Analog to Digital and Back Again

Lecture 10

Microprocessor-based Systems (E155)

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µP

Quiz

- What sampling conditions must be satisfied to capture all the information in analog signal using a discrete sequence of samples?
- Can you generate a true analog output (no discretization) using the MCP4801 DAC?
  - If yes, why and how would you do it?
  - If not, why not?

https://docs.google.com/presentation/d/1ShVehgj6aX2Dr44j0UIh4JXsUJaZQ8HdsNg32T6HZcs/edit

Outline

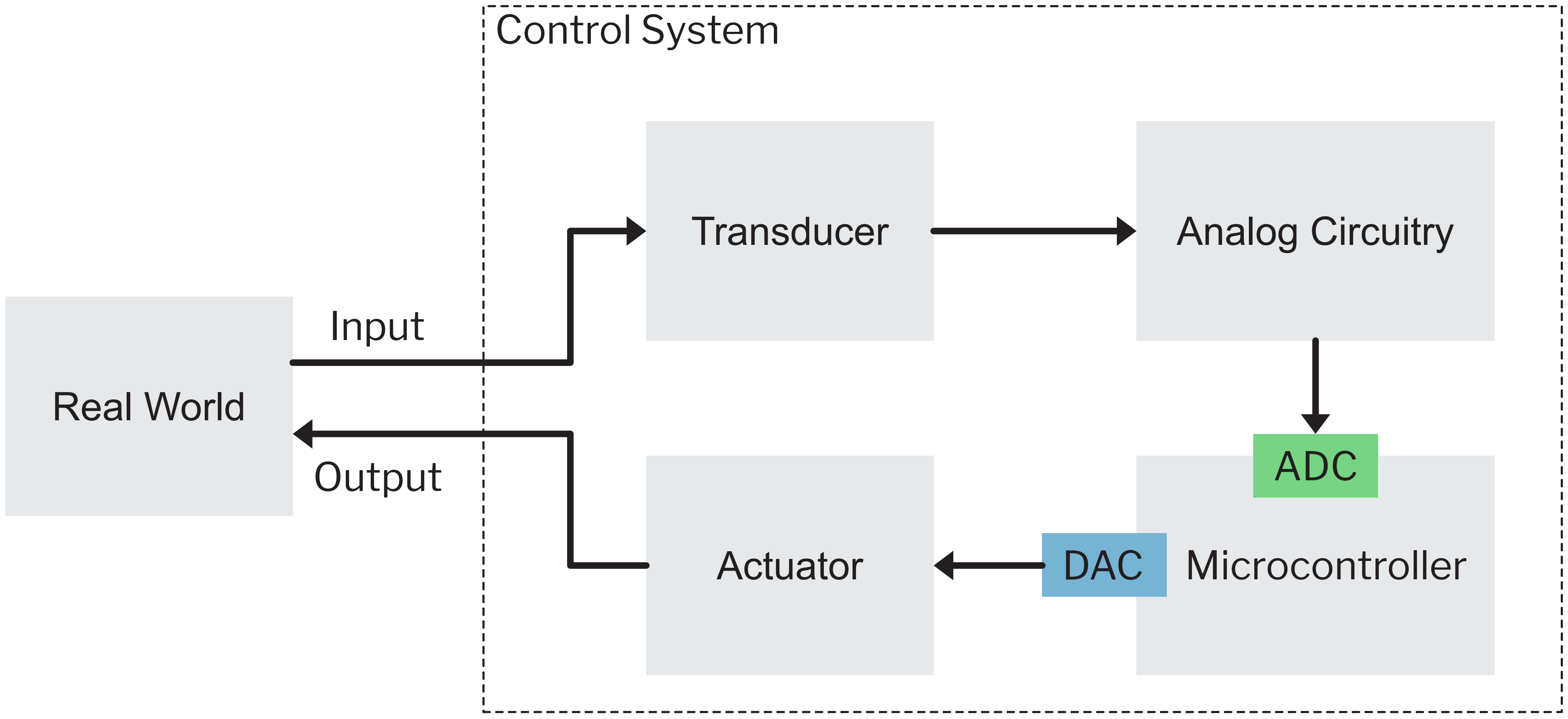
- Analog vs. Digital Signal review
- Analog to digital convertors (ADCs)
- Digital to analog convertors (DACs)
- Examples
    - MCP4801 DAC
    - STM32F401RE ADC

Learning Objectives

By the end of this lecture you will be able to

- Articulate the basic operation of digital to analog conversion
- List some of the basic performance and noise specifications of ADCs and explain what they mean
- Understand the operation of the ADC on our STM32F401RE MCU

Motivation



Control System
Transducer
Analog Circuitry
Input
Real World
Output
ADC
Actuator
DAC
Microcontroller

Sampling Theory Refresher

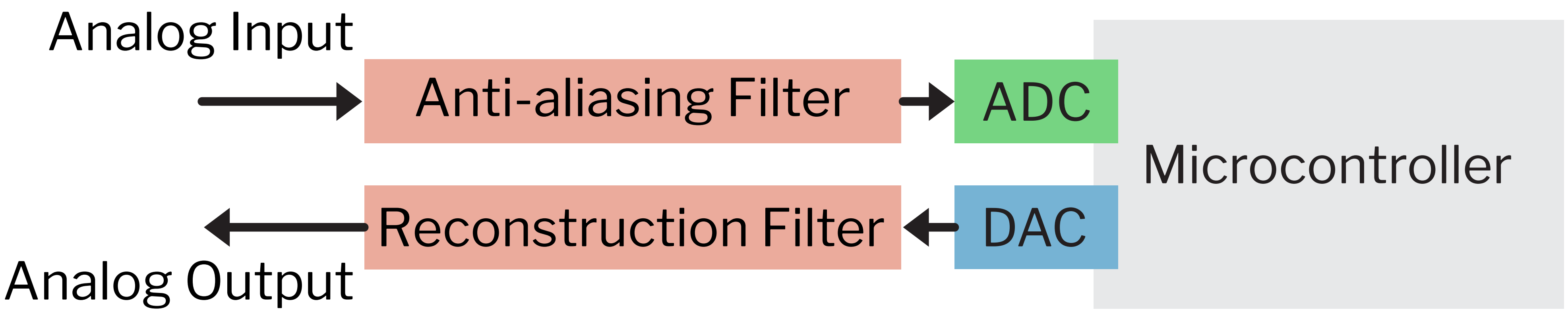
Nyquist-Shannon sampling theorem

If a function $x(t)$ contains no frequencies higher than B hertz, it is completely determined by giving its values at a series of points spaced $1/(2B)$ seconds apart.

This guarantees perfect sampling or reconstruction of a signal given that our sampling frequency is more than twice the bandlimit of the signal.

Reconstruction and anti-aliasing filters

- To ensure Nyquist-Shannon sampling is enforced, we place a filter with specified passbands on digital-to-analog outputs or analog-to-digital inputs
- The filter structure is a low-pass filter where the passband is such that the bandwidth after the filter is less than half the sampling frequency.



