SJSU SAN JOSÉ STATE UNIVERSITY

Charles W. Davidson College of Engineering

Department of Computer Engineering

Real-Time Embedded System Co-Design
CMPE 146 Section 1
Fall 2024

Analog-to-Digital Converter

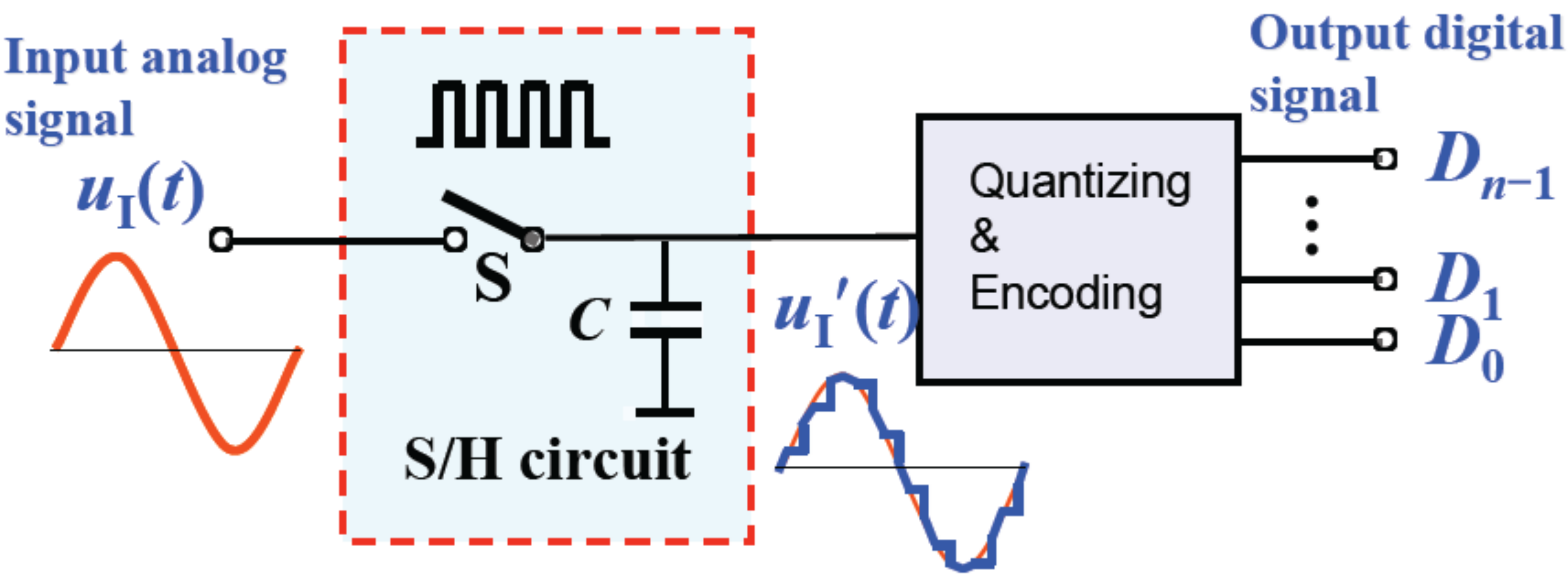
Analog-to-Digital Conversion

- Most of the signals in real world is continuous
- Digital computers can only process signals in discrete form
- A conversion process is needed to convert a signal's continuous form to a discrete form that a computer can process
- The discrete or digital form is just a sample of the continuous form
  - A snapshot in time
- The digital information is also a quantized form of the continuous signal
  - A (mostly) non-exact amplitude
- Analog-to-digital converter (ADC)
  - Converts an analog voltage to a digital word

Conversion Process

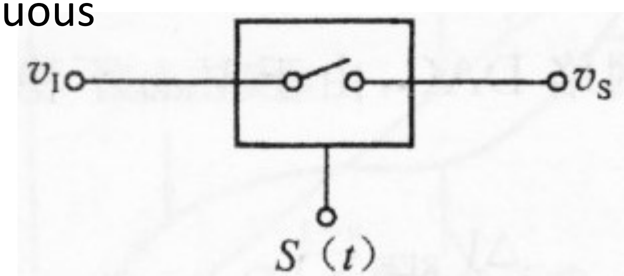
A two-step process

- Sample and hold (S/H)
- Quantize and Encode (Q/E)



