Digital Acquisition of Analog Signals – A Practical Guide

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Senior Design Presentation

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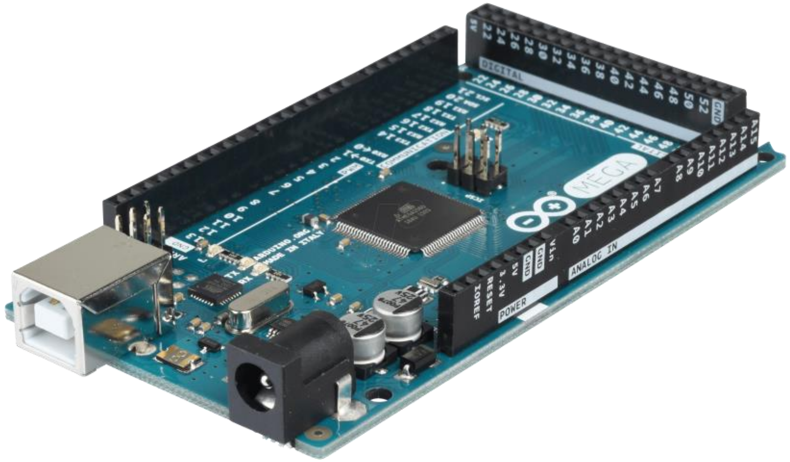
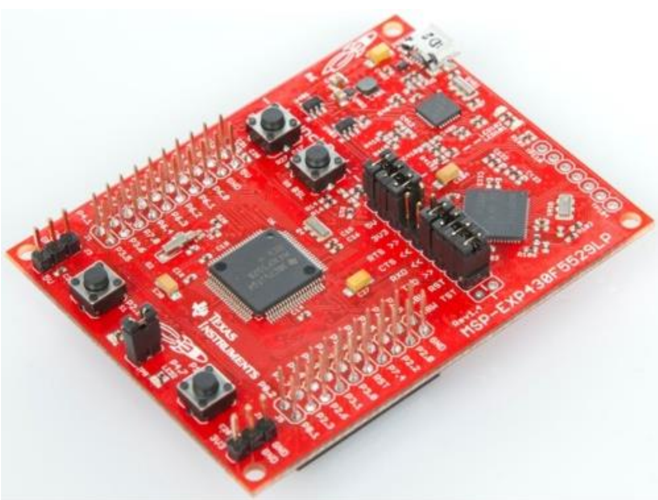
Motivation

- A common task for many senior design projects is to interface an analog signal with a digital system



- The digital system will typically be a microcontroller
  - MSP430
  - Arduino Mega



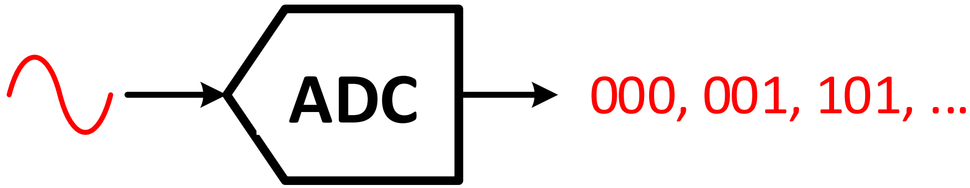
- There are several important considerations that need to be made when performing this type of interface
  - Voltage levels
  - Interface circuits
  - Sampling rates

Outline

- Resolution and Dynamic Range
- Sampling Rate
- Some Common Applications

Interfacing with the ADC

- The analog-to-digital converter takes an analog signal as an input and generates a digital number as the output