Reconstruction and anti-aliasing filters

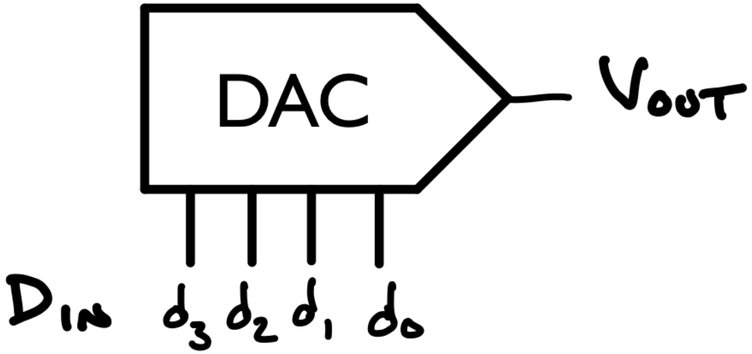
- Low pass filter to remove samples higher than half the sampling rate
  - Reconstruction filter – performs interpolation on digital output
  - Anti-aliasing filter – performs filtering on analog input
- Many filter designs available
  - Simple passive RC lowpass filter
  - Active filters
    - Butterworth – maximally flat passband
    - Chebyshev – Sharper cutoff with passband ripple

Digital to Analog Convertors

DACs

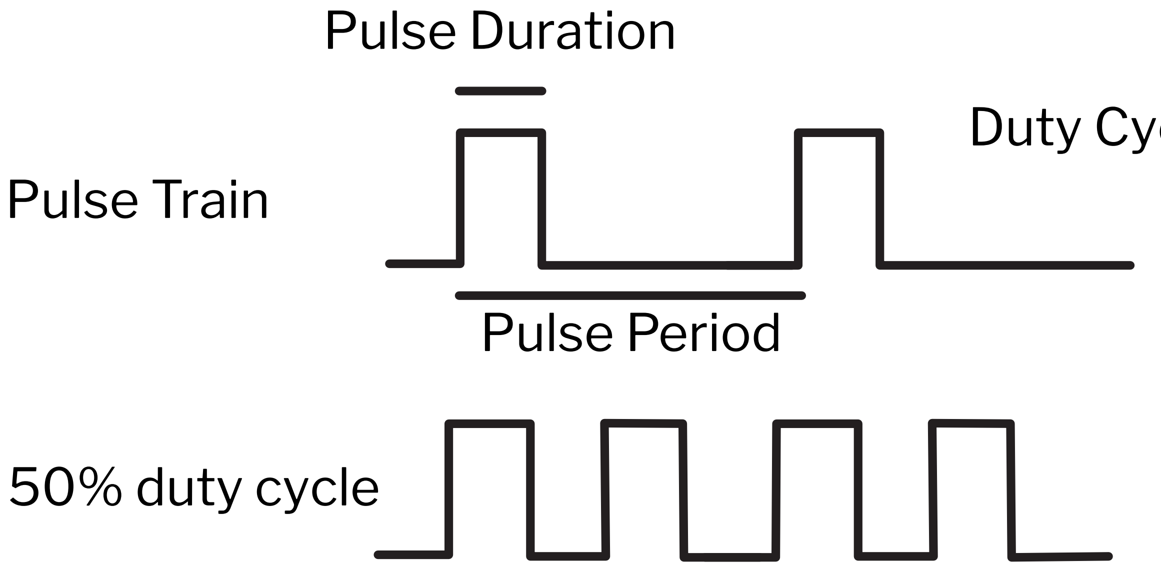
Main Types

- Pulse-width modulation
- Thermometer-coded or string DAC
- Binary-weighted DAC
- Oversampling DAC



Pulse-width Modulation

- Generate timed pulses at high frequency and low pass filter the output
- Can also be used to generate precisely timed pulses for control applications (e.g., with motors)



$$\text{Duty Cycle} = \frac{\text{Pulse Duration}}{\text{Pulse Period}}$$

Thermometer-coded or string DAC

- Simplest DAC (1-bit) is just a switch
- The thermometer DAC architecture uses the same basic idea with an array of resistors for voltage division

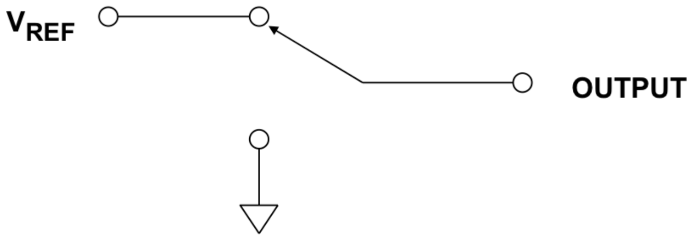


Figure 1: 1-Bit DAC: Changeover Switch (Single-Pole, Double Throw, SPDT)