Sample and Hold

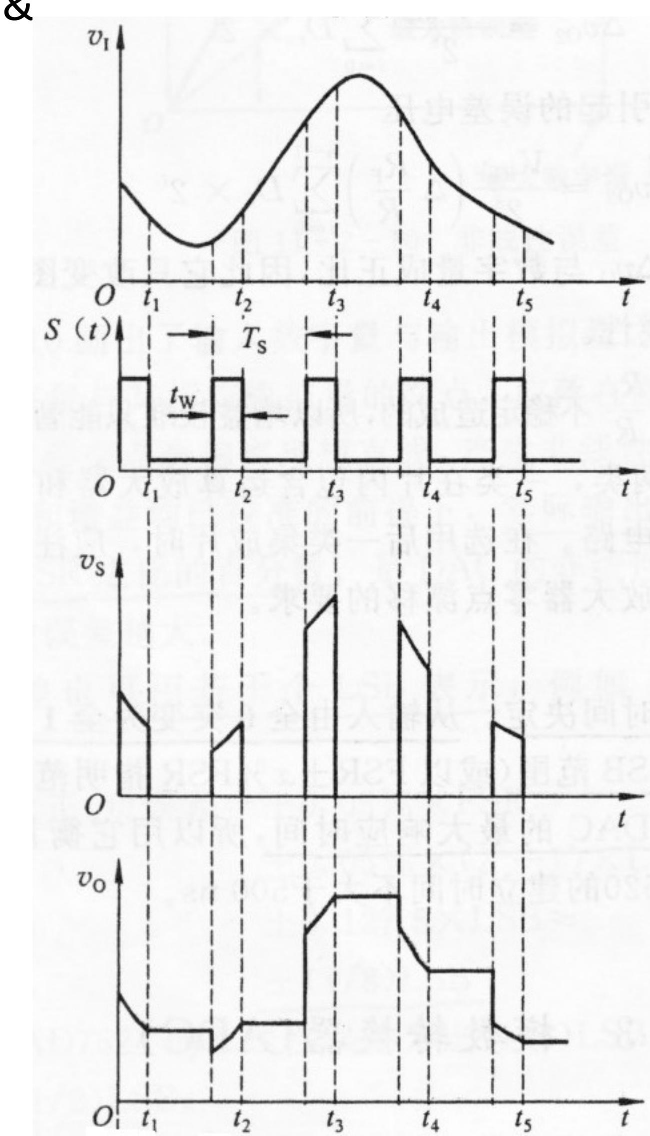
Continuous Input Signal



Sampled & Held Signal

Sampling Signal

- Input signal is sampled for a short duration (switch is closed momentarily)
- Sampled signal is then held steady for digitization



Continuous Signal

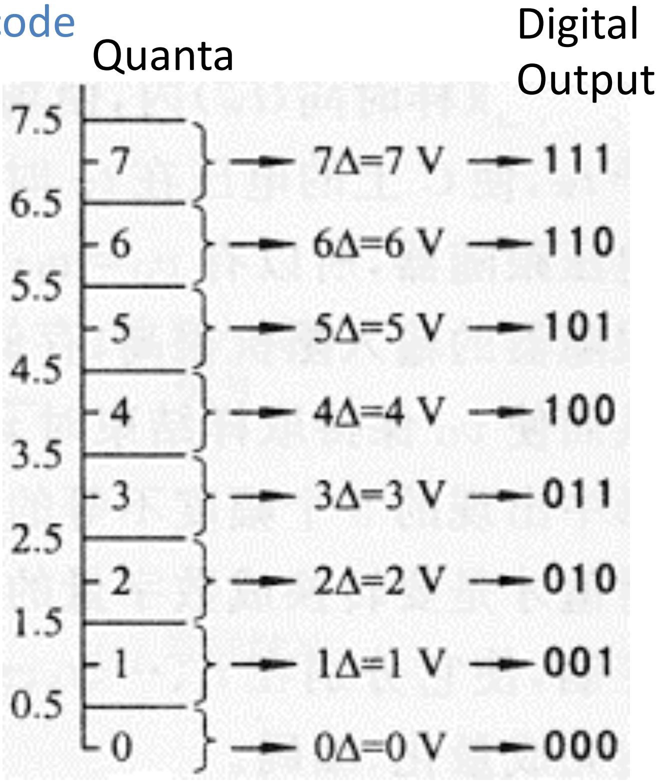
Sampling Signal

Sampled Signal

Sampled & Held Signal

Quantize and Encode

- Quantize
  - A reference voltage range partitioned into a number of discrete quanta
  - Map the input signal to the correct quantum
- Encode
  - Each quantum assigned with a unique digital code
  - Map measured quantum (input signal) to digital code
- Example
  - Reference signal range: 0 to 7.5 V
  - Quantum size: Δ = 1 V
  - Eight quanta: Represent 0, 1, 2,..., 7 V
  - Use three bits to encode eight quanta



