Analog-to-Digital Converter (ADC)

Embedded System 2561, KU CSC

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Outline

1. Analog-to-Digital Conversion
2. Keywords
3. ADC Applications
4. Nyquist Sampling Theorem
5. ADC architecture
6. STM32F411 ADC Module

Learning Outcomes

1. Understanding analog-to-digital conversion
2. Using analog input with MCU
3. Reading analog-to-digital data

Analog-to-Digital Conversion : Terminology

Analog : continuously valued signal, such as temperature or speed, with infinite possible values in between

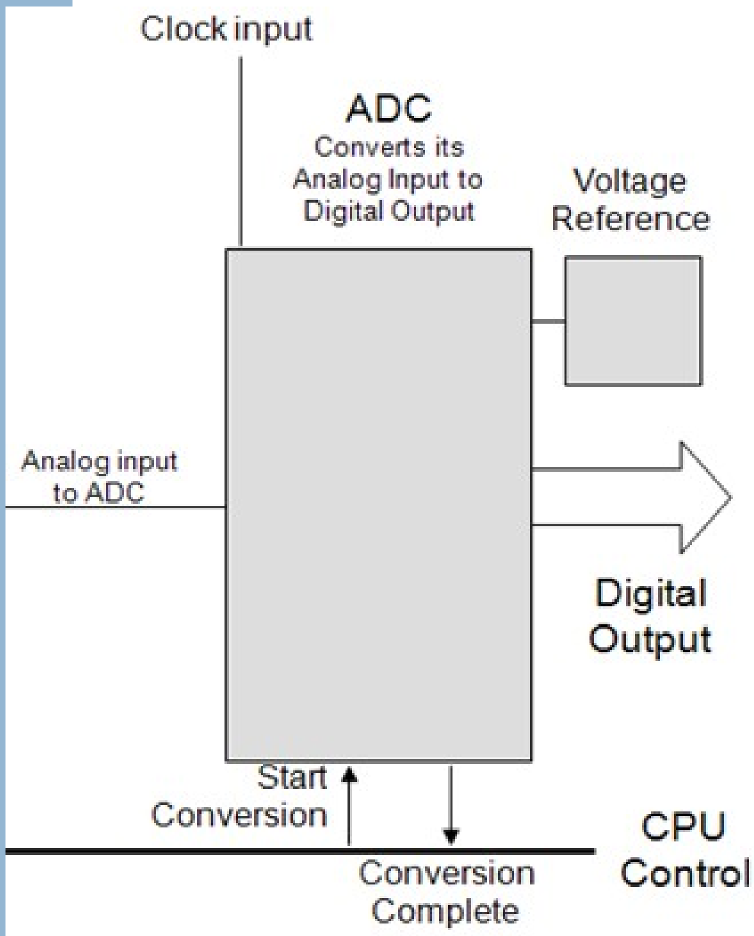
Digital : discretely valued signal, such as integers, encoded in binary

analog-to-digital converter: ADC, A/D, A2D; converts an analog signal to a digital signal

digital-to-analog converter: DAC, D/A, D2A

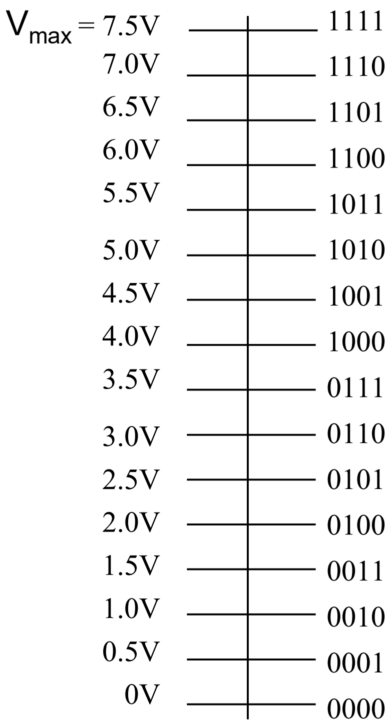
An embedded system's surroundings typically involve many analog signals.

Analog-to-Digital Converter

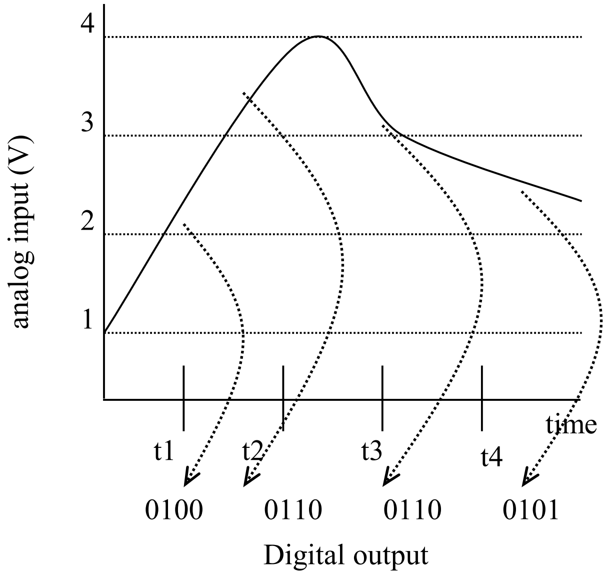


- ADC is an electronic circuit that measures the input voltage, and gives a binary output number proportional to its size.
- ADC compares an input voltage to a reference voltage.
- Conversion takes time (μs++), so the ADC needs to signal when it has finished.

Analog-to-digital converters

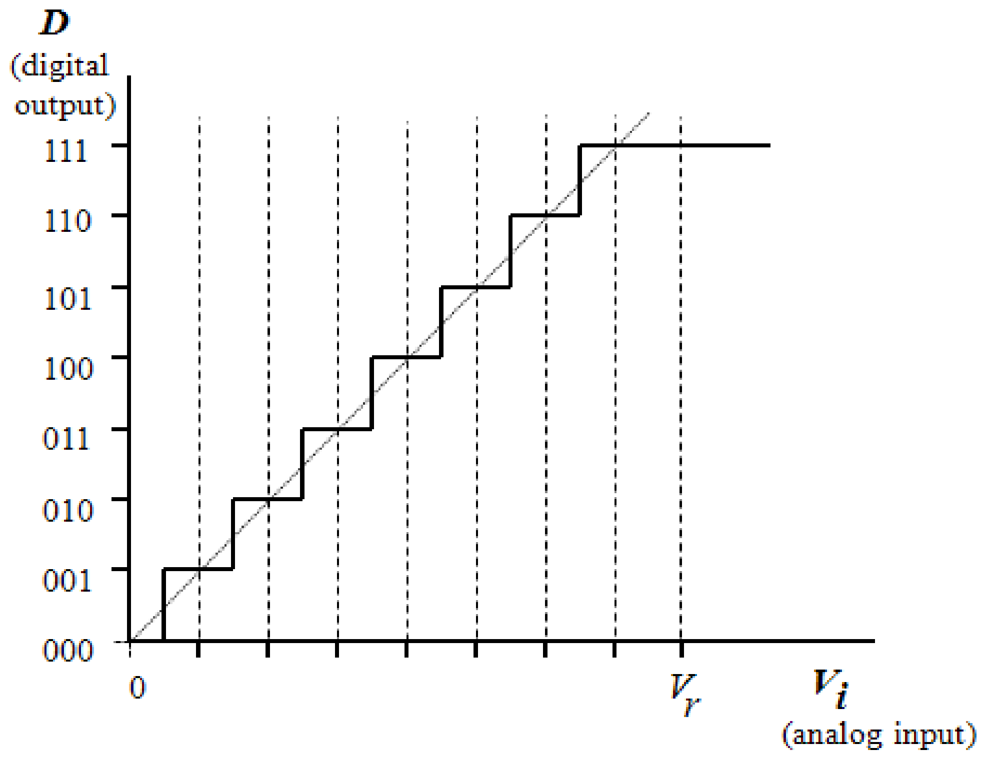


proportionality



analog to digital

Range, Resolution and Quantisation



$$D = \frac{V_i}{V_r} \, x \, 2^n$$

- The ADC action follows Equation
  - D : output binary number
  - n : bit number
  - V_i : input voltage
  - V_r : reference voltage
- The difference between the maximum and minimum input values is called the Range.
- many ADC circuits the range is equal to the reference voltage.

Proportional Signals

<u>Simple Equation</u>

Assume minimum voltage of 0 V.