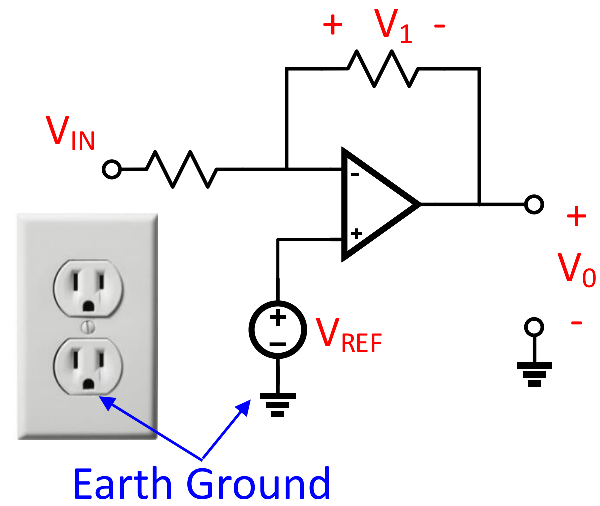


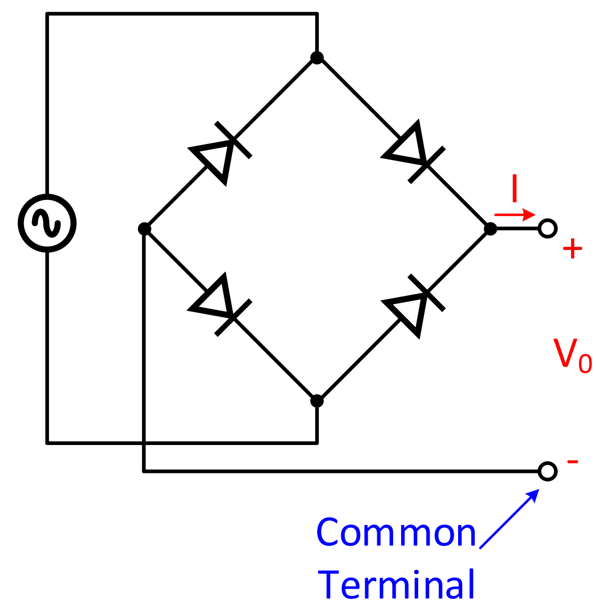
- The ADC has 3 important characteristics
  - Reference Voltage – The maximum voltage that can be converted
  - Resolution – The minimum voltage change that can be detected
  - Sampling Rate – The time interval between consecutive samples

- We will discuss each of these in detail

Interfacing with the ADC

- **All voltages are measured w.r.t. some reference point**
  - Usually the reference point is “ground” or “common”
  - Sometimes the reference point can be another voltage
- **“Earth ground” is a direct connection to the physical earth**
- **“Common” is simply a reference point that is common to the entire circuit**
- **Some power supplies use earth ground as the reference and others use a common terminal as the reference**