ADC Characteristics

Important characteristics

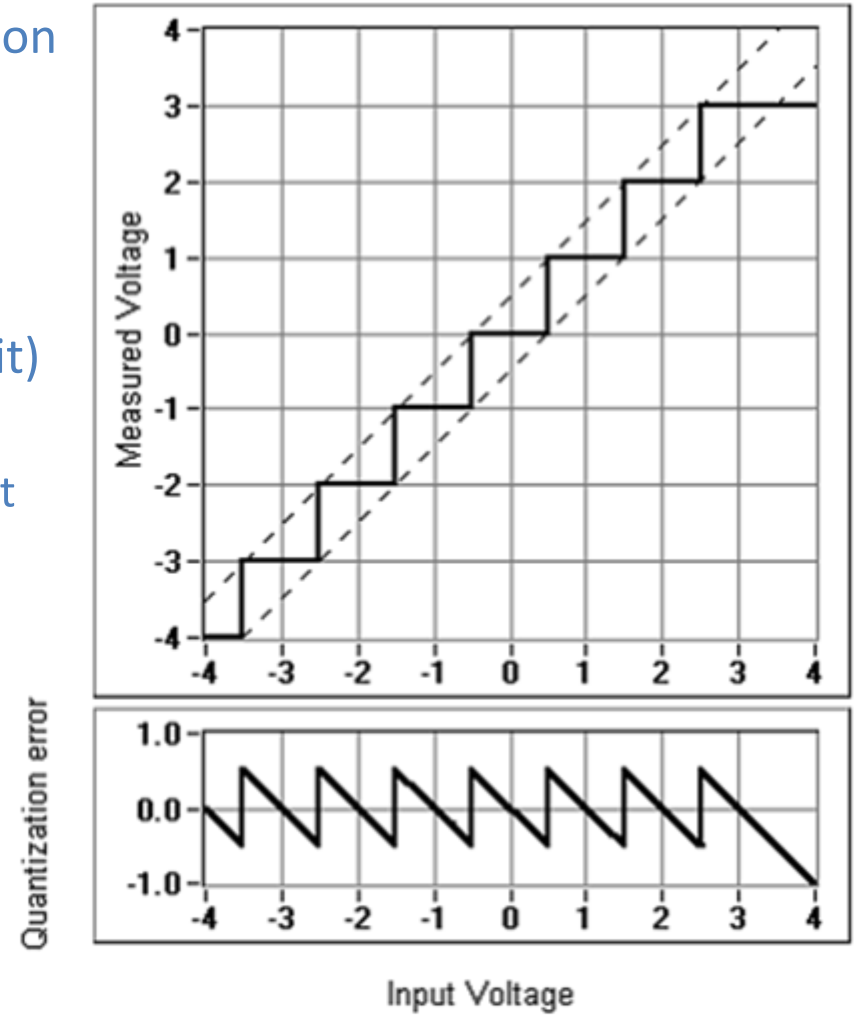
- Resolution
- Quantization error
- Accuracy
- Sampling Rate

Resolution

- The number of bits output by the ADC
- Number of discrete values that represent a range of analog values is equal to 2^N, where N = number of bits of the ADC
- A higher number means better resolution
- Example 1: 12-bit ADC, reference voltage range = 10 V
  - 2^{12} = 4096 discrete values
  - Voltage resolution = 10 / 4096 = 2.44 mV
- Example 2: 10-bit ADC, reference voltage range = 10 V
  - 2^{10} = 1024 discrete values
  - Voltage resolution = 10 / 1024 = 9.77 mV

Quantization Error

- The resolution also directly relates to the quantization error inherent in the conversion of the analog signal to digital form
- Quantization error is how far off discrete value is from actual analog value
- Maximum error: ½ LSB (Least Significant Bit) within the measurable range
  - LSB = smallest level that an ADC can detect
- Error appears as random noise uniformly distributed between ±½ LSB
- Example: 12-bit ADC, voltage range = 10 V
  - 2^{12} = 4096 discrete values
  - LSB = 10 / 4096 = 2.44 mV
  - Max. error = ½ LSB = 1.22 mV