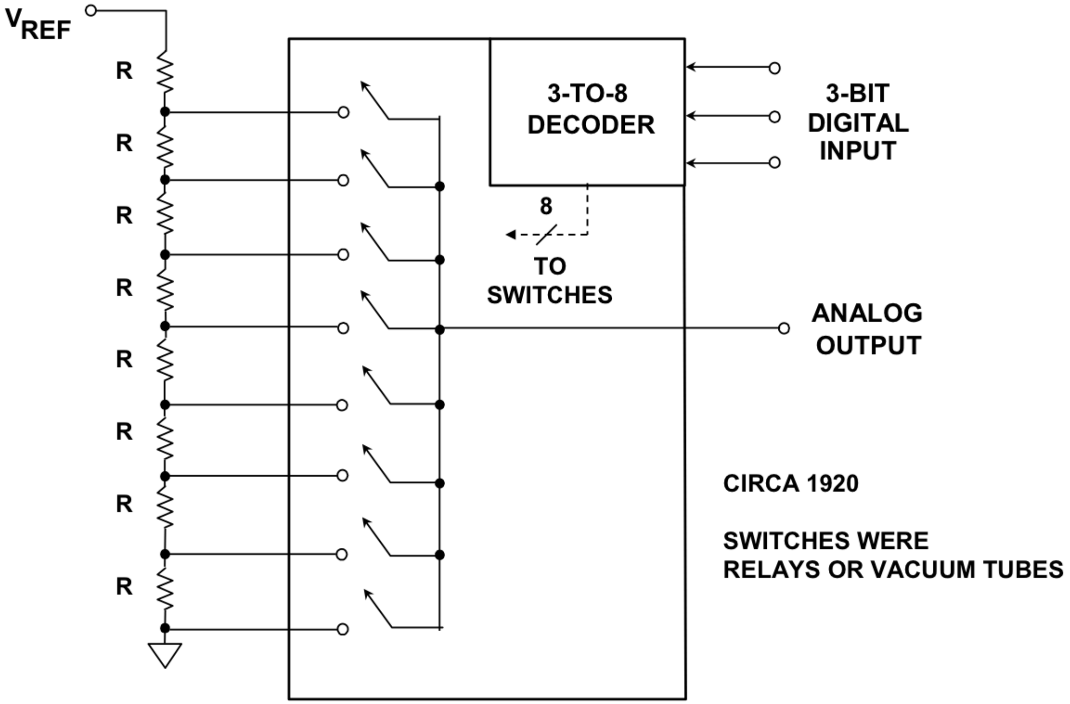


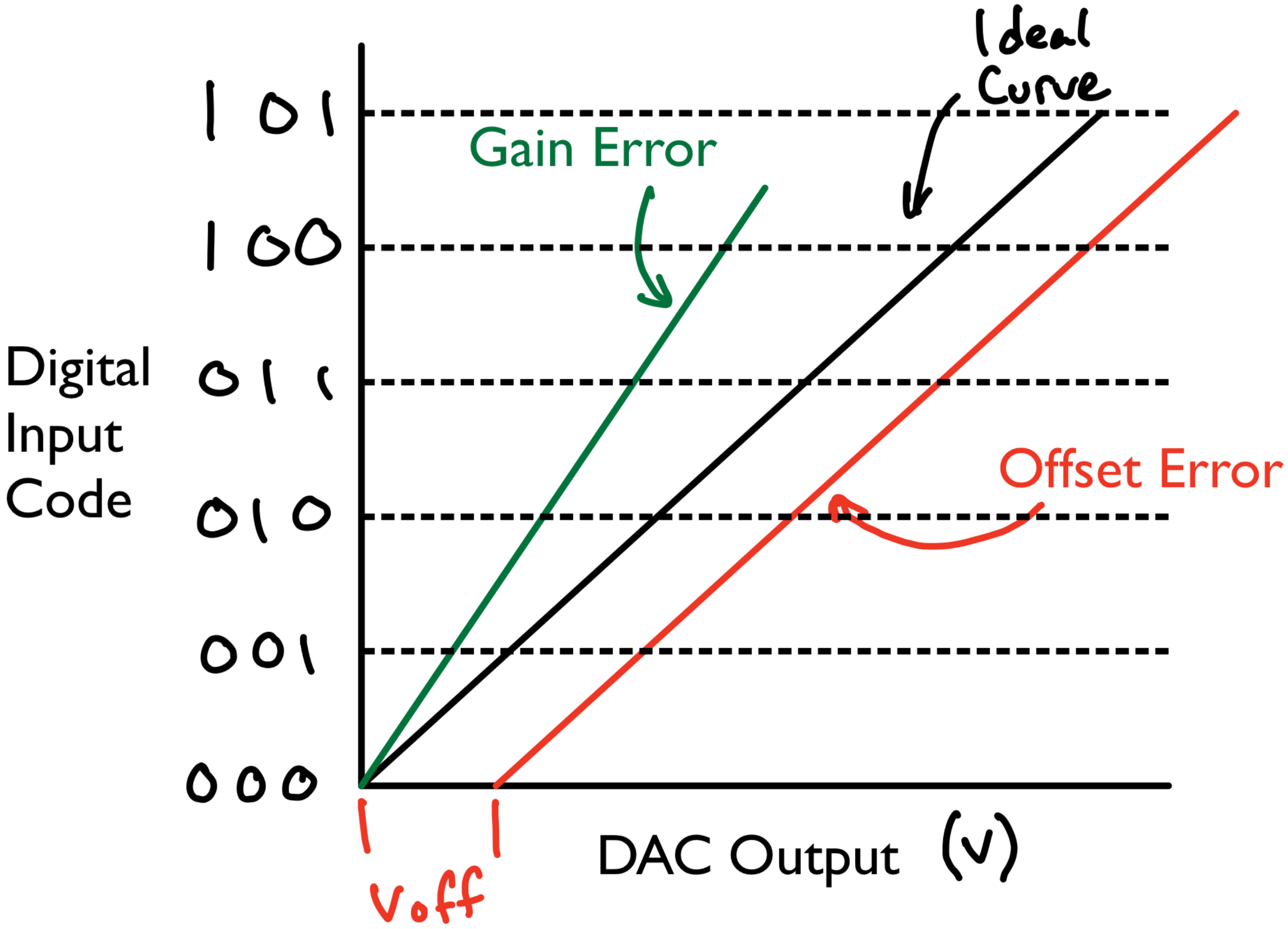
Figure 2: Simplest Voltage-Output Thermometer DAC: The Kelvin Divider ("String DAC")

Walt Kester, "Basic DAC Architectures I: String DACs and Thermometer (Fully Decoded) DACs", Analog Devices MT-014 Tutorial (link)

Performance Specifications

- Resolution
- Maximum sampling rate
- Monotonicity
- Errors
  - Gain
  - Integral non-linearity (INL)
  - Differential non-linearity (DNL)

Offset and Gain errors



Integral Non-Linearity (INL)

- Integral non-linearity is the maximum deviation between an actual code transition point and its corresponding ideal transition point once offset and gain errors have been removed.

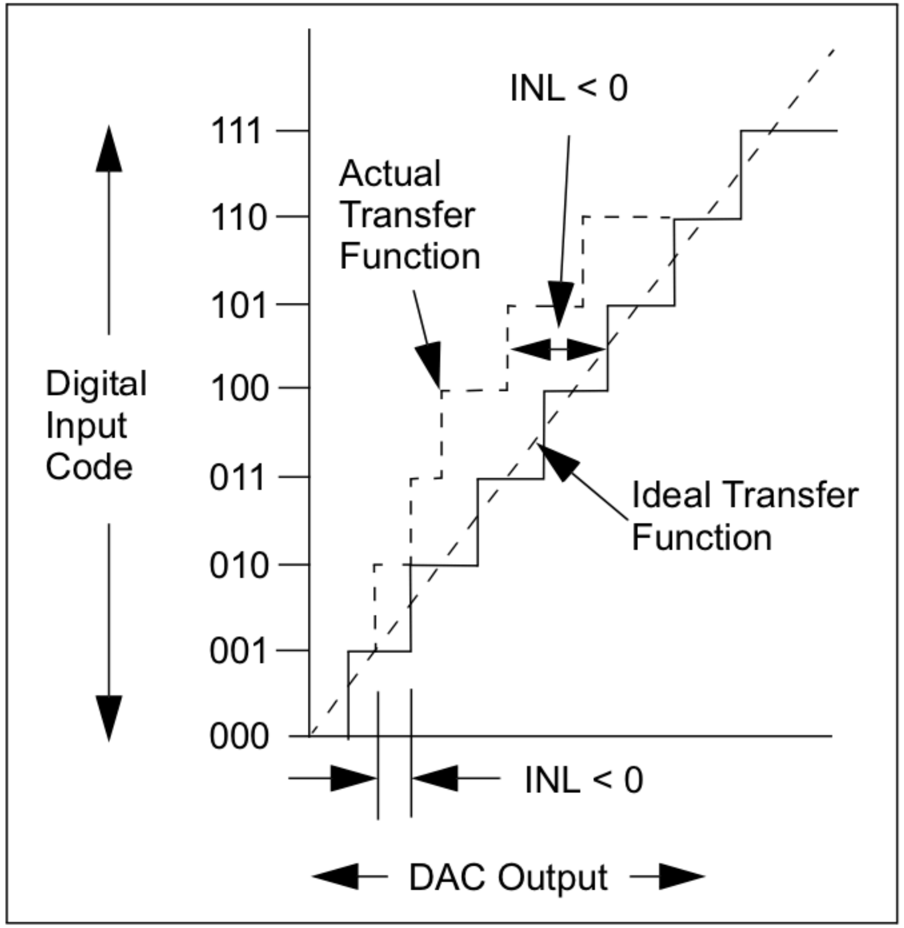


FIGURE 4-1: _Example for INL Error._

Differential Non-Linearity (DNL)

- Measure of variations in code width from ideal
- A DNL error of zero indicates that each code is exactly 1 Lsb wide