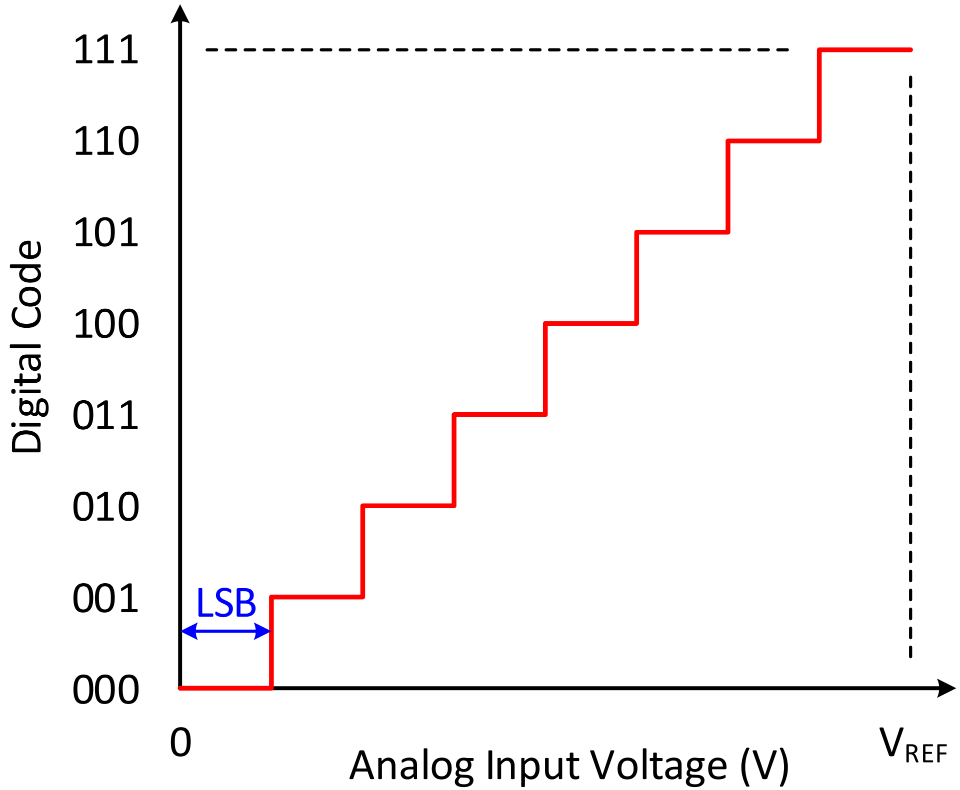




Resolution and Dynamic Range

Resolution and Voltage Levels

- **The reference voltage is the maximum voltage that the ADC can convert**
  - The minimum voltage is typically 0 V
- **The resolution of the ADC is the smallest voltage change that can be measured**



$$V_{LSB} = \frac{V_{ref}}{2^N - 1}$$

V_{ref} – Reference voltage in V

N – Word width of ADC output

Resolution and Voltage Levels

$$\frac{Resolution\ of\ the\ ADC}{System\ Voltage} = \frac{ADC\ Reading}{Analog\ Voltage\ Measured}$$

- Given an analog voltage, we can compute the expected digital output

$$D_N = V_{in}\frac{2^N - 1}{V_{ref}}$$

D_N is an N-bit digital word
V_{in} is the analog input voltage

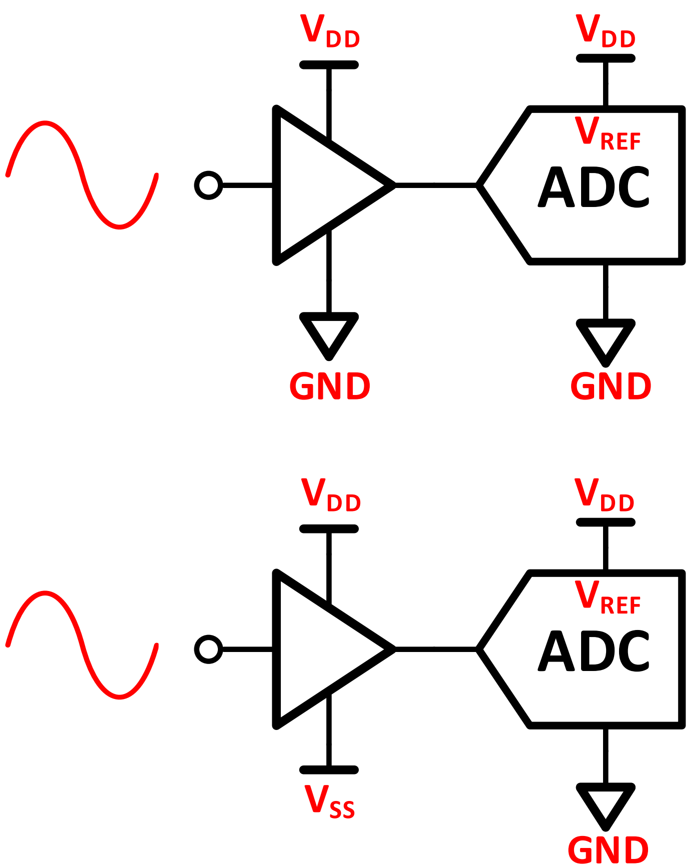
- Given the ADC digital output, we can compute the expected analog input