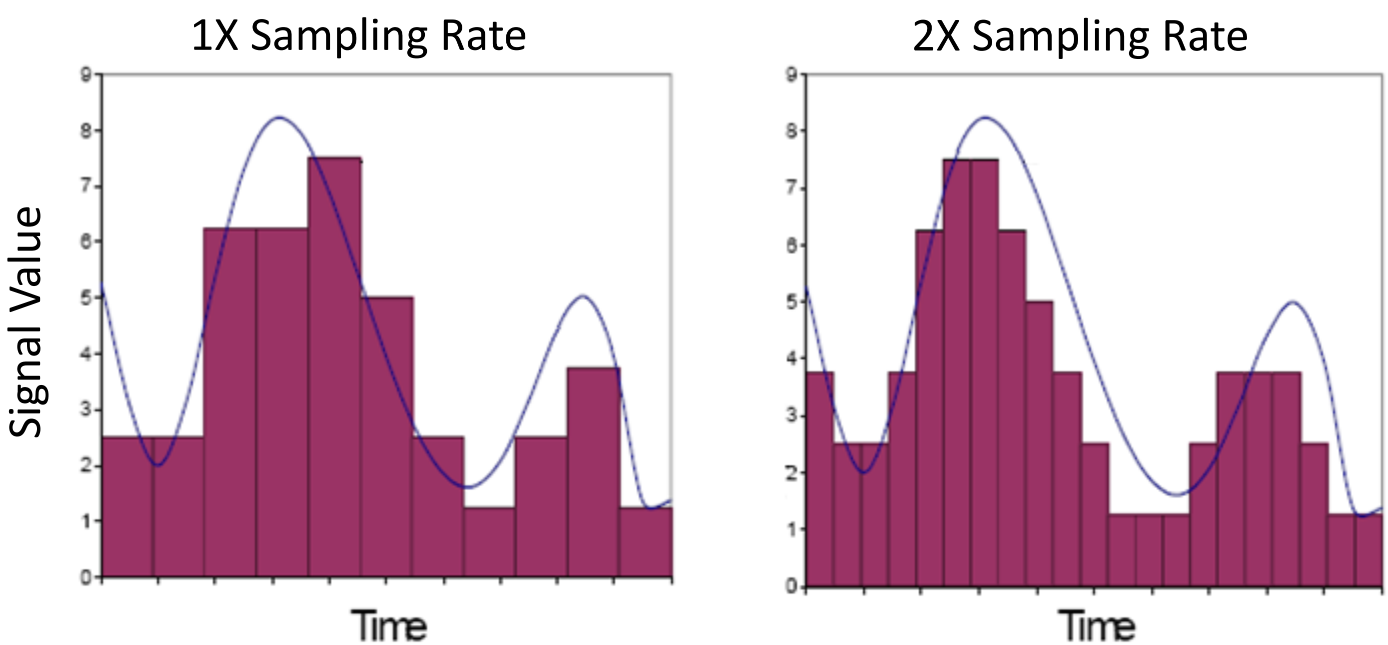


Reference voltage range: -4 to 3 V

Accuracy

Two ways to improve accuracy of A-D conversion

- Increase the resolution
  - Improve the accuracy of the measured magnitude of the analog signal
  - By increasing the number of bits produced by the ADC
- Increase the sampling rate
  - Produce more data points per unit time
  - Digitized signal becomes a better representation of the analog signal



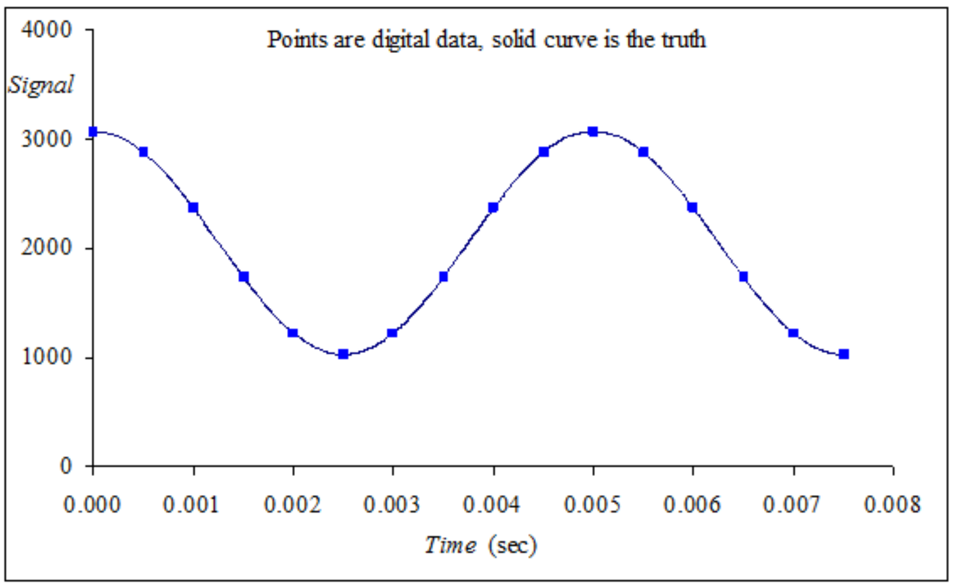
Sampling Rate

- What sampling rate do we need?
  - Too low: Analog signal cannot be adequately represented in digital domain
  - Too high: Waste resources in computation (time) and cost (components)
- Shannon-Nyquist sampling theorem comes to rescue!
- If a continuous-time signal contains no frequencies higher than F_{MAX}, it can be completely reconstructed from discrete samples taken at a rate of twice of F_{MAX} or higher
- Example:
  - Human can process audio signals 20 Hz – 20 kHz
  - Audio sound is typically sampled at 44.1 kHz and stored as digital data in a medium

Aliasing

- Aliasing can occur when the input analog signal oscillates faster than the rate of the ADC sampling the signal
- Example
  - Two sinusoidal signals: one 200 Hz, the other 2200 Hz
  - Sampled at rate of 2000 Hz, i.e., every 0.5 ms
  - Sampled data look exactly the same on both cases
  - But the 2200-Hz signal would be interpreted as a 200-Hz signal — aliasing

200-Hz signal. Properly sampled.



2200-Hz signal. Improperly sampled.

