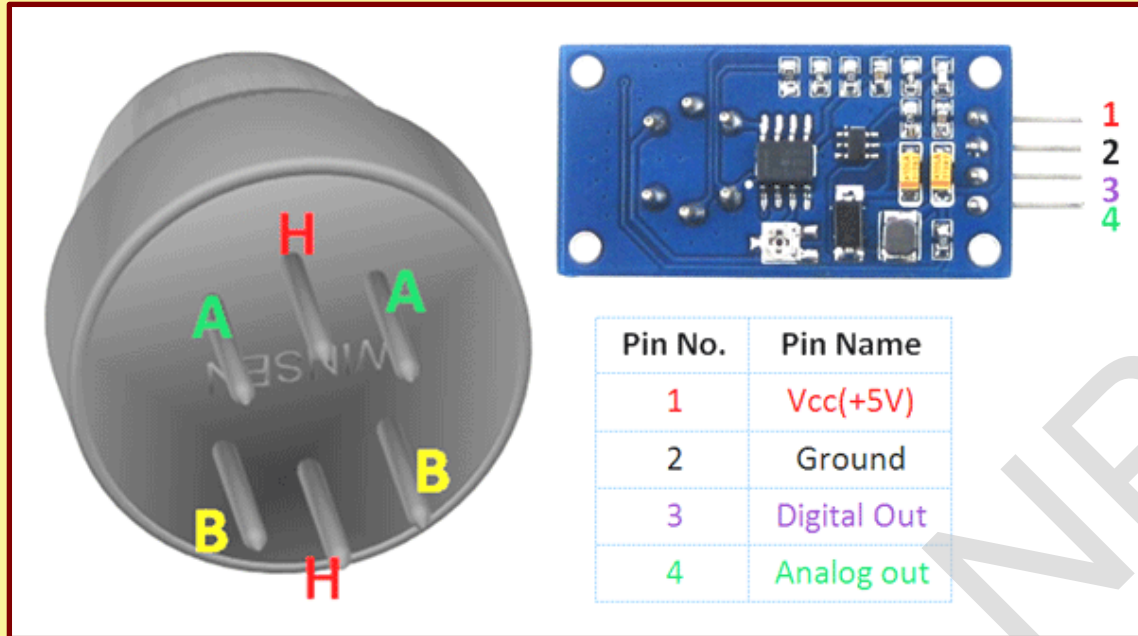
Sensor: Smoke

About the MQ135 Gas Sensor



- The MQ135 sensor is used to measure air quality.
 - Uses a small heater inside with an electrochemical sensor.
 - They are sensitive to a range of gases and are used indoors at room temperature.
 - It generates an analog voltage signal as output.
- What is there inside?
 - A layer of tin dioxide (SnO_2) inside aluminum oxide microtubes (measuring electrodes), and a heating element inside a tubular casing.
 - Has high sensitivity to Ammonia, Sulphide and Benzene steam, and also sensitive to other harmful gases.