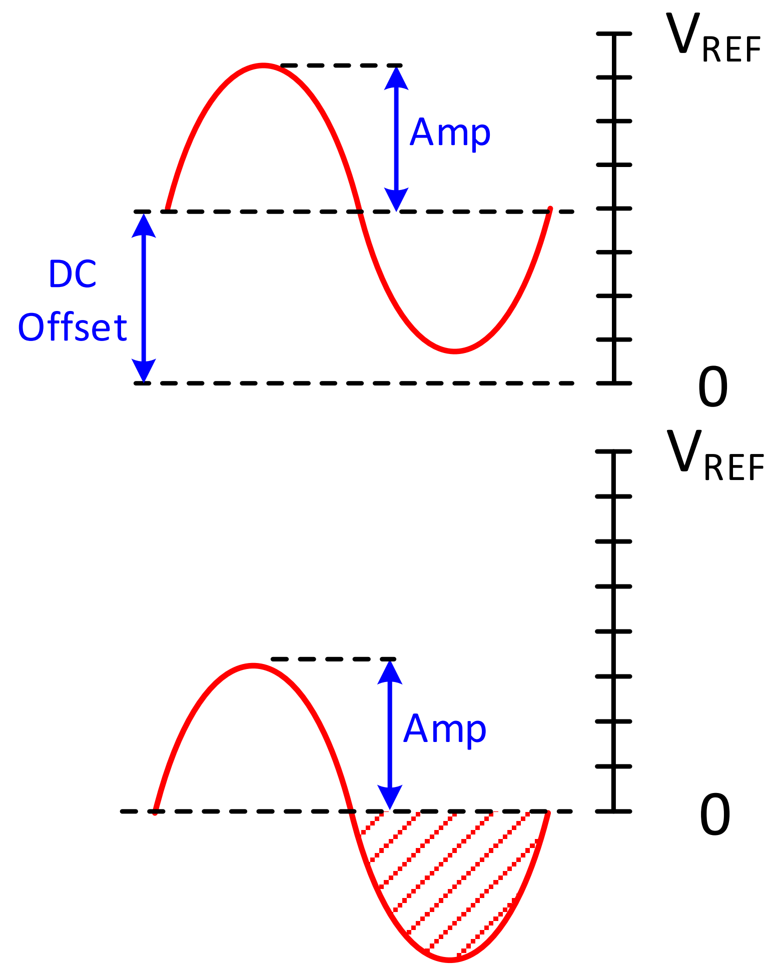
$$V_{in} = \frac{V_{ref}}{2^N - 1}D_N$$

- If $V_{in} \geq V_{ref}$ then D_N is all ONEs
- If $V_{in} \leq 0$ then D_N is all ZEROs