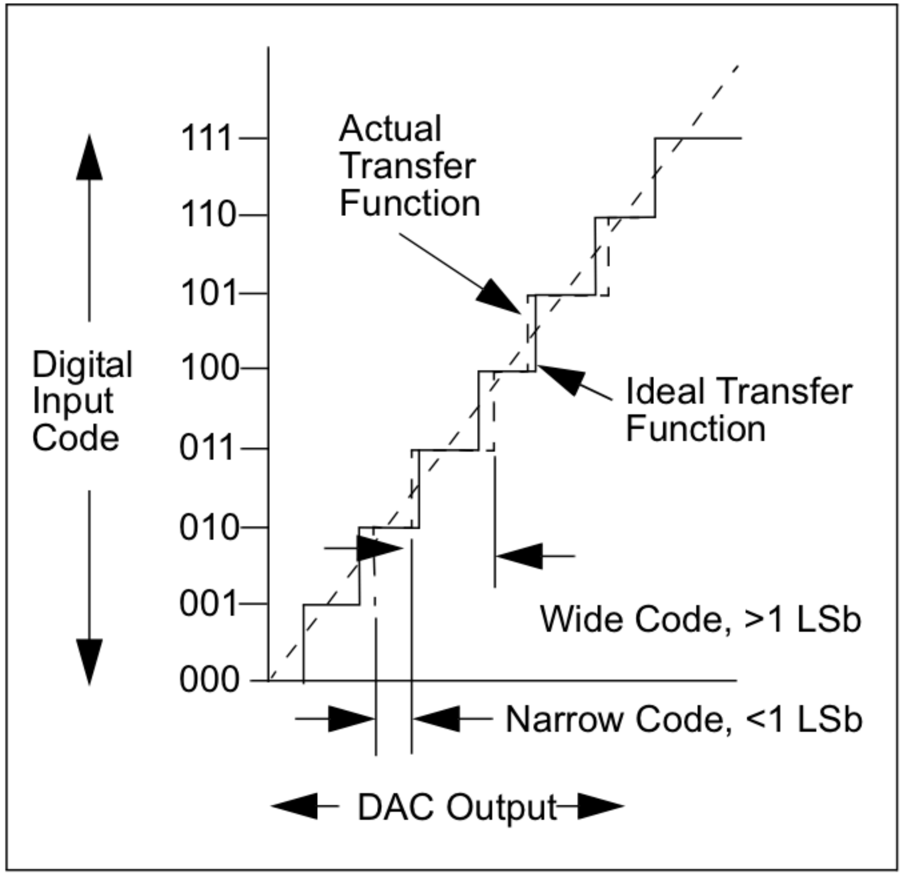
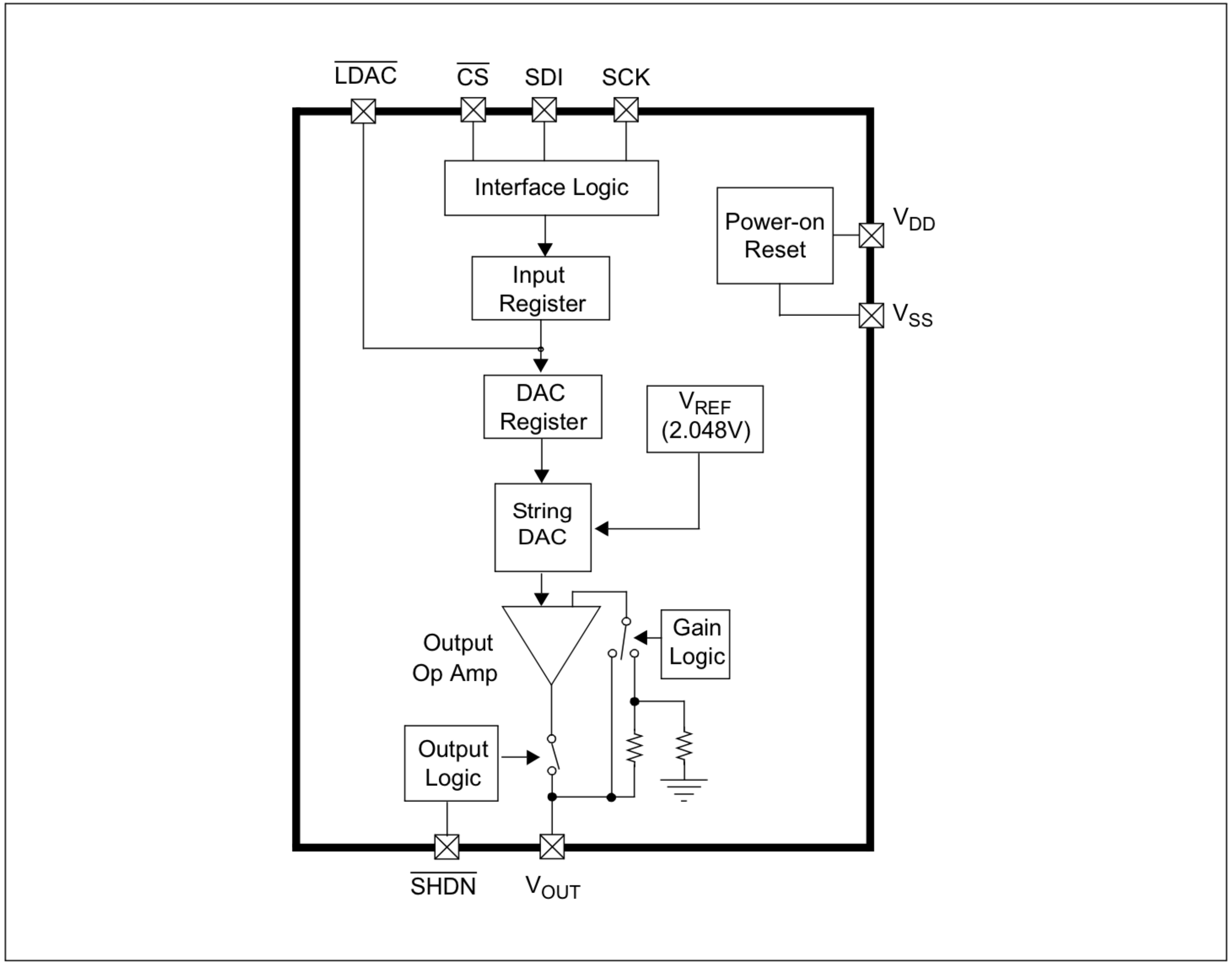


FIGURE 4-2: *Example for DNL Error.*

MCP4801

Block Diagram



MCP4801 Datasheet ([link]())