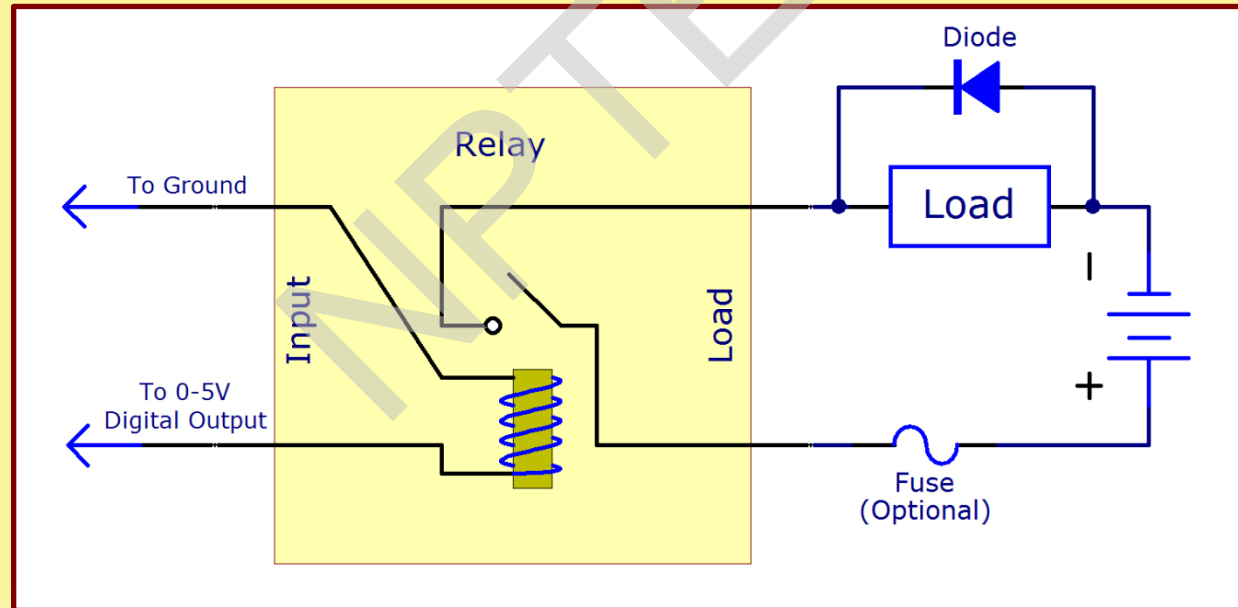
Interfacing with Arduino UNO



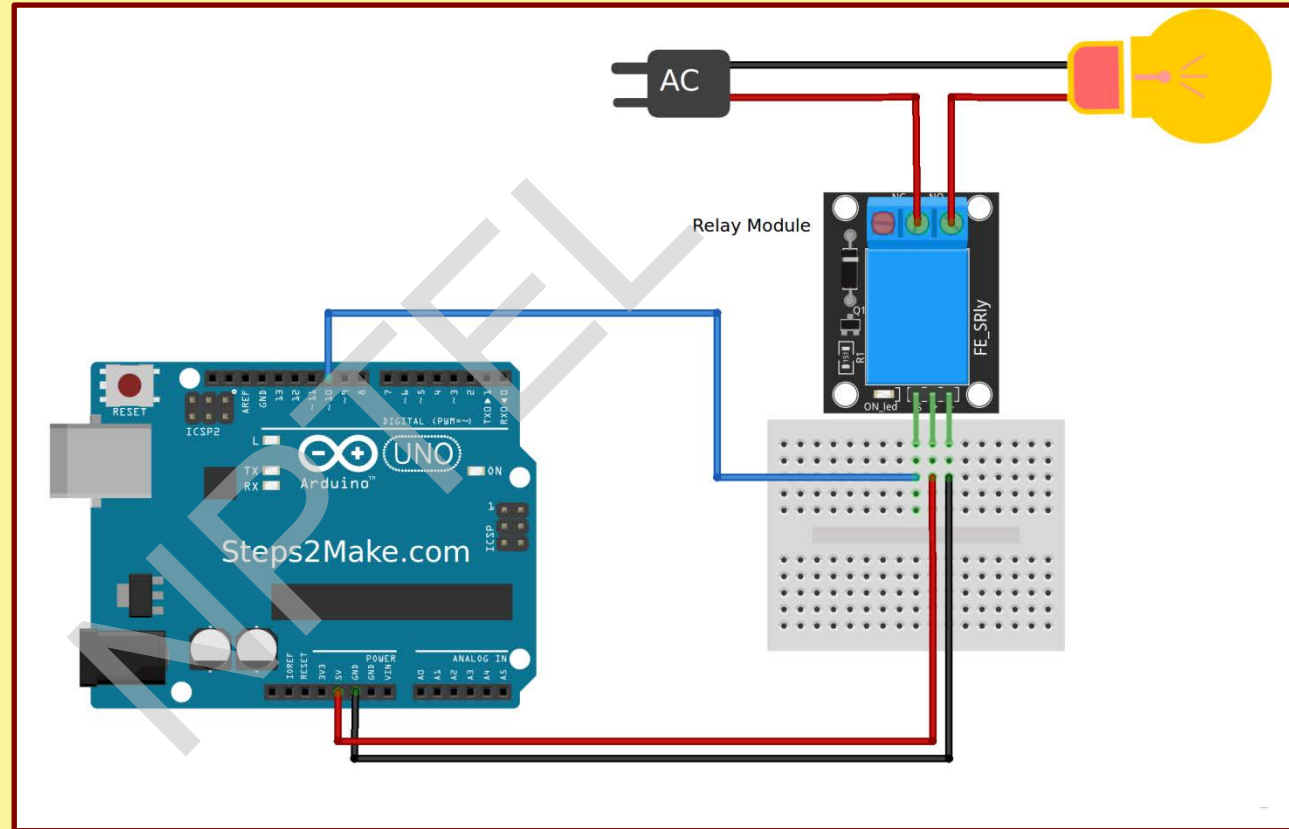
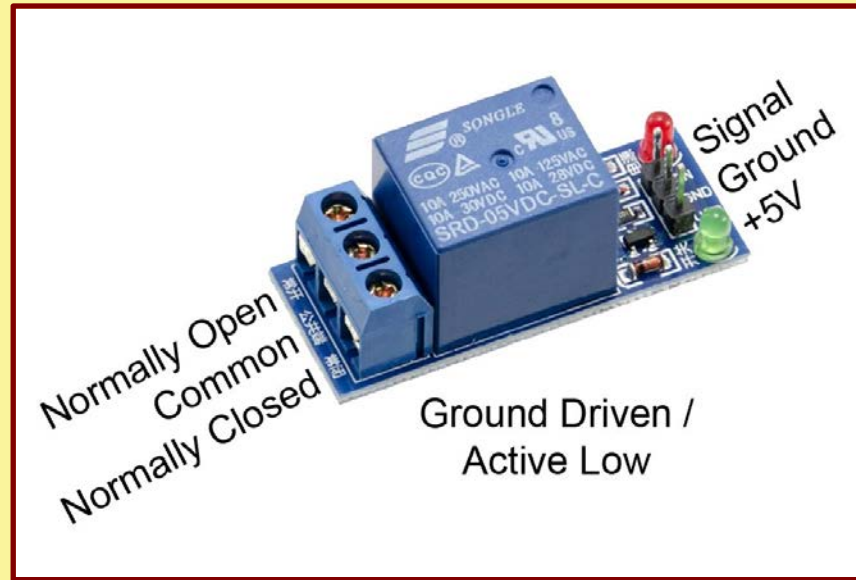
Actuator: Mechanical Relay