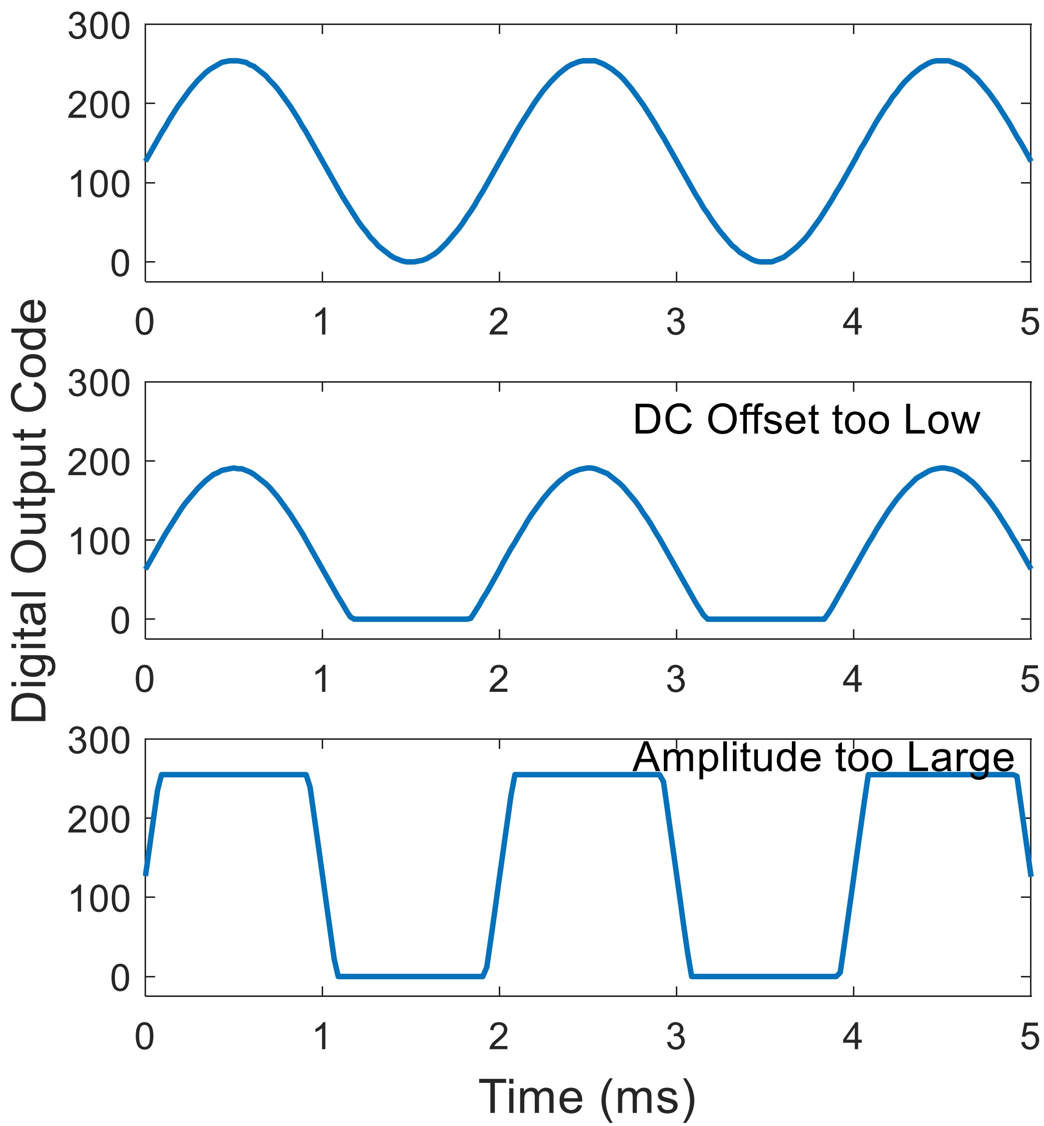
Resolution and Voltage Levels

- In order for your ADC to function properly, your analog input signal must be within range of the ADC reference voltage
  - Pay attention to circuits that require dual-polarity power supplies