MCP4801 INL and DNL Graphs

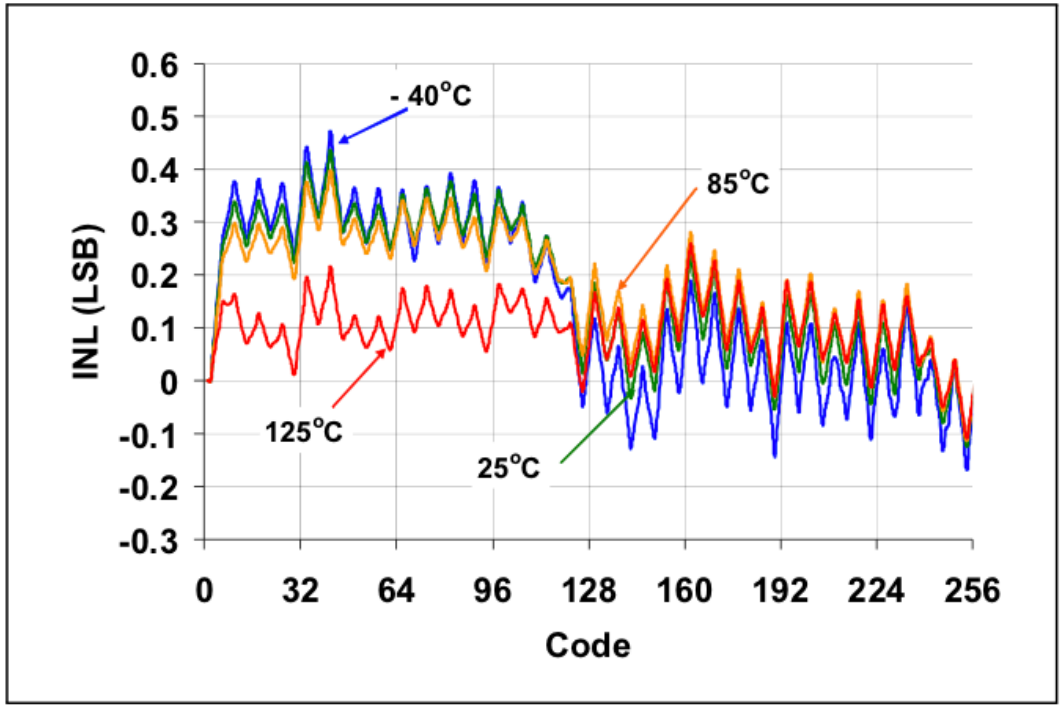


FIGURE 2-10: *INL vs. Code and Temperature (MCP4801).*

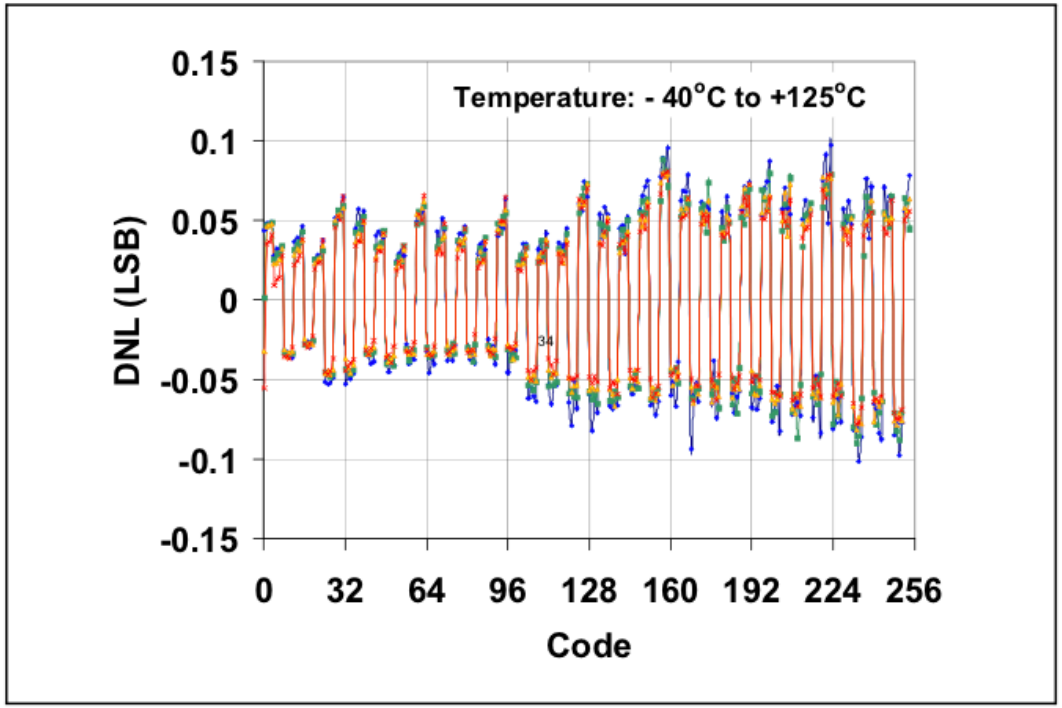


FIGURE 2-9: *DNL vs. Code and Temperature (MCP4801).*

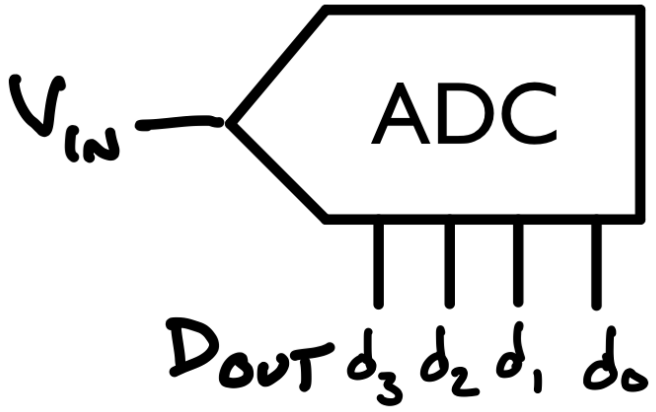
MCP4801 Datasheet (link)

Analog to Digital Convertors

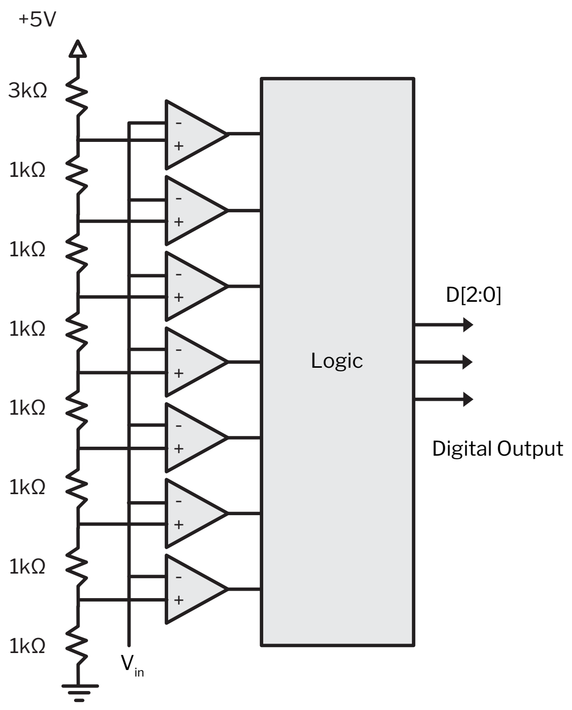
ADCs

Purpose

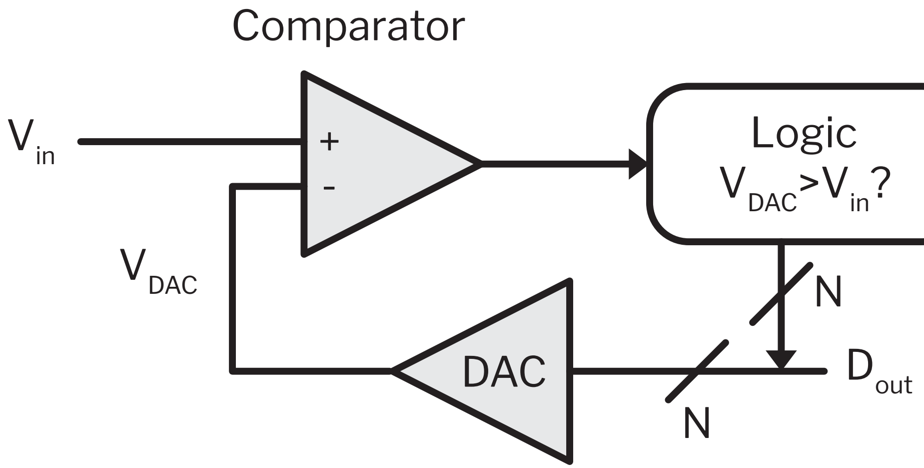
- Convert from analog voltage to digital number
- Specified by number of bits of resolution
- Commonly used in embedded systems to read interface with a sensor



Main Types



Flash ADC



Successive approximation ADC

Specifications

- Resolution – step size between input values. Related to the number of bits.
- Errors
  - Offset error
  - Gain error
  - Integral linearity error
  - Differential linearity error
- Sampling rate – how fast can we get samples?