What is Mechanical Relay?

- It is a device that can turn on or turn off power supplied to another device.
 - For switching, we need to apply a small amount of power (to an electromagnet).
 - This allows high-power circuits to be controlled by low-power devices.



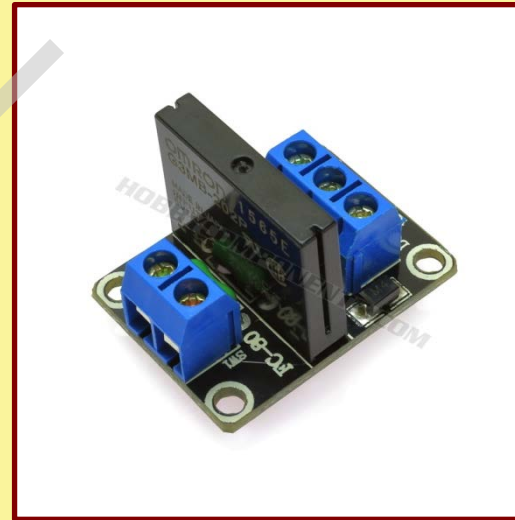
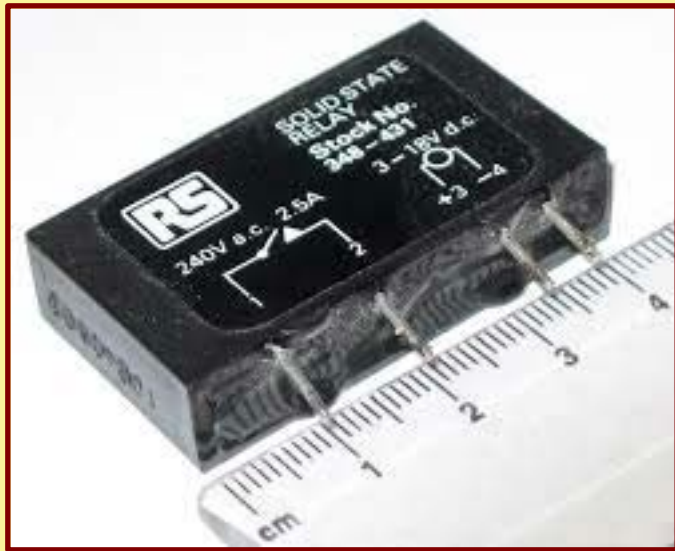
Interfacing with Arduino UNO



Actuator: Solid-state Relay

What is Solid-state Relay?

- It is an electronic switching device that switches ON or OFF when a small external voltage is applied across its control terminals.
- It consists of:
 - A sensor that responds to an appropriate input (control signal).
 - A solid-state electronic switching device that switches power to the load circuitry.
 - A coupling mechanism to enable the control signal to activate this switch.
- Similar to electromechanical relay in functionality, but no moving parts.
 - They use semiconductor devices like thyristors and power transistors.
 - Currents of 100's of amperes can be switched.





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Thank
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