Vmax = maximum voltage of the analog signal

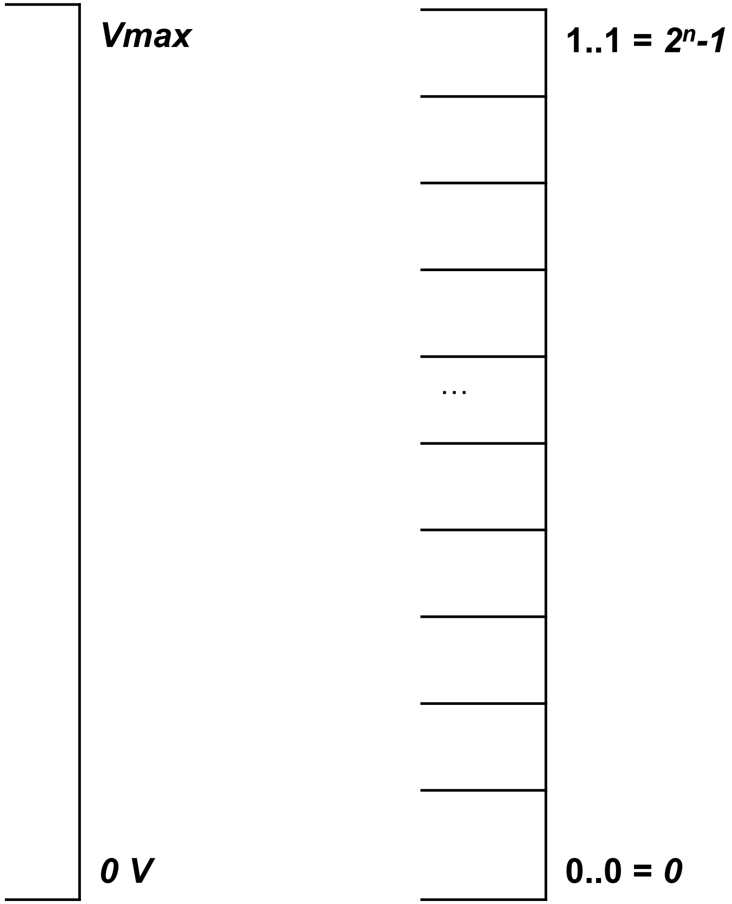
a = analog value

n = number of bits for digital encoding

- 2^n = number of digital codes
- *M* = number of steps, either 2^n or $2^n - 1$

d = digital encoding

$a / Vmax = d / M$



Resolution

Let $n = 2$

$\underline{M = 2^n - 1}$

3 steps on the digital scale

$d_0 = 0 = 0b00$

$d_{Vmax} = 3 = 0b11$

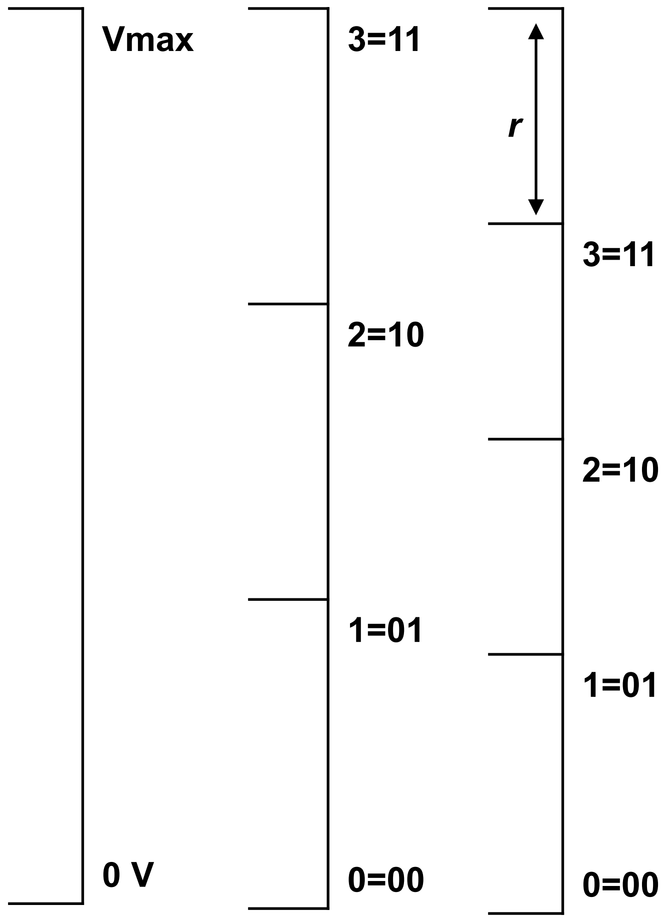
$\underline{M = 2^n}$

4 steps on the digital scale

$d_0 = 0 = 0b00$

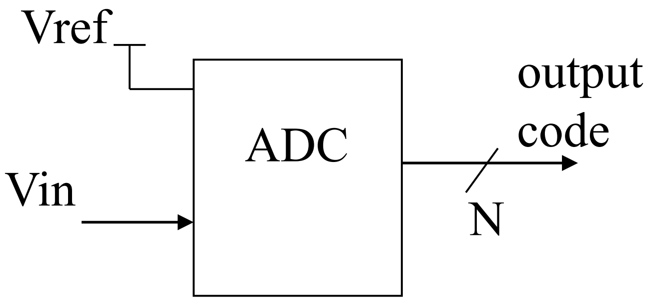
$d_{Vmax - r} = 3 = 0b11$ (no d_{Vmax})

***r*, resolution**: smallest analog change resulting from changing one bit



Resolution

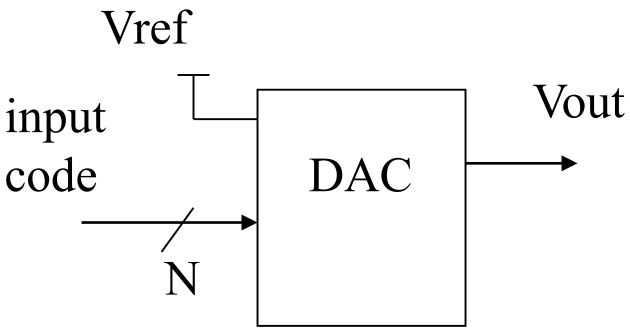
ADC: Vin = input voltage, Vref = reference voltage
N = number of bits of precision



$Vin / Vref * 2^N =$ output_code
output_code$/ 2^N * Vref = Vin$

1 LSB = $Vref/2^N$

DAC: Vout = output voltage, Vref = reference voltage,
N = number of bits of precision



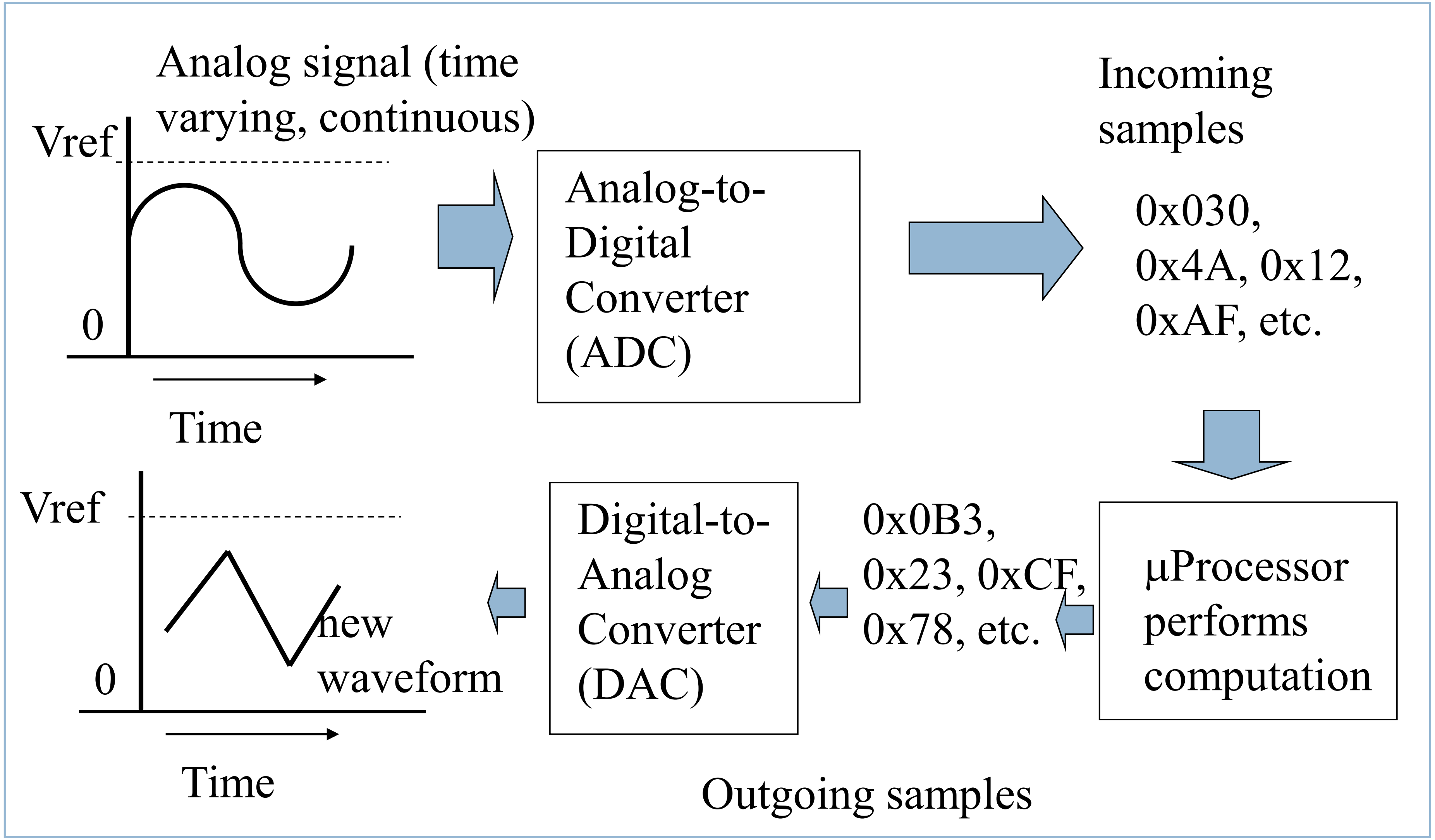
$Vout / Vref * 2^N =$ input_code
input_code$/ 2^N * Vref = Vout$