Table 67. ADC accuracy at f_{ADC} = 18 MHz(1)

Symbol	Parameter	Test conditions	Typ	Max(2)	Unit
ET	Total unadjusted error	f_{ADC} =18 MHz V_{DDA} = 1.7 to 3.6 V V_{REF} = 1.7 to 3.6 V $V_{DDA} - V_{REF}$ < 1.2 V	±3	±4	LSB
EO	Offset error		±2	±3	
EG	Gain error		±1	±3	
ED	Differential linearity error		±1	±2	
EL	Integral linearity error		±2	±3	

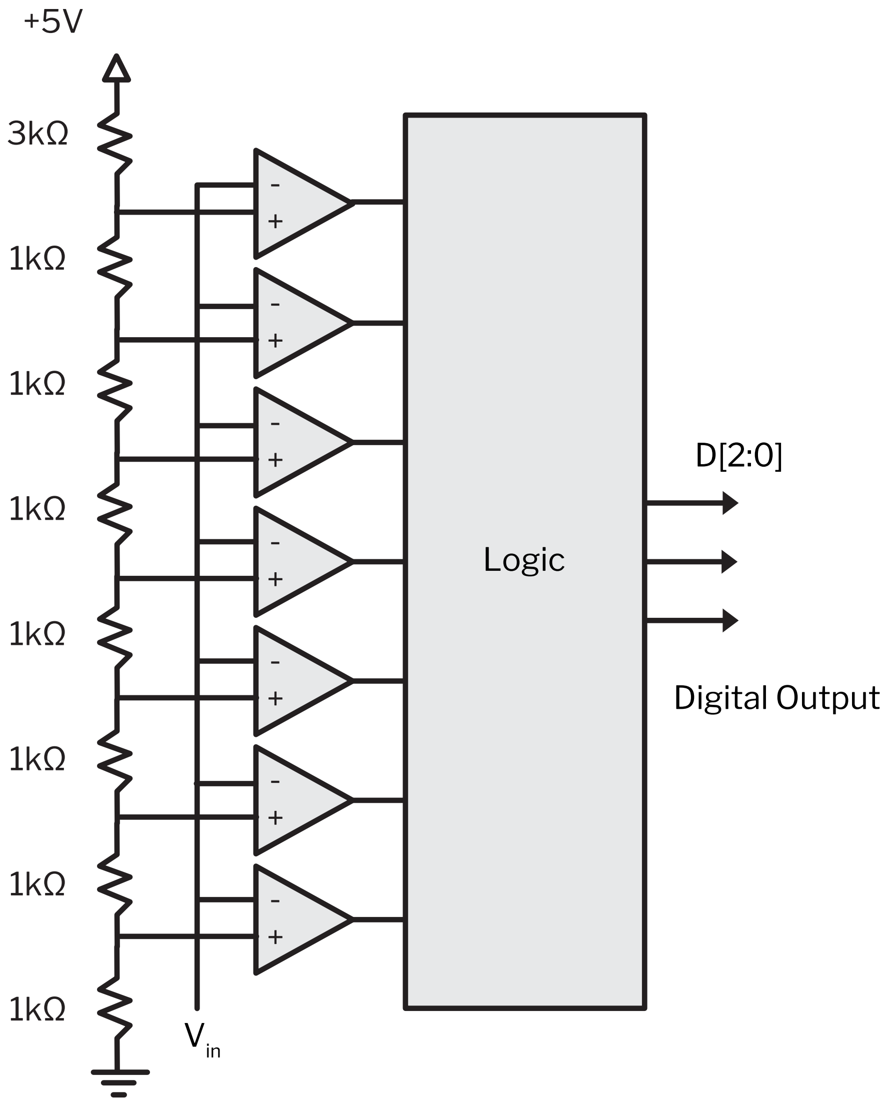
1. Better performance could be achieved in restricted V_{DD}, frequency and temperature ranges.
2. Guaranteed by characterization, not tested in production.

STM32F401RE Datasheet

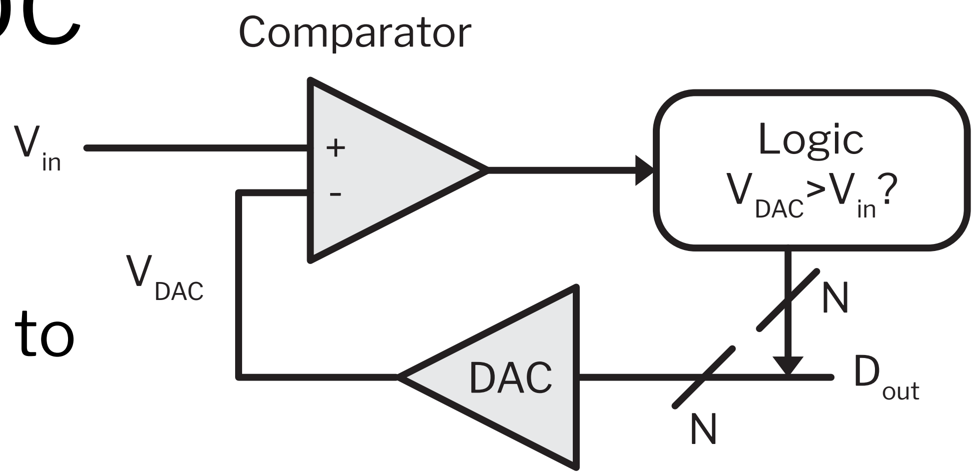
Total unadjusted error incorporates offset, gain, and INL errors (TI explainer link)

Flash ADC

- Pros
  - Combinational
    - Fast – only limited by propagation delay through the comparators and decoding logic
    - Not connected to clock rate
- Cons
  - Expensive – 2^N-1 comparators where N is the number of bits

