LA-CoNGA physics
Introduction to Measurements Systems
Digital *vs* Analog

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Digital vs Analog

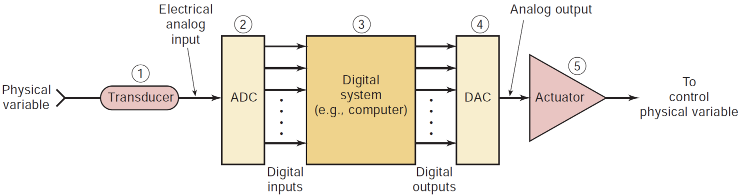
- **A digital quantity** can assume only a discrete numbers of symbols called "digits", i.e. binary, decimal, hexadecimal.
- In the binary system, a digit is represented as a voltage that may actually have a value that is anywhere within specified ranges
- For example, for the *Arduino* logic:

$$\begin{aligned} 0V \;\; to \;\; 0.5V &= ''0'' \\ 2V \;\; to \;\; 3.5V &= ''1'' \end{aligned}$$

- By contrast, **an analog quantity** can take on any value over a continuous range of values, its exact value is significant.
- differences between analog and digital

Digital vs Analog

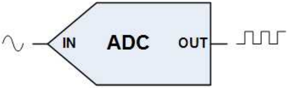
- Most physical variables are analog in nature and can take on any value within a continuous range of values. Examples include:
  - temperature, pressure
  - light intensity, audio signals
  - position, rotational speed, and flow rate.



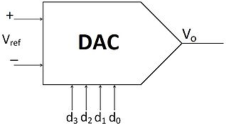
- Analog-to-digital converter (ADC) and digital-to-analog converter (DAC) are used to interface a computer to the analog world so that the computer can monitor and control a physical variable

ADCs and DACs

- **Analog-to-digital converter (ADC)**. The ADC converts an analog input to a digital output. This digital output consists of a number of bits that represent the value of the analog input



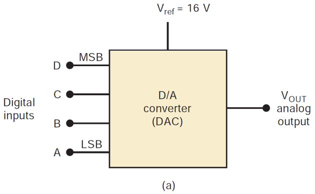
- **Digital-to-analog converter (DAC)**. This digital output from the computer is connected to a digital-to-analog converter (DAC), which converts it to a proportional analog voltage or current



Digital to Analog Conversion

4-bit DAC

- D/A conversion is the process of taking a value represented in digital code (such as straight binary or BCD) and converting it to a voltage or current that is **proportional to the digital value**



(a)

D	C	B	A	V_{OUT}	
0	0	0	0	0	Volts
0	0	0	1	1	
0	0	1	0	2	
0	0	1	1	3	
0	1	0	0	4	
0	1	0	1	5	
0	1	1	0	6	
0	1	1	1	7	
1	0	0	0	8	
1	0	0	1	9	
1	0	1	0	10	
1	0	1	1	11	
1	1	0	0	12	
1	1	0	1	13	
1	1	1	0	14	
1	1	1	1	15	Volts

- Notice that there is an input for a **voltage reference**, V_{ref}. This input is used to determine the **full-scale output** or maximum value that the D/A converter can produce

Digital to Analog Conversion

4-bit DAC

- The analog output is proportional to the digital input

$$Analog\ \ Output = K\ \ x\ \ Digital\ \ Input$$

- where K is the proportionality factor and is a constant value for a given DAC connected to a fixed reference voltage
- In this example:

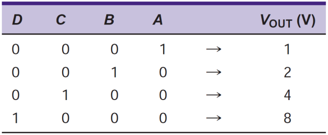
$$V_{out} = (1V)\ \ x\ \ Digital\ \ In$$

- A five-bit DAC has a current output. For a digital input of *10100*, an output current of *10 mA* is produced.What will I_{out} be for a digital input of *11101*?
- What is the largest value of output voltage from an 8-bit DAC that produces *1.0 V* for a digital input of *00110010*?

Digital to Analog Conversion

Characteristics

- **Analog Output** The output of a DAC is technically not an analog quantity because it can take on only specific values
- However, the number of different possible output values can be increased and the difference between successive values decreased by increasing the number of input bits



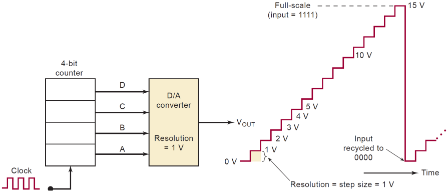
D	*C*	*B*	*A*		V_{OUT} (V)
0	0	0	1	→	1
0	0	1	0	→	2
0	1	0	0	→	4
1	0	0	0	→	8

- **Input Weights** note that each digital input contributes a different amount to the analog output. This is easily seen if we examine the cases where only one input is *HIGH*

Digital to Analog Conversion

Resolution

- **Resolution** of a DAC is defined as the smallest change that can occur in the analog output as a result of a change in the digital input. It is always equal to the weight of the *LSB* and is also referred to as the **step size**