1 LSB = $Vref/2^N$

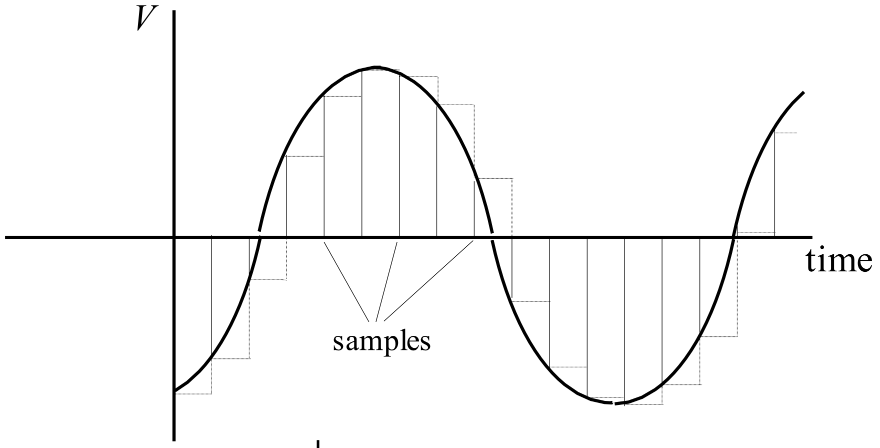
ADC Applications

- Data logging
- Audio
  - Speech recognition
  - special effects (reverb, noise cancellation, etc)
- Video
  - Filtering
  - Special effects
  - Compression

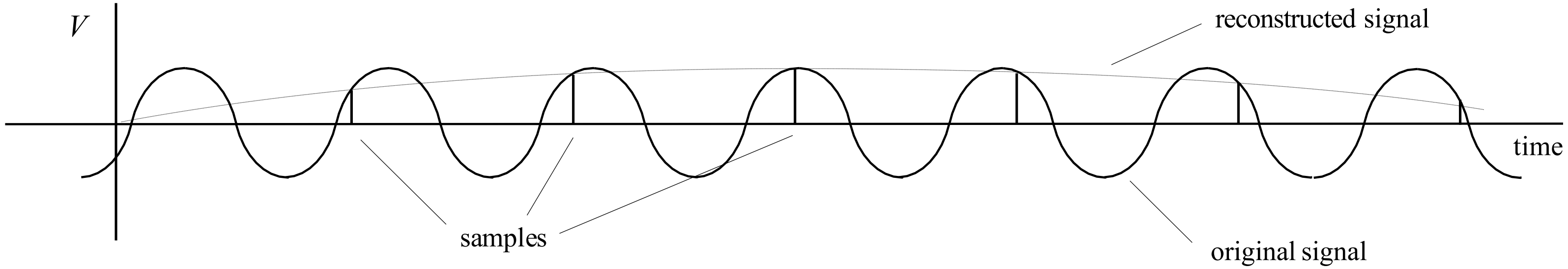
Digital Signal Processing



Sampling Frequency and Aliasing



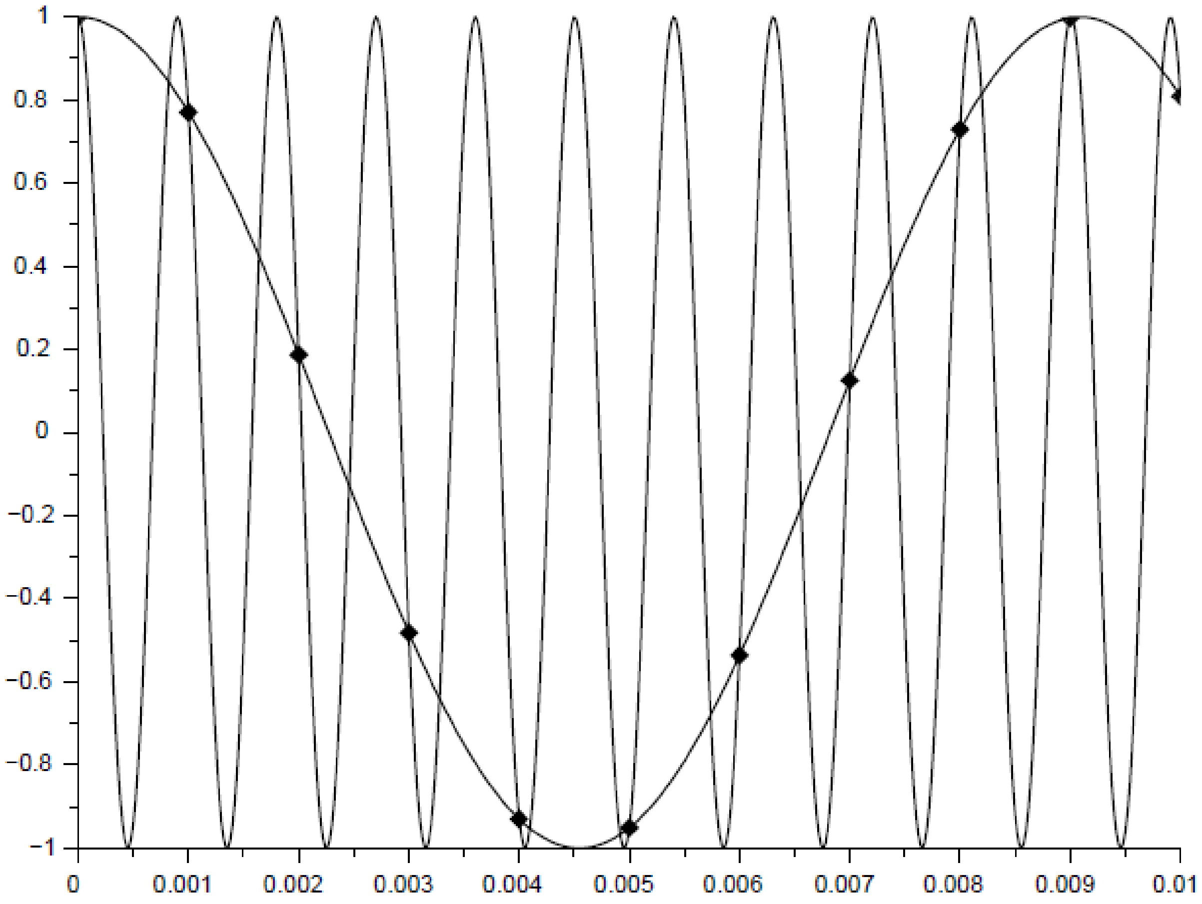
- Sample and quantise
- More samples more accurate the digital data
- sampling frequency



The Nyquist theorem (sampling theorem):

- Sampling frequency must be at least twice of the maximum signal frequency.
- If the sampling is less than twice, then *aliasing* occurs
- Aliasing : a new lower frequency signal.