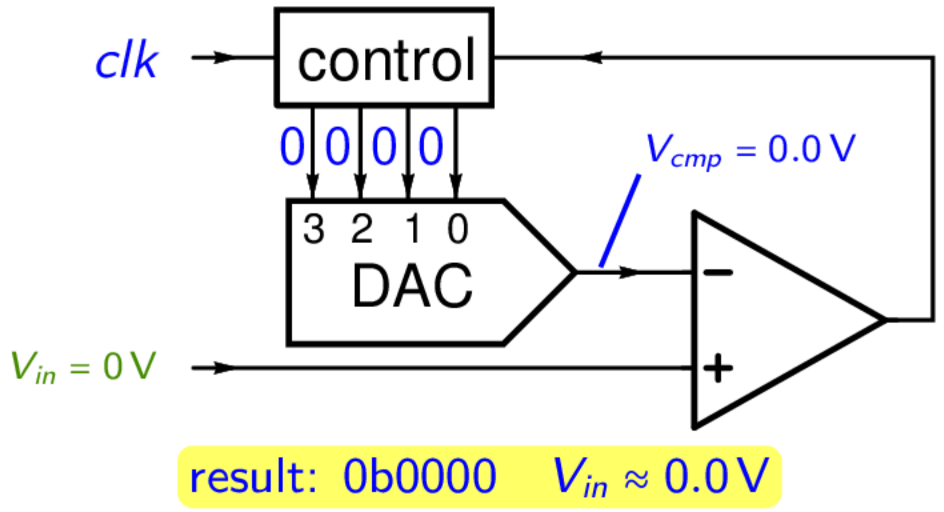


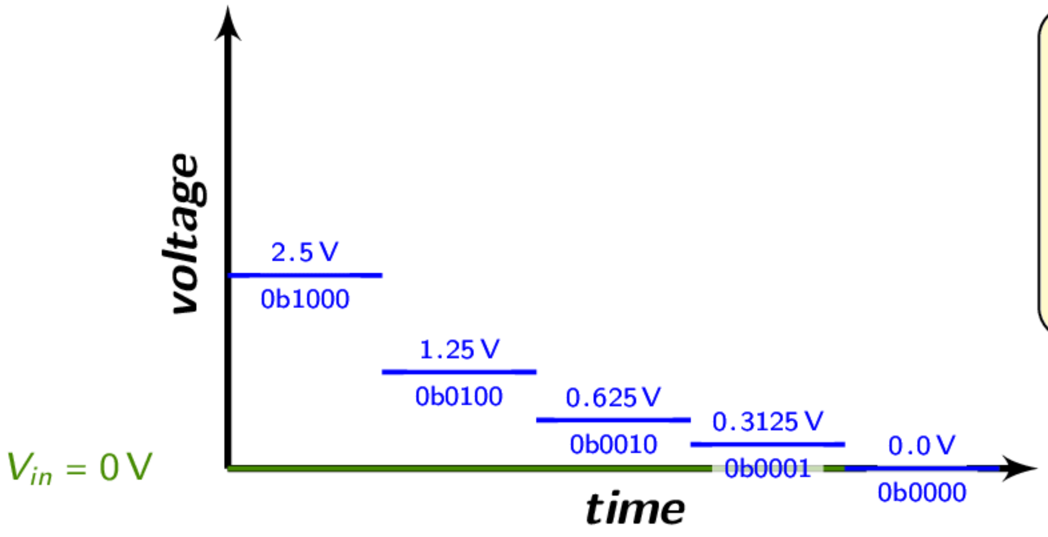
Successive approximation ADC



- Most popular ADC type
- Uses iterative feedback loop to converge to the right value
- Algorithm
  - Start with MSB of DAC. Set to 1 which sets the DAC to $V_{ref}/2$
    - Check if $V_{in} > V_{DAC}$
    - Y: set bit to 0
    - N: set bit to 1
  - Move to next bit, repeat

Successive Approximation – example of a 4-bit ADC

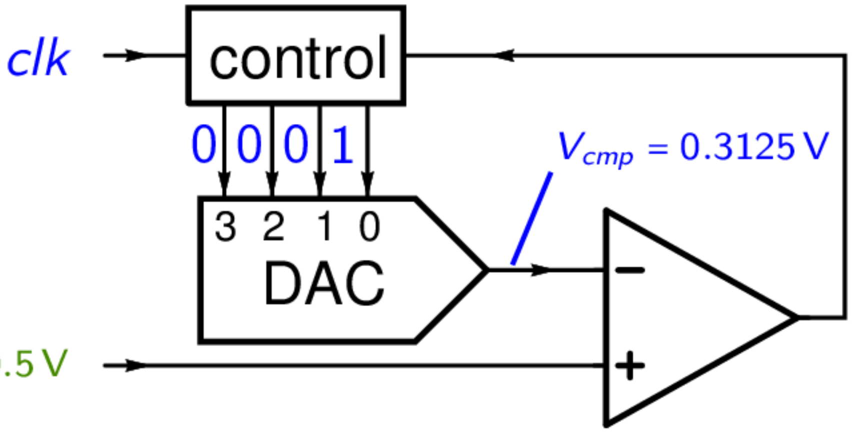




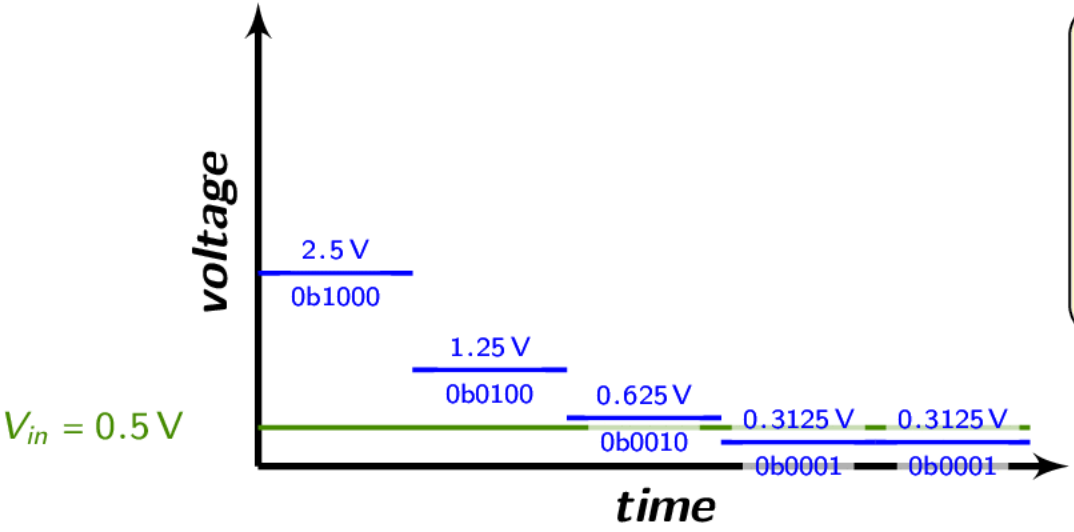
Resolution:

5 V × 1/2	2.5000 V
5 V × 1/4	1.2500 V
5 V × 1/8	0.6250 V
5 V × 1/16	0.3125 V
...	
5 V × 1/1024	0.0049 V

Successive Approximation – example of a 4-bit ADC



result: 0b0001 $V_{in} \approx 0.3125\,V$



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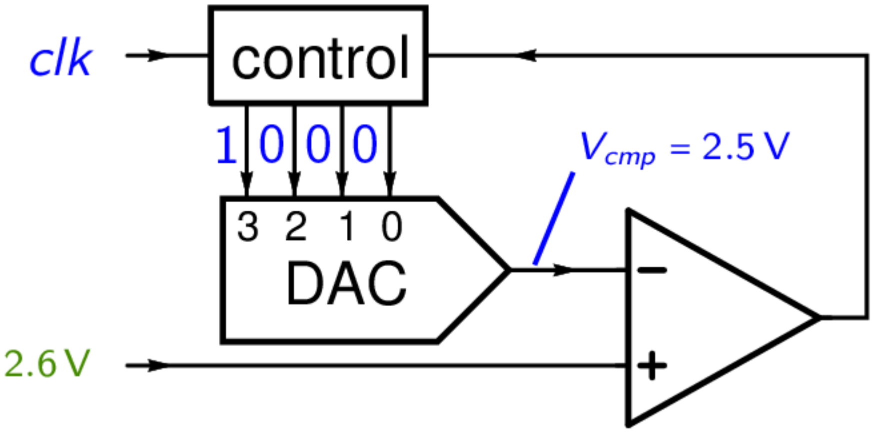
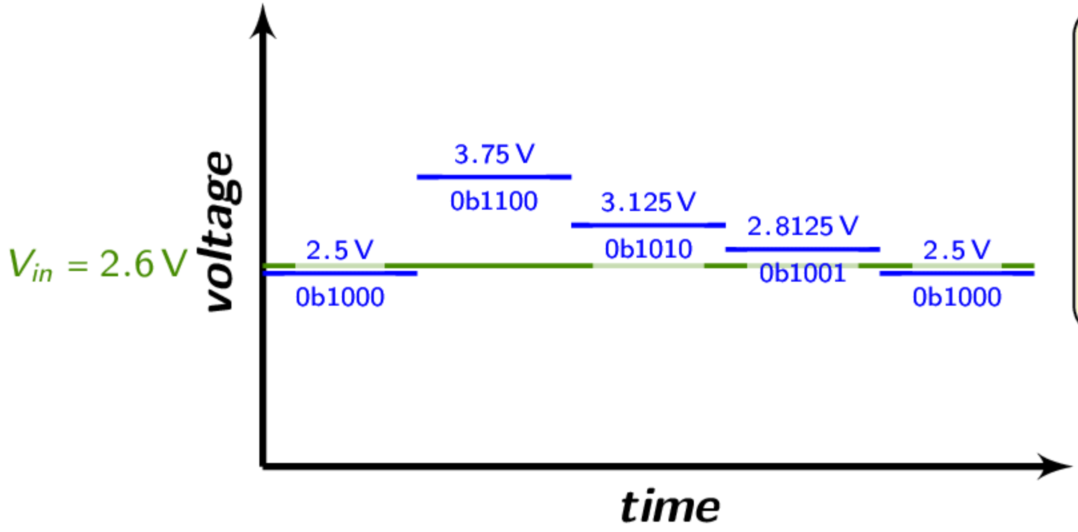
...	
$5\,V \times 1/1024$	0.0049 V