- Note that the staircase has 16 levels corresponding to the 16 input states, but there are only 15 steps or jumps between the 0-V level and full-scale. For an *N-bit DAC* the number of different levels will be 2^N, and the number of steps will be $2^N - 1$

Digital to Analog Conversion

Resolution

- You may have already figured out that **resolution** (step size) is the same as the **proportionality factor** K in the DAC input/output relationship:

$$resolution = K = \frac{A_{fs}}{2^N - 1}$$

- where A_{fs} is the *analog full-scale output* and N is the *number of bits*.
- **Percentage Resolution** It is also useful to express it as a percentage of the full-scale output

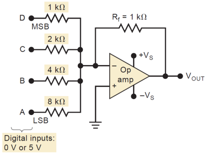
$$\% \ \ resolution = \frac{K}{A_{fs}} \, x \, 100$$

- A *10-bit DAC* has a step size of *10 mV*. Determine the full-scale output voltage and the percentage resolution.

DAC circuitry

Basic circuit

- A 4-bit DAC circuitry. The inputs are assumed to have values of either *0* or *5 V*. An op-amp is employed as a *summing amplifier*



(a)

Input code

D	C	B	A	V_{OUT} (volts)	
0	0	0	0	0	
0	0	0	1	−0.625	← LSB
0	0	1	0	−1.250	
0	0	1	1	−1.875	
0	1	0	0	−2.500	
0	1	0	1	−3.125	
0	1	1	0	−3.750	
0	1	1	1	−4.375	
1	0	0	0	−5.000	
1	0	0	1	−5.625	
1	0	1	0	−6.250	
1	0	1	1	−6.875	
1	1	0	0	−7.500	
1	1	0	1	−8.125	
1	1	1	0	−8.750	
1	1	1	1	−9.375	← Full-scale

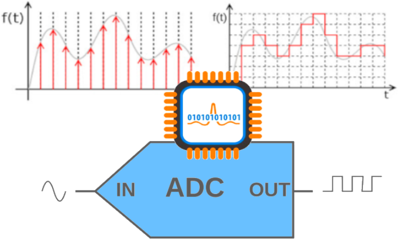
- Recall that the *summing amplifier* multiplies each input voltage by the ratio of the feedback resistor R_F to the corresponding input resistor R_{IN}

$$V_{OUT} = -(V_D + \frac{1}{2}V_C + \frac{1}{4}V_B + \frac{1}{8}V_A)$$

Analog to Digital Conversion

ADC

- An analog-to-digital converter takes an analog input voltage and, after **a certain amount of time**, produces a digital output code that represents the analog input.
- The A-D conversion process is generally more complex and time consuming than the D-A process

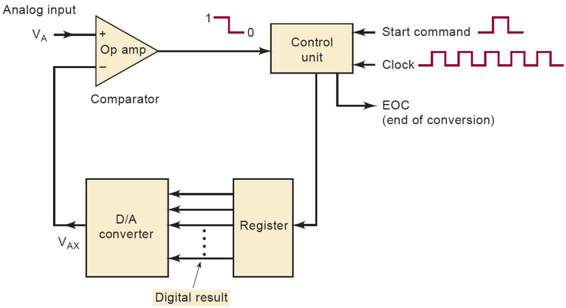


- An *ADC* circuit is more complex compared to a DAC

Analog to Digital Conversion

Basic Circuit

- Several important types of ADCs utilize a DAC as part of their circuitry.
- Figure below is a general block diagram for this class of ADC



- The op-amp comparator has two analog inputs and a digital output that switches states, depending on which analog input is greater

Analog to Digital Conversion

Digital-Ramp ADC

- One of the simplest versions of the general ADC uses a binary counter as the register and allows the clock to increment the counter one step at a time until

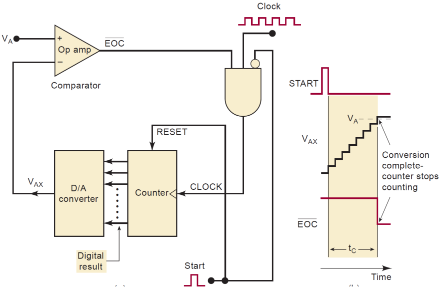
$$V_{AX} \geq V_A$$

- It is called a **digital-ramp ADC** because the waveform at V_{AX} is a step-by-step ramp (actually a staircase)
- A digital-ramp ADC contains:
  - a counter
  - a DAC
  - an analog comparator
  - a control AND gate

Analog to Digital Conversion

Digital-Ramp ADC

- A START pulse is applied to reset the counter to 0. The *HIGH* at *START* also inhibits clock pulses from passing through the AND gate into the counter.



- When conversion process is complete, a $\overline{EOC}$ is generated and and the contents of the counter are the digital representation of V_A.