Aliasing of Two Sinewaves



Sample ADC Computations

If Vref = 5V, and the 10-bit A/D output code is 0x12A, what is the ADC input voltage?

$$\text{output\_code}/2^N * \text{Vref} = (0x12A)/2^{10} * 5\text{ V}$$
$$= 298/1024 * 5\text{ V} = 1.46\text{ V (Vin)}$$

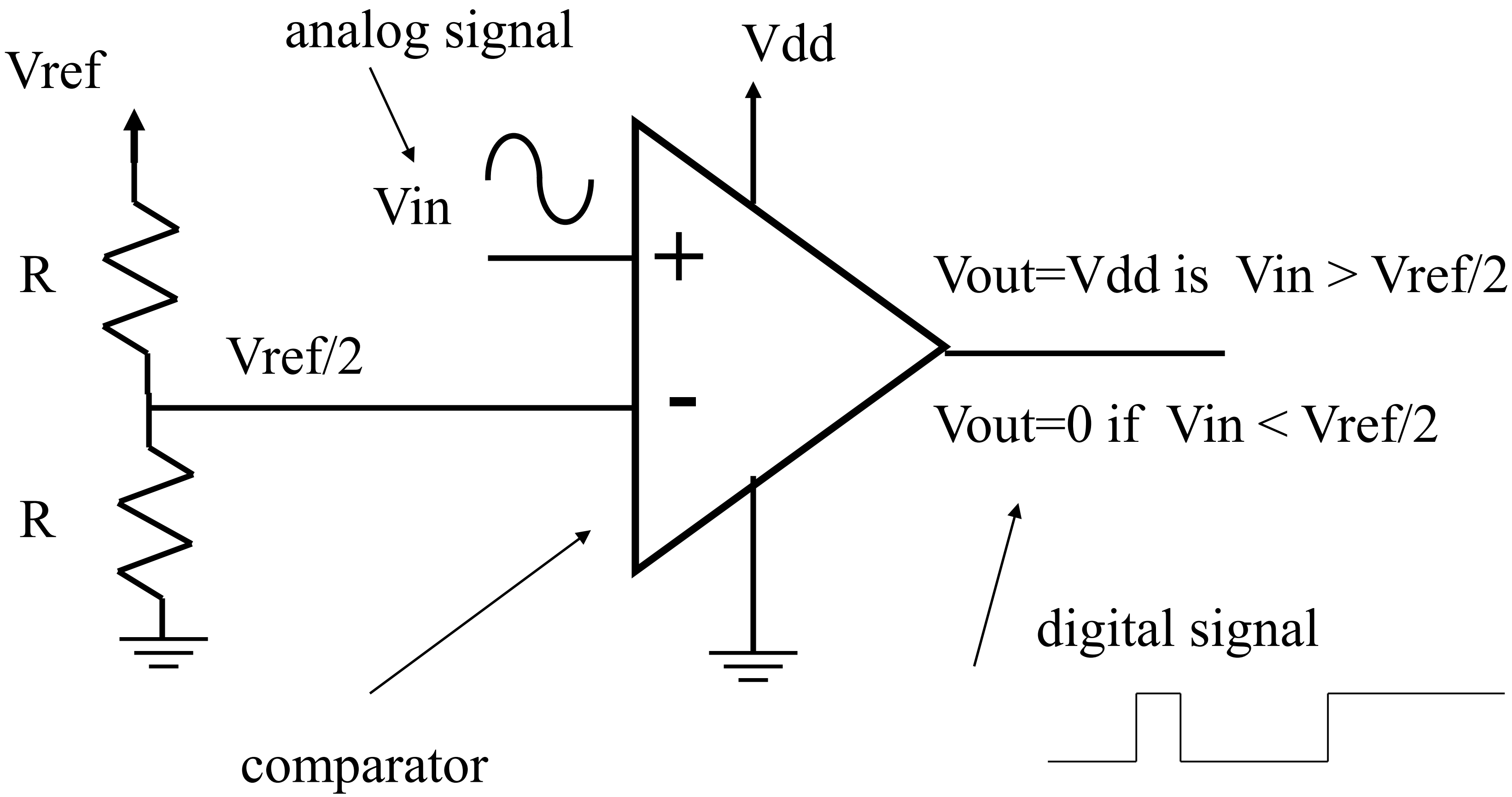
If Vref = 5V, and the upper 8 bits of the A/D output code is 0xA9, what is the ADC input voltage?

$$\text{output\_code}/2^N * \text{Vref} = (0xA9)/2^{8} * 5\text{ V}$$
$$= 169/256 * 5\text{ V} = 3.3\text{ V (Vin)}$$

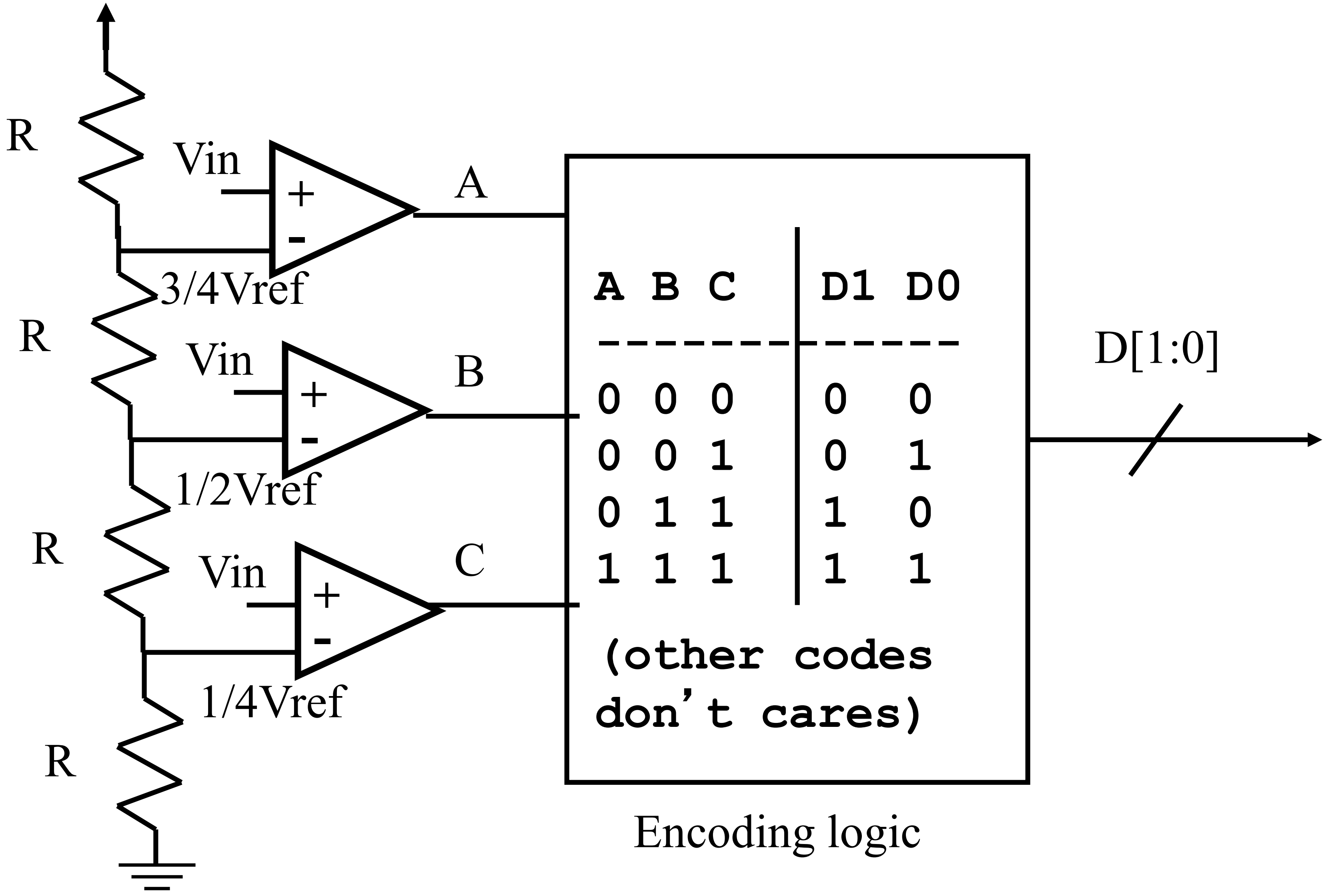
If Vref = 4V, and the A/D input voltage is 2.35 V, what is the ADC output code, upper 8-bits?

$$\text{Vin}/\text{Vref} * 2^{N} = 2.35\text{ V}/4\text{ V} * 2^8$$
$$= .5875 * 256 = 150.4 = 150 = 0x96$$