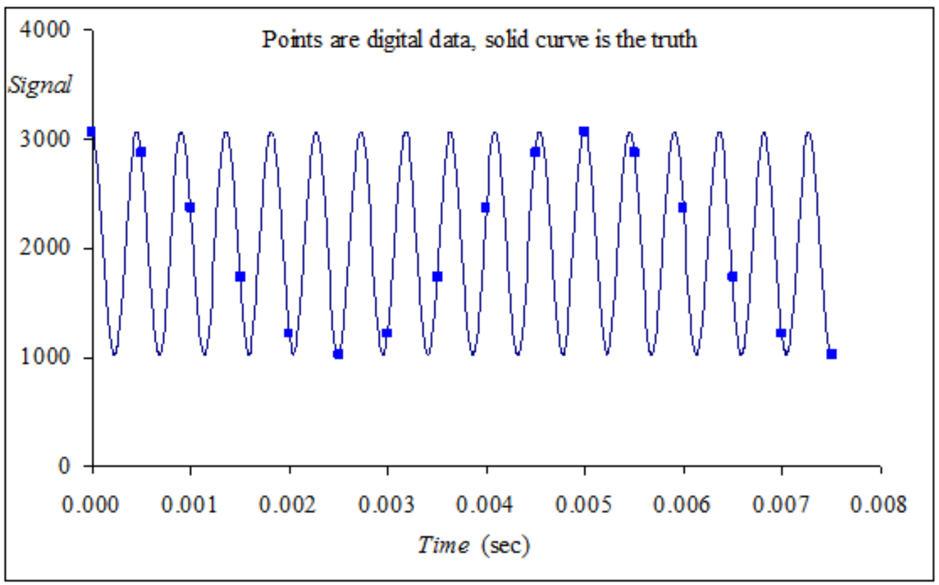
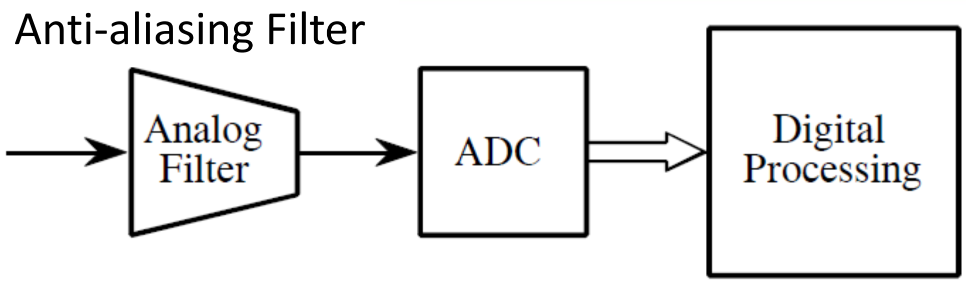
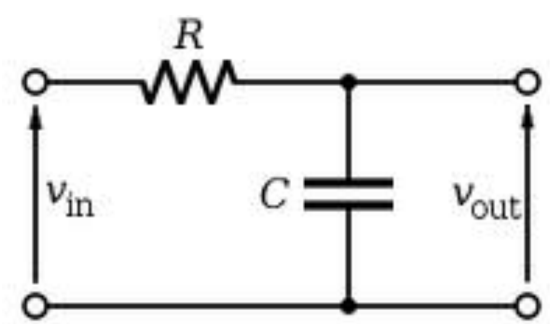


Diagram source: http://users.ece.utexas.edu/~valvano/Volume1/E-Book/C14_ADCdataAcquisition.htm

Anti-aliasing Filter



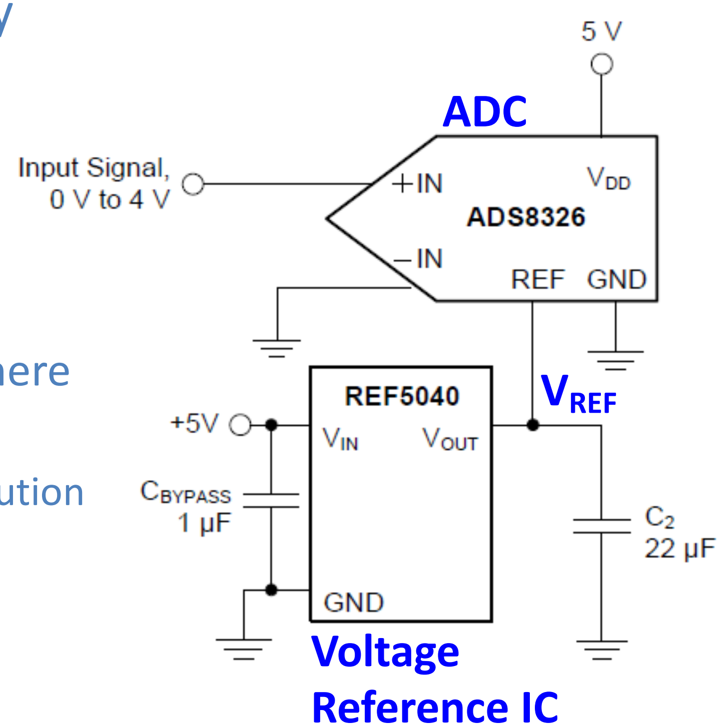
- Use anti-aliasing filter on ADC input to ensure that the Shannon-Nyquist requirement is satisfied
  - Essentially an analog low-pass filter to remove frequency components that are higher than the sampling frequency
- A simple low-pass filter can be implemented using a RC network
  - At high frequencies, the impedance of C is very small compared to R
    - v_{out} is a small portion of v_{in}