ADC characteristics

- **Conversion time** t_c: is the time interval between the end of the $START$ pulse and the activation of the output $\overline{EOC}$

$$t_c(max) = (2^N - 1) clock\ cycles$$

- An average conversion time is useful

$$t_c(avg) = \frac{t_c(max)}{2} \approx 2^{N-1} clock\ cycles$$

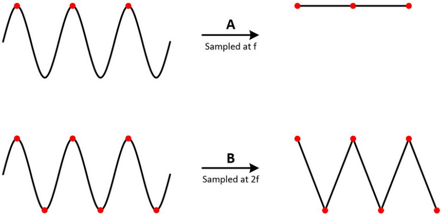
- **Resolution**: Resolution of the ADC is the same as the internal DAC
- **Quantization Error** It is a rounding error between the analog input voltage to the ADC and the output digitized value

ADC characteristics

Nyquist-Shannon Theorem

- The terms Nyquist, aliasing, undersampling, and oversampling are basic ADC terms.
- The **Nyquist-Shannon sampling theorem** states that for a true representation of waveform X, greater than two samples per period are required, i.e.

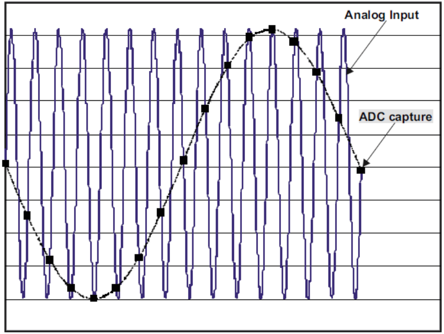
$$f_{in} \leq f_s/2$$



ADC characteristics

Undersampling and aliasing

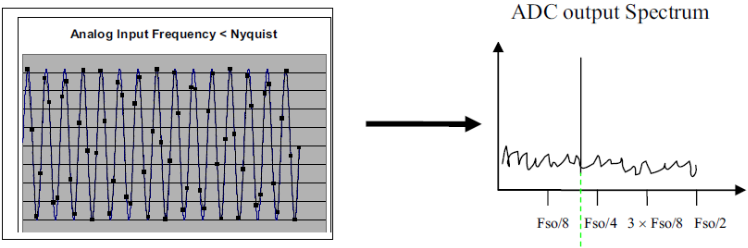
- With $F_{in} > f_{Nyquist}$, the *ADC* capture output has translated the analog input signal at a lower frequency. This frequency translation is called **aliasing**.



ADC characteristics

Oversampling

- With $F_{in} << f_{Nyquist}$, the *ADC* capture output has translated the analog input signal at the exact frequency.

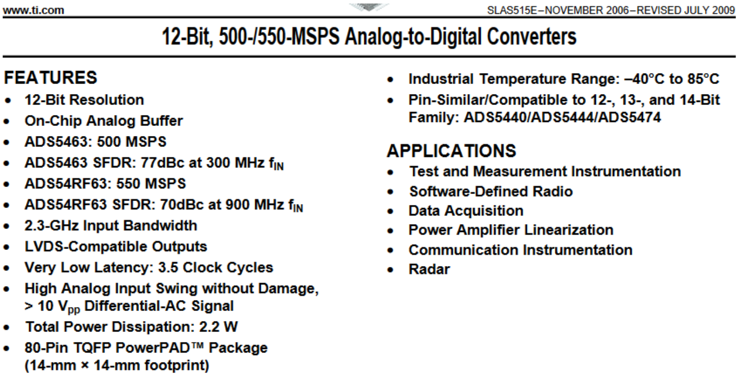


- Examples above refers to a monotone signal, in general the analog input signal bandwidth must be less than the ADC's Nyquist frequency.

ADC characteristics

Oversampling

- The *ADC* used in your system must ensure that the ADC input specifications are capable of meeting your requirements



www.ti.com SLAS515E–NOVEMBER 2006–REVISED JULY 2009

12-Bit, 500-/550-MSPS Analog-to-Digital Converters

FEATURES

- 12-Bit Resolution
- On-Chip Analog Buffer
- ADS5463: 500 MSPS
- ADS5463 SFDR: 77dBc at 300 MHz f_{IN}
- ADS54RF63: 550 MSPS
- ADS54RF63 SFDR: 70dBc at 900 MHz f_{IN}
- 2.3-GHz Input Bandwidth
- LVDS-Compatible Outputs
- Very Low Latency: 3.5 Clock Cycles
- High Analog Input Swing without Damage, > 10 V_{pp} Differential-AC Signal
- Total Power Dissipation: 2.2 W
- 80-Pin TQFP PowerPAD™ Package (14-mm × 14-mm footprint)
- Industrial Temperature Range: –40°C to 85°C
- Pin-Similar/Compatible to 12-, 13-, and 14-Bit Family: ADS5440/ADS5444/ADS5474

APPLICATIONS

- Test and Measurement Instrumentation
- Software-Defined Radio
- Data Acquisition
- Power Amplifier Linearization
- Communication Instrumentation
- Radar

References

- Digital systems and applications, Tocci, 10th Ed Chap 11
- Arduino Basics DAC
- High-Speed, Analog-to-Digital Converter Basics