A 1-bit ADC


analog signal
Vdd
Vref
Vin
+
-
R
Vref/2
R
Vout=Vdd is Vin > Vref/2
Vout=0 if Vin < Vref/2
digital signal
comparator

A 2-bit ADC

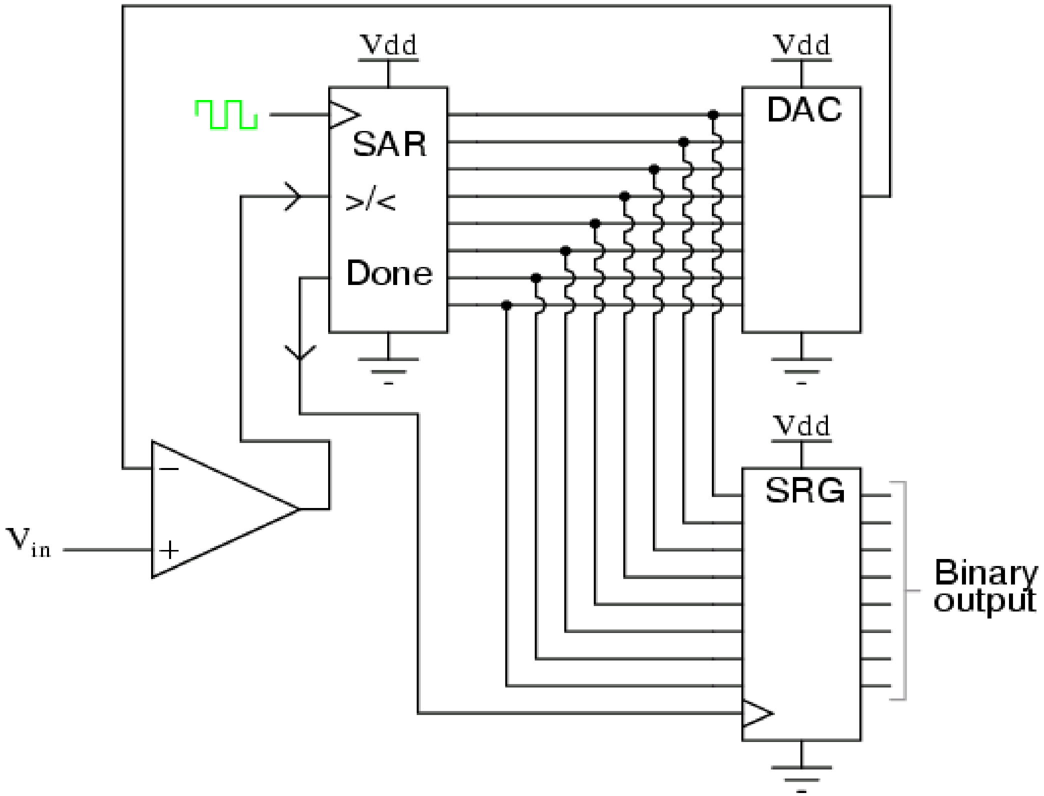

R
Vin
+
-
A
3/4Vref
R
Vin
B
1/2Vref
R
Vin
C
1/4Vref
R
A B C | D1 D0
0 0 0 | 0 0
0 0 1 | 0 1
0 1 1 | 1 0
1 1 1 | 1 1
(other codes don't cares)
D[1:0]
Encoding logic

ADC Architectures

- The previous architectures are called *Flash* ADCs
  - Fastest possible conversion time
  - Requires the most transistors of any architecture
  - N-bit converter requires 2^N-1 comparators.
  - Commercially available flash converters up to 12 bits.
  - Conversion done in one clock cycle

- *Successive approximation* ADCs
  - Use only one comparator
  - Take one clock cycle per bit
  - High precision (16-bit converters are available)

Successive Approximation ADC



Output is Q[N]

First, set DAC to produce Vref/2.

Output of Comparator is Q[N-1] (MSB)

If MSB =1 , then Vin between Vref and Vref/2, so set DAC to produce ¾ Vref.

If MSB=0, then Vin between Vref/2 and 0, so set DAC to ½ Vref.

Output of comparator is now Q[N-2].

Do this for each bit.

Takes N cycles.

ADC using successive approximation

- Given an analog input signal whose voltage should range from 0 to 15 volts, and an 8-bit digital encoding, calculate the correct encoding for 5 volts. Then trace the successive-approximation approach to find the correct encoding.
- Assume $M = 2^n - 1$

$$a / Vmax = d / M$$

$$5 / 15 = d / (256 - 1)$$

$d = 85$ or binary 01010101

ADC using successive approximation

Step 1-4: determine bits 0-3

$\frac{1}{2}(V_{max} - V_{min}) = 7.5$ volts
$V_{max} = 7.5$ volts.

0	0	0	0	0	0	0	0

$\frac{1}{2}(7.5 + 0) = 3.75$ volts
$V_{min} = 3.75$ volts.

0	1	0	0	0	0	0	0

$\frac{1}{2}(7.5 + 3.75) = 5.63$ volts
$V_{max} = 5.63$ volts

0	1	0	0	0	0	0	0

$\frac{1}{2}(5.63 + 3.75) = 4.69$ volts
$V_{min} = 4.69$ volts.

0	1	0	1	0	0	0	0

ADC using successive approximation

Step 5-8: Determine bits 4-7

$\frac{1}{2}(5.63 + 4.69) = 5.16$ volts
$V_{max} = 5.16$ volts.

0	1	0	1	0	0	0	0

$\frac{1}{2}(5.16 + 4.69) = 4.93$ volts
$V_{min} = 4.93$ volts.

0	1	0	1	0	1	0	0

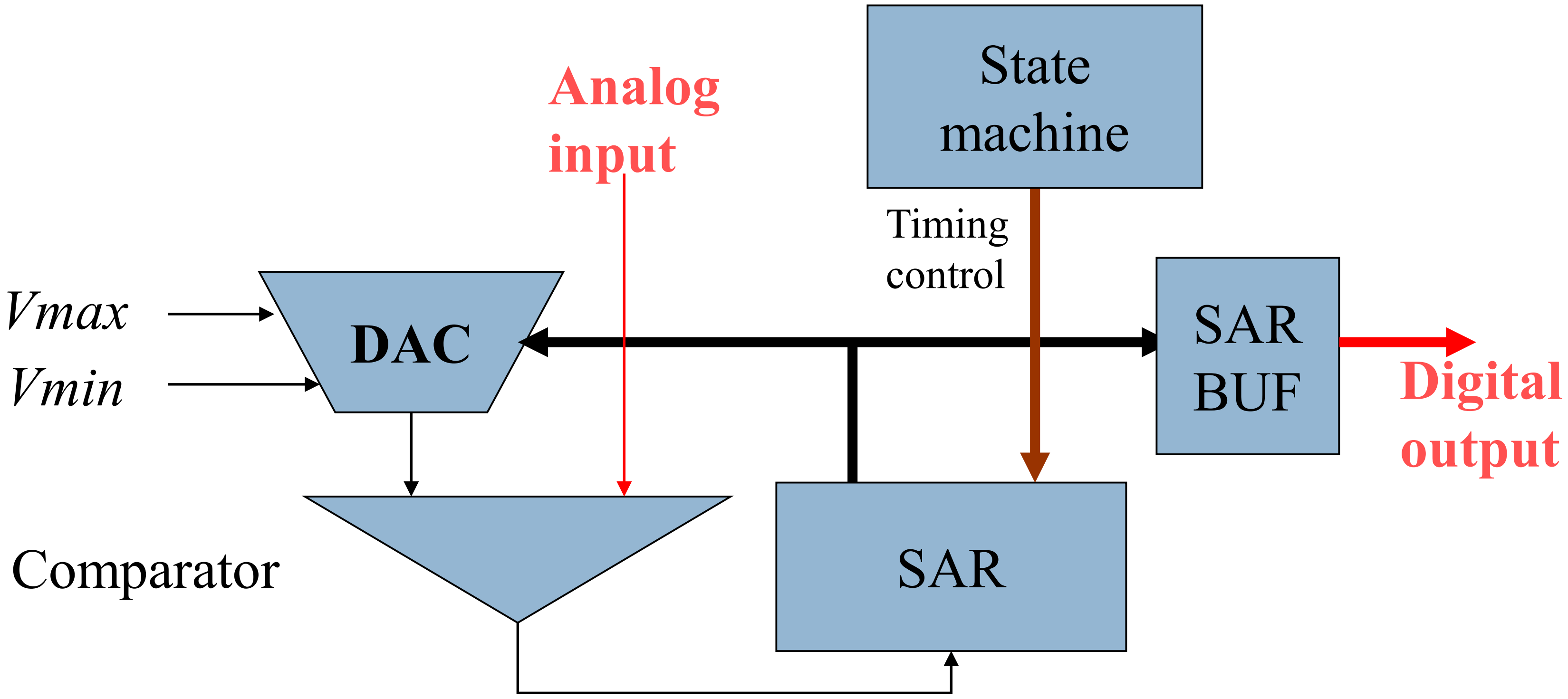
$\frac{1}{2}(5.16 + 4.93) = 5.05$ volts
$V_{max} = 5.05$ volts.