SJSU SAN JOSÉ STATE UNIVERSITY

Voltage Reference

- ADC needs a voltage reference to work properly
  - Regular power supply voltage is not adequate
    - An accuracy of 2-5% is common
    - 2% of a nominal 5-V regulator is 100 mV
- Defines the voltage ceiling of A-D conversion
  - Determines the voltage resolution: $V_{REF} / 2^N$, where N=number of bits of ADC
    - 10-bit ADC with 5-V reference ➔ 4.88-mV resolution
  - Affects the precision of A-D conversion
- Usually external to ADC (or MCU)
  - Customize for different applications
- Important attributes: precision, accuracy and low noise
- V_{REF} should be very stable within the operating range of the temperature



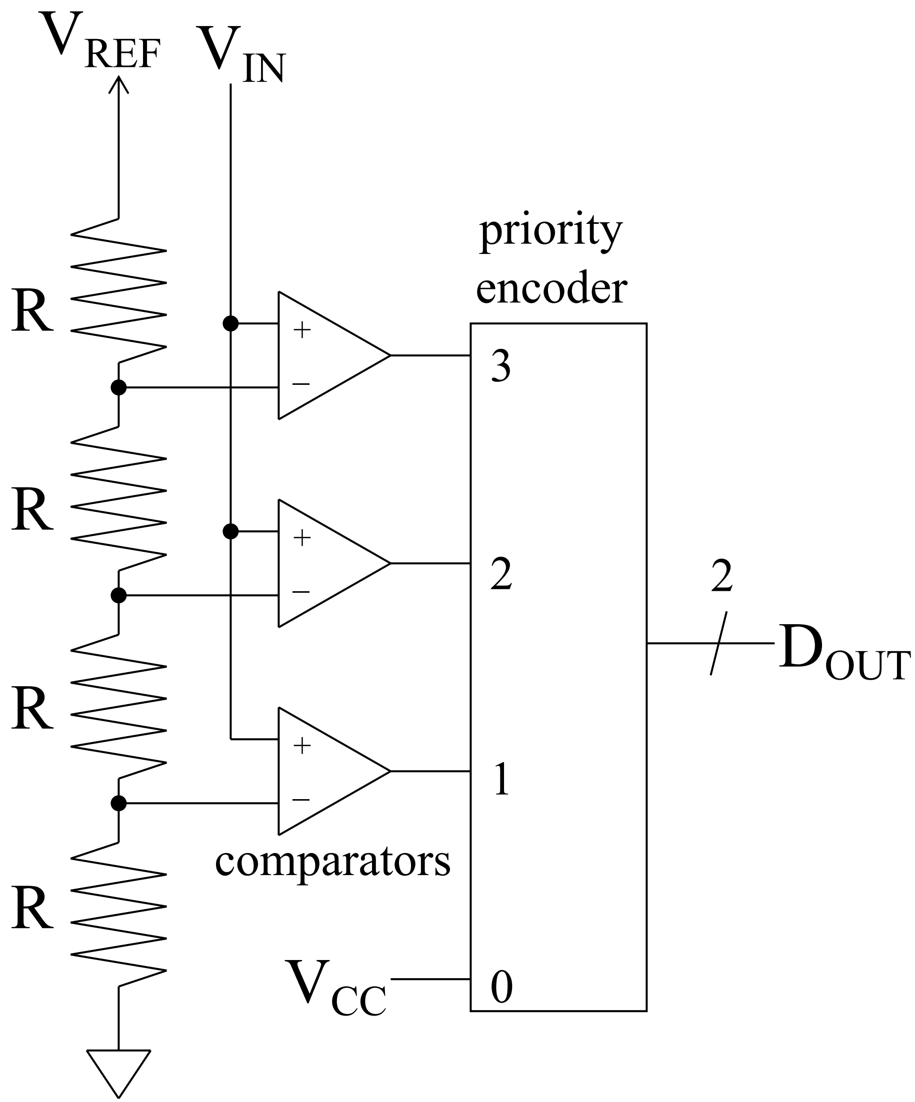
ADC Design

Popular designs

- Flash
- Integrating
- Successive Approximation Register (SAR)