Successive Approximation – example of a 4-bit ADC



result: 0b1000 $V_{in} \approx 2.5\,V$



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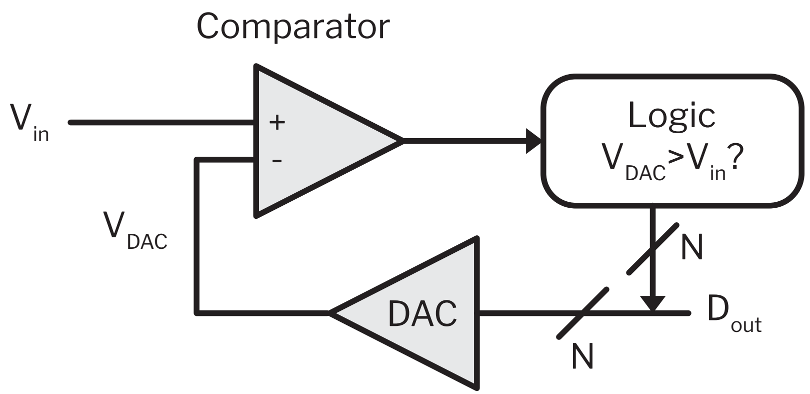
Successive approximation ADC



- Pros
    - Cheap and small – only need 1 comparator
- Cons
    - Iterative
    - Sequential – speed depends on clock speed and must obey timing specs

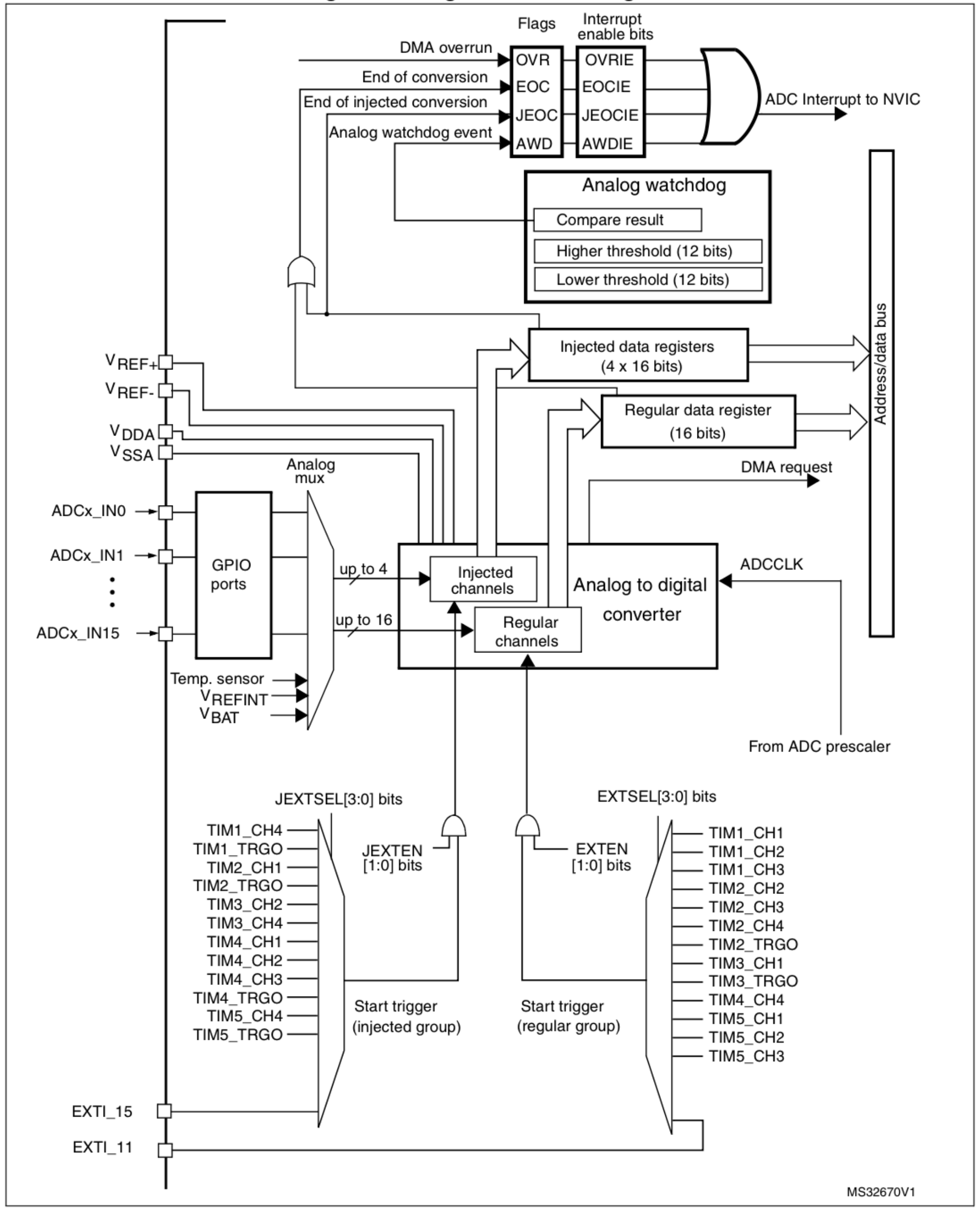
STM32F401RE ADC

11.1 ADC introduction

The 12-bit ADC is a successive approximation analog-to-digital converter. It has up to 19 multiplexed channels allowing it to measure signals from 16 external sources, two internal sources, and the V_{BAT} channel. The 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.

The analog watchdog feature allows the application to detect if the input voltage goes beyond the user-defined, higher or lower thresholds.

Figure 31. Single ADC block diagram



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By the end of this lecture you will be able to

- Articulate the basic operation of digital to analog conversion
- List some of the basic performance and noise specifications of ADCs and explain what they mean
- Understand the operation of the ADC on our STM32F401RE MCU

Next week

- Monday: Cortex Microcontroller Software Interface Standard (CMSIS)
- Wednesday: Interrupts
- Lab 5: Pulse-width modulation (PWM)
  - Use as DAC to drive LED with heartbeat pattern
  - Generate pulses with arbitrary frequencies and pulse durations

Lecture Feedback

- What is the most important thing you learned in class today?
- What point was most unclear from lecture today?

https://forms.gle/Ay6MkpZ6x3xsW2Eb8

Feedback