0	1	0	1	0	1	0	0

$\frac{1}{2}(5.05 + 4.93) =$
4.99 volts

0	1	0	1	0	1	0	1

Constructing ADC



SAR: Successive approximation register

STM32F411 ADC Module

- 12-bit ADC is a successive approximation analog-to-digital converter
- A/D conversion of the channels can be performed in single, continuous, scan or discontinuous mode.
- The result of the ADC is stored into a left or right-aligned 16-bit data register.

STM32F411 ADC Features

- 12-bit, 10-bit, 8-bit or 6-bit configurable resolution
- Interrupt generation at the end of conversion
- Single and continuous conversion modes
- Regular and Injection mode
- Data alignment with in-built data coherency
- ADC supply requirements: 2.4 V to 3.6 V at full speed and down to 1.8 V at slower speed
- ADC input range: VREF– ≤ VIN ≤ VREF+

Examples of Conversion Mode

Figure 4. Single-channel, continuous conversion mode

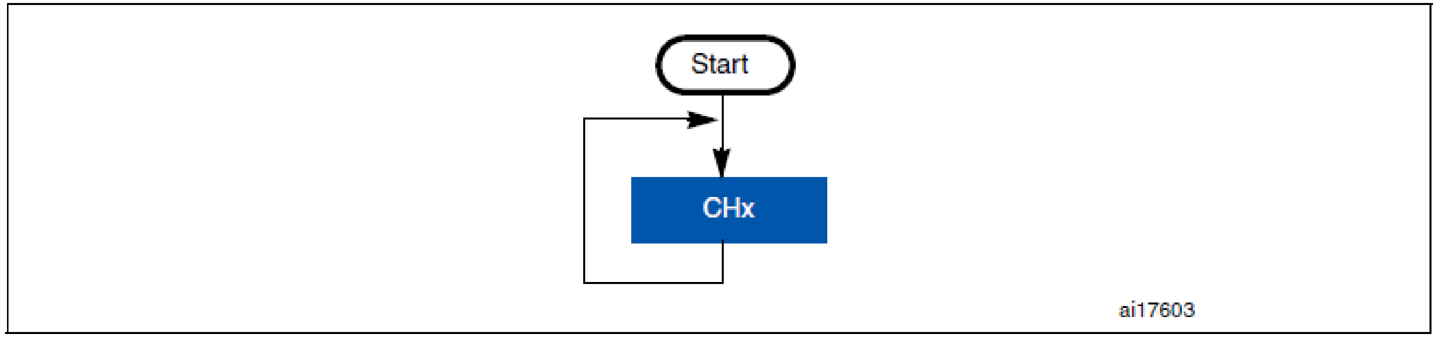
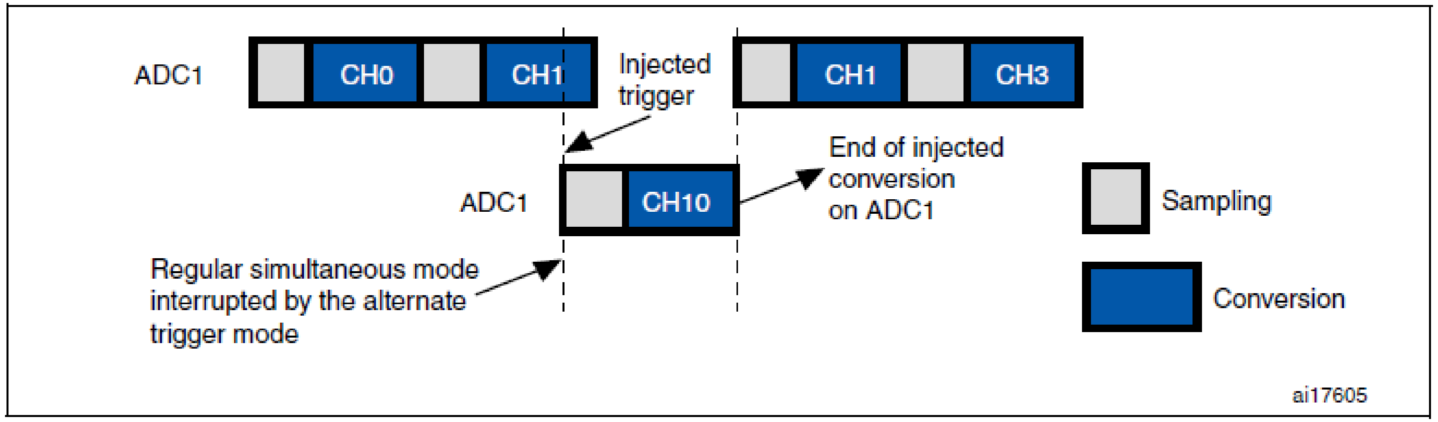
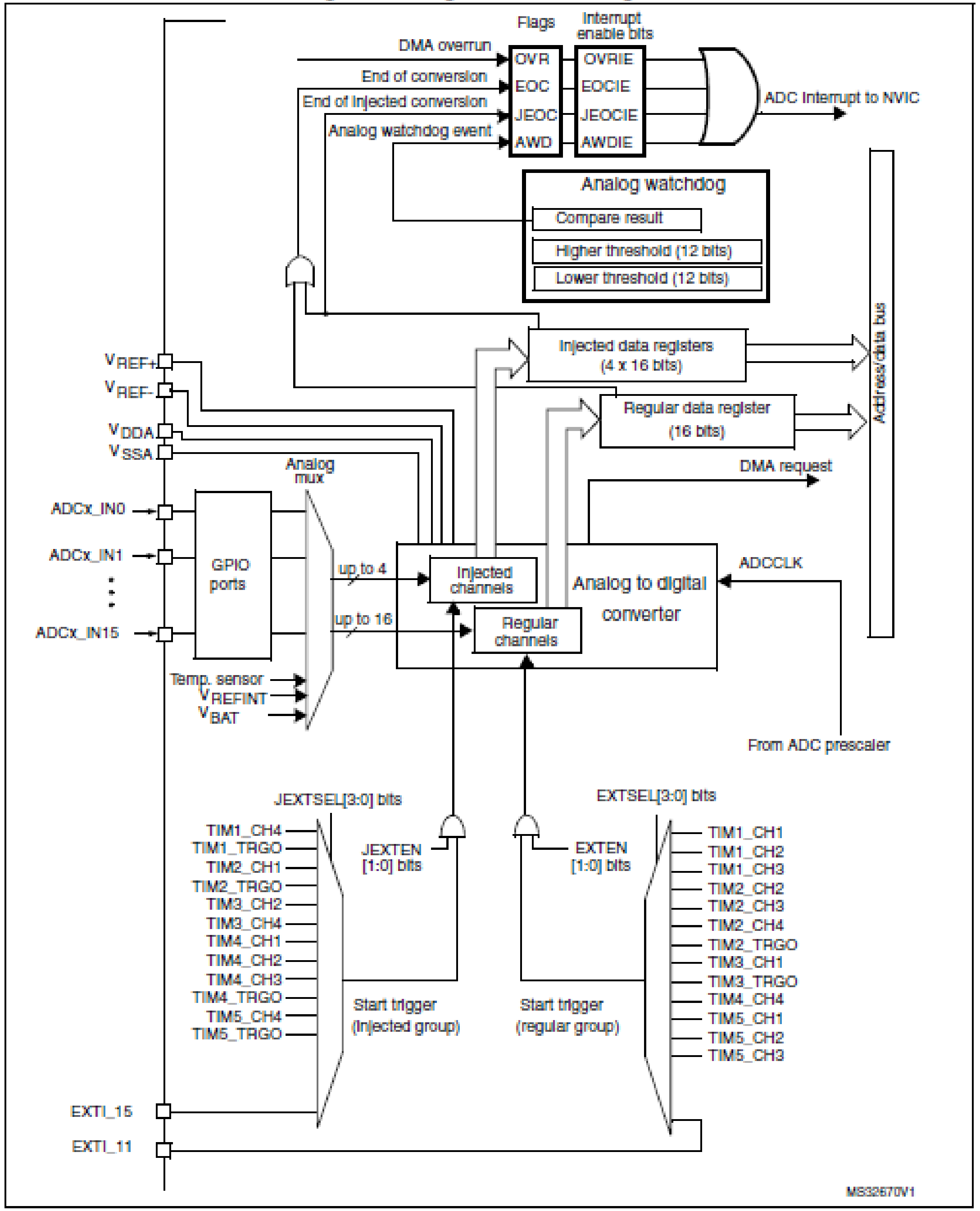