Flash ADC

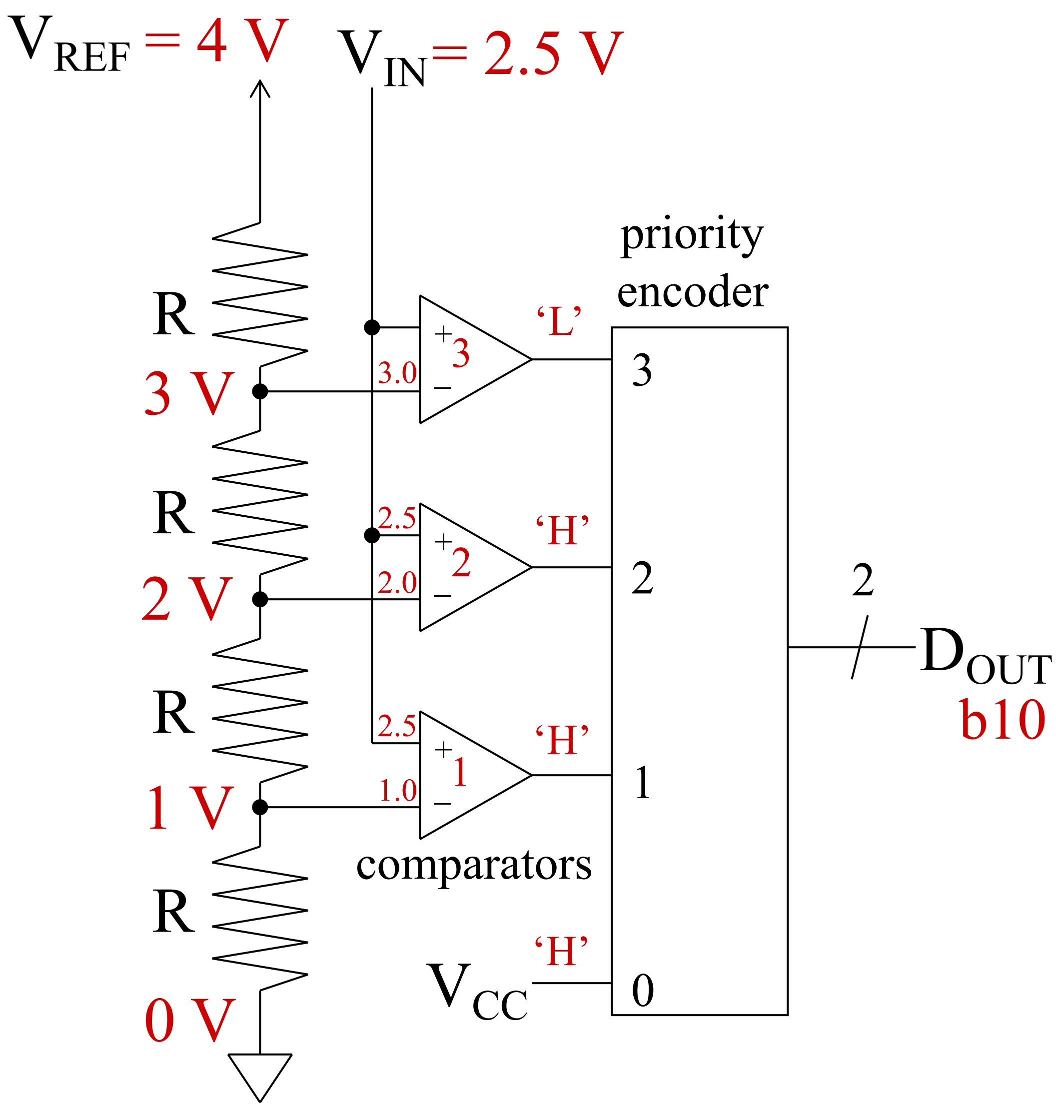
- Consists of a series of comparators
  - Each one compares the input signal to a unique reference voltage
- Comparator outputs a High state if V_{IN} is greater than its reference voltage
- The priority encoder generates a binary number to indicate the highest comparator number with a High state
- Advantages
  - Simple operational theory
  - Fast
- Disadvantages
  - Not scalable to high resolutions
  - High number of components (affects cost and size)



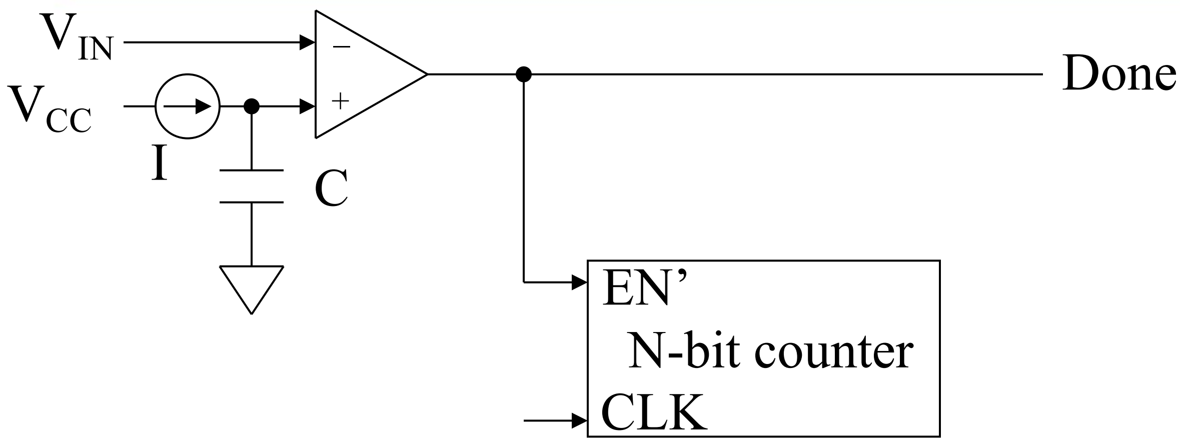
Flash ADC (cont'd)

An example

- V_{REF} = 4 V
- V_{IN} = 2.5 V
- Highest comparator number with High state is 2
- D_{OUT} = 2

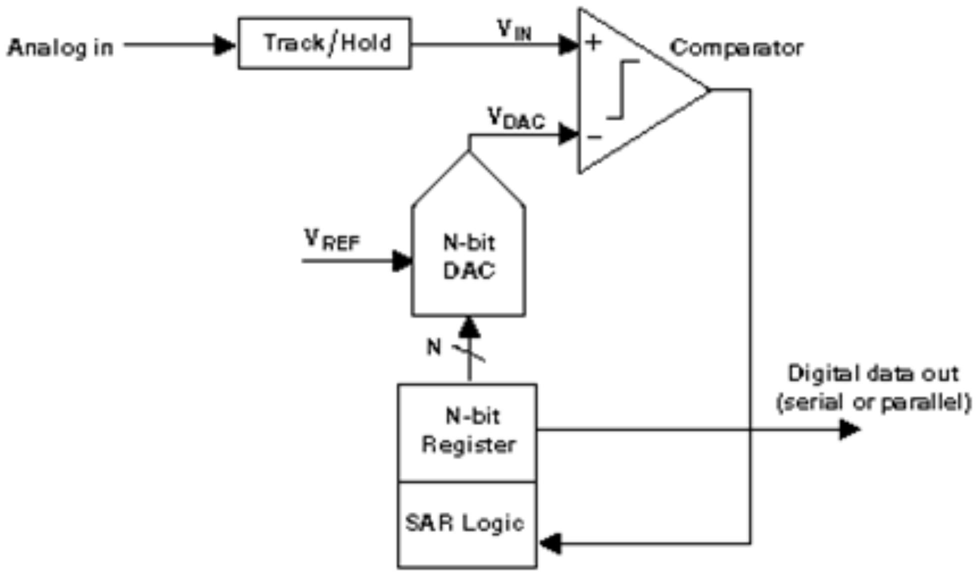


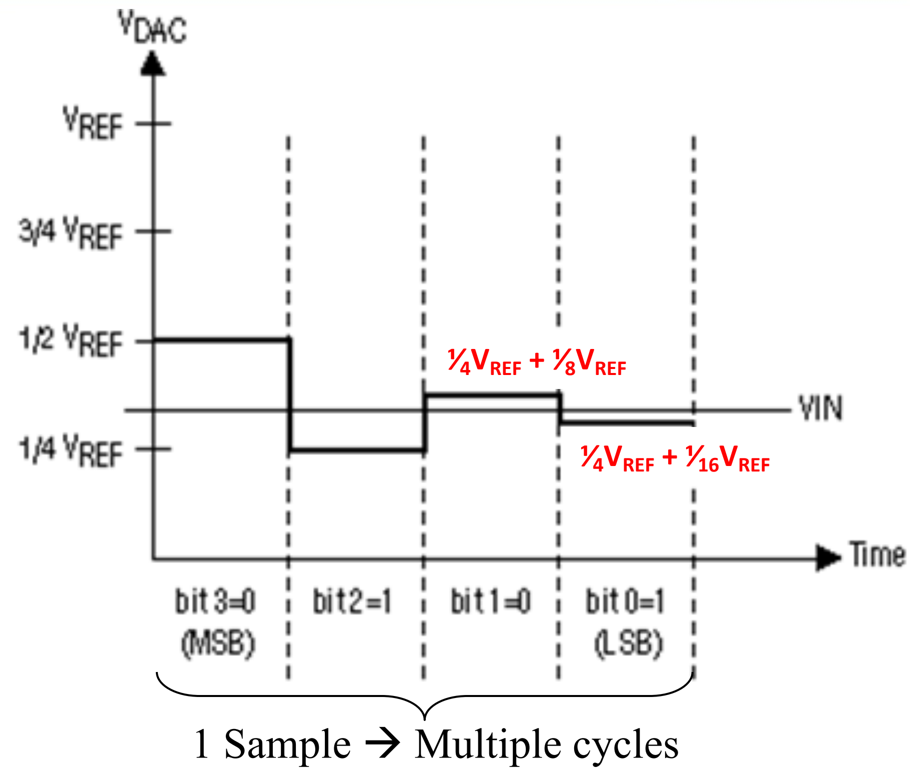
Integrating ADC



- Start: Reset counter, discharge C
- Charge C at fixed current I. Counter increments
- End: $V_C > V_{IN}$. Counter stops incrementing
  - Higher final counter value means higher input voltage
- Advantages
  - Small number of components
  - Scalable to high resolutions
- Disadvantage
  - Slow (higher input voltage means longer conversion time)

Successive Approximation ADC





- Compares V_{IN} with voltage value of each digital output bit
  - Start from MSB and ends at LSB
- Requires N-cycles per sample, where N is # of bits
- Advantage: Good tradeoff between speed and cost
- Disadvantage: Higher resolution means slower conversion