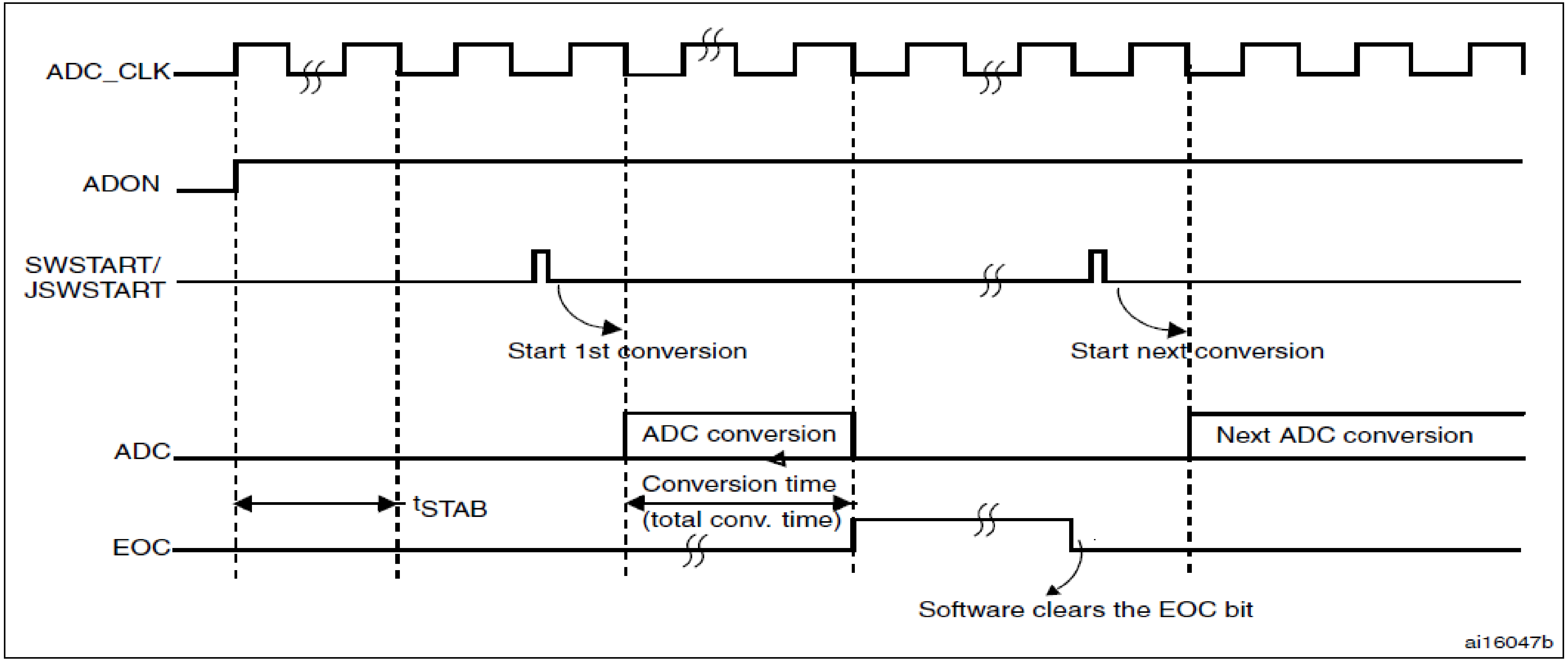
Figure 6. Injected conversion mode



ADC Block Diagram



ADC Timing Diagram



Data Alignment

Figure 35. Right alignment of 12-bit data

Injected group	SEXT	SEXT	SEXT	SEXT	D11	D10	D9	D8	D7	D6	D5	D4	D3	D2	D1	D0
Regular group	0	0	0	0	D11	D10	D9	D8	D7	D6	D5	D4	D3	D2	D1	D0

ai16050

Figure 36. Left alignment of 12-bit data

Injected group	SEXT	D11	D10	D9	D8	D7	D6	D5	D4	D3	D2	D1	D0	0	0	0
Regular group	D11	D10	D9	D8	D7	D6	D5	D4	D3	D2	D1	D0	0	0	0	0

ai16051

Figure 37. Left alignment of 6-bit data

Injected group	SEXT	SEXT	SEXT	SEXT	SEXT	SEXT	SEXT	SEXT	SEXT	D5	D4	D3	D2	D1	D0	0
Regular group	0	0	0	0	0	0	0	0	D5	D4	D3	D2	D1	D0	0	0

ai16052

11.12.14 ADC regular data register (ADC_DR)

Address offset: 0x4C

Reset value: 0x0000 0000

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16
Reserved															
15	**14**	**13**	**12**	**11**	**10**	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**	**0**
DATA[15:0]															
r	r	r	r	r	r	r	r	r	r	r	r	r	r	r	r

Bits 31:16 Reserved, must be kept at reset value.

Bits 15:0 **DATA[15:0]:** Regular data

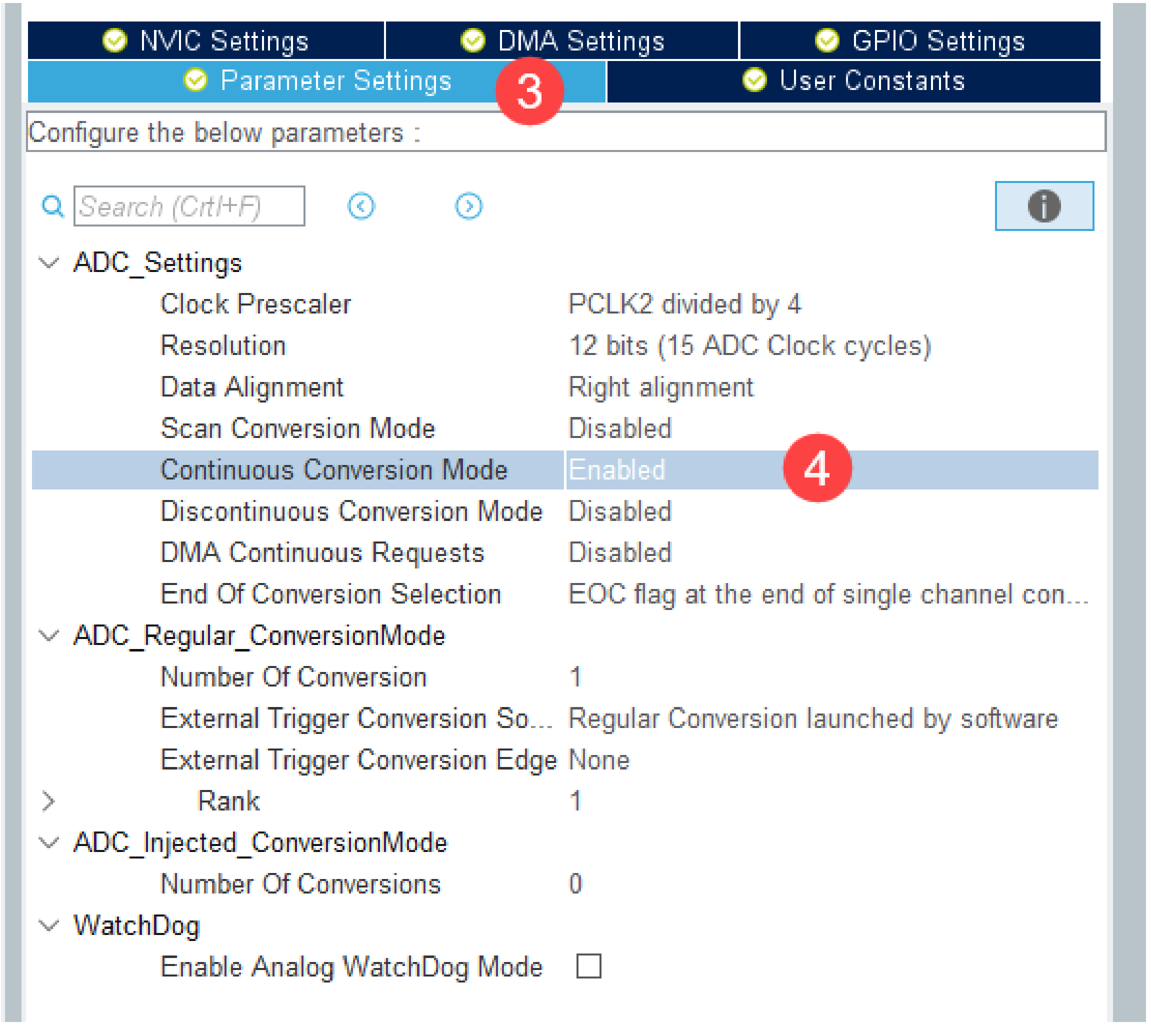
These bits are read-only. They contain the conversion result from the regular channels. The data are left- or right-aligned as shown in *Figure 35* and *Figure 36*.

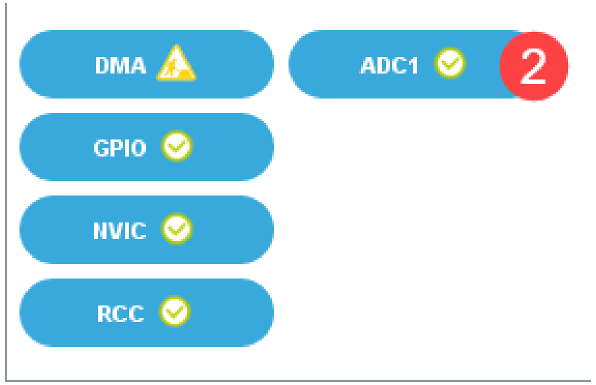
```
volatile uint32_t adc_val = 0;

HAL_ADC_Start(&hadc1);
```

```
while (1){
  while ( HAL_ADC_PollForConversion(&hadc1, 100) != HAL_OK ){}
  adc_val = HAL_ADC_GetValue(&hadc1);
}
```

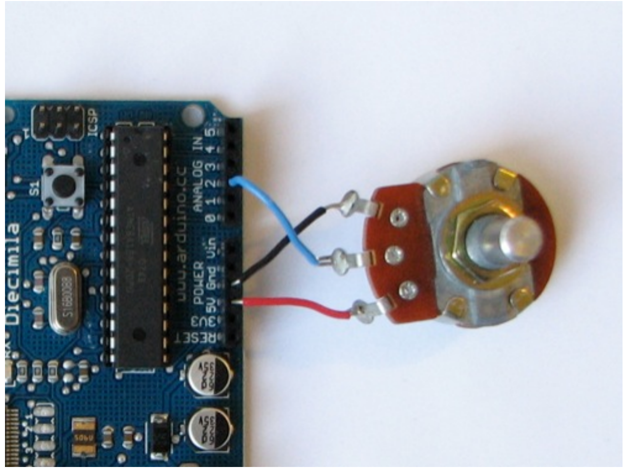
ADC Configuration

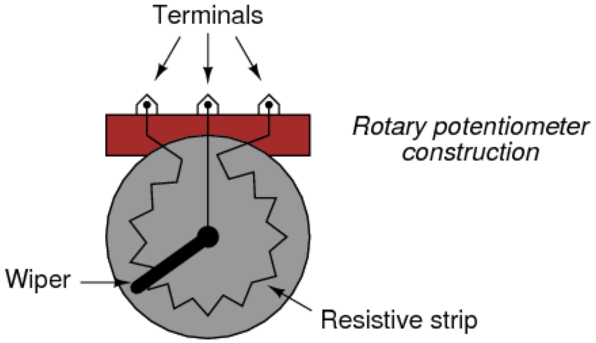


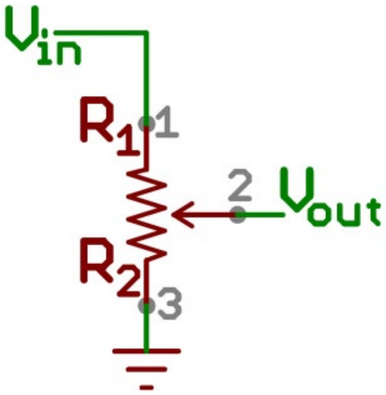


Pin number					Pin name (function after reset)[1]	Pin type	I/O structure	Notes	Alternate functions	Additional functions
UQFN48	LQFP64	WLCSP49	LQFP100	UFBGA100L						
-	24	-	33	K5	PC4	I/O	FT	-	EVENTOUT	ADC1_14
-	25	-	34	L5	PC5	I/O	FT	-	EVENTOUT	ADC1_15
18	26	G5	35	M5	PB0	I/O	FT	-	TIM1_CH2N, TIM3_CH3, SPI5_SCK/I2S5_CK, EVENTOUT	ADC1_8
19	27	G4	36	M6	PB1	I/O	FT	-	TIM1_CH3N, TIM3_CH4, SPI5_NSS/I2S5_WS, EVENTOUT	ADC1_9

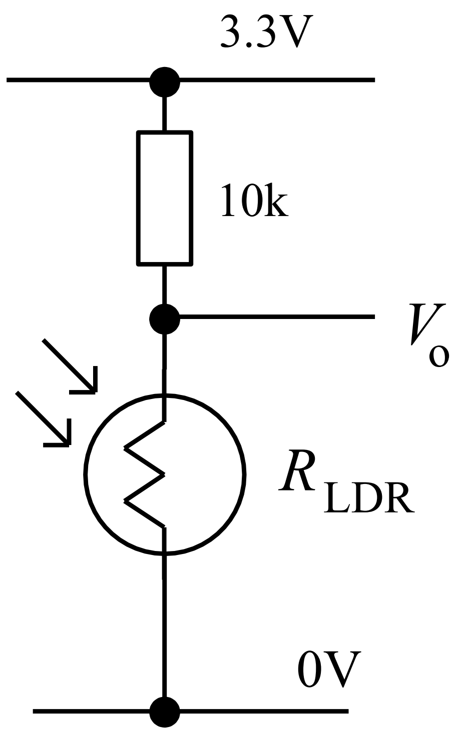
Potentiometer as Voltage Devider







Simple Analog Sensors : the Light Dependent Resistor

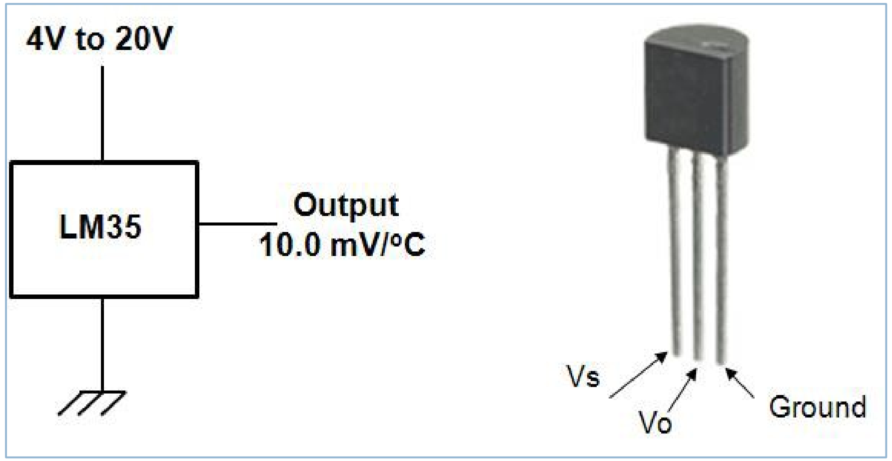


- LDR is made from semiconductor material.
- the brighter the light, the more electrons are releaseds
- Released electrons are available to conduct electricity; the resistance falls
- Remove the light, electrons are back into their place; the resistance goes up again.

Illumination (lux)	R_{LDR} (Ω)	V_o
Dark	$\geq$ 1.0 M	$\geq$ 3.27 V
10	9k	1.56 V
1,000	400	0.13 V

Integrated Circuit Temperature Sensor

- Semiconductor action is highly dependent on temperature
- LM35 has an output of 10 mV/°C
- Up to 110 °C



Summary

- Many applications using Analog voltage as input to MCU
- ADC converts analog signal to n bit digital code
- Keywords: input range, resolution, sampling rate and conversion time
- Nyquist's sampling theorem : The sampling frequency must be at least twice of the highest frequency analog input.
- ADC Data can be further processed, and displayed or stored.
- Numerous sensors have an analog output; can be directly connected to MCU ADC input.