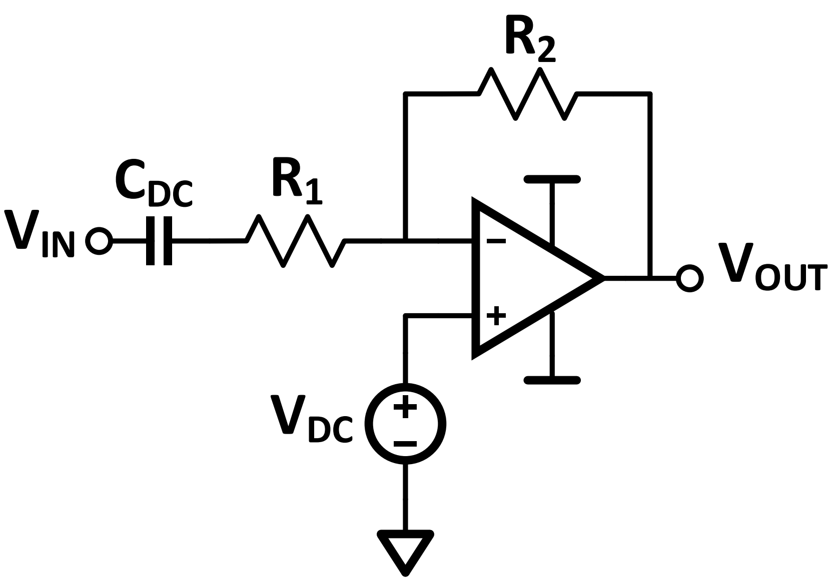
Resolution and Voltage Levels



Resolution and Voltage Levels

- You may not always have the ability to control the DC offset of your analog source

- You can shift the average value (or DC offset) of your input signal externally using an op-amp



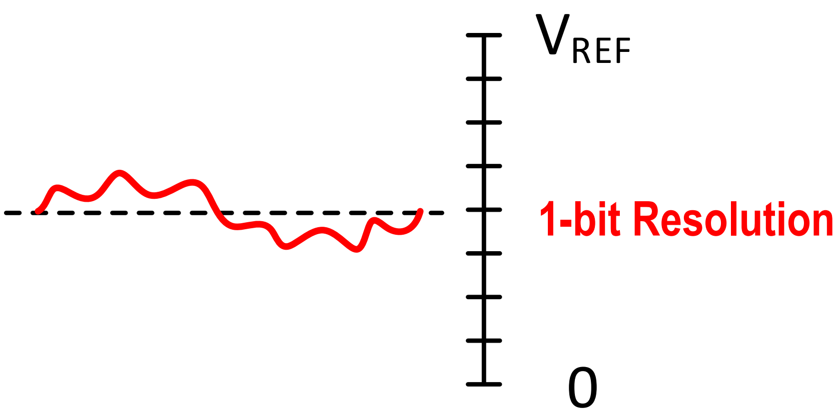
$$V_{OUT} = -V_{IN}\frac{R_2}{R_1} + V_{DC}\left(\frac{R_2}{R_1} + 1\right)$$

To avoid saturating the output:

$$\frac{V_{SS} + |V_{in,max}|\frac{R_2}{R_1}}{1 + R_2/R_1} \leq V_{DC} \leq \frac{V_{DD} - |V_{in,max}|\frac{R_2}{R_1}}{1 + R_2/R_1}$$

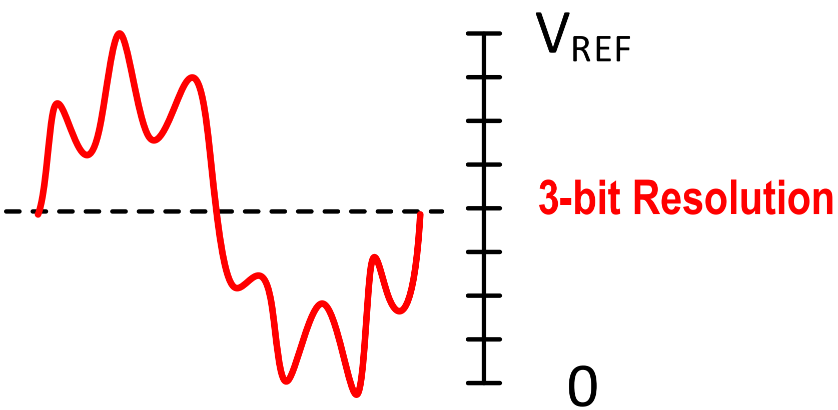
Resolution and Voltage Levels

- Maximum resolution will only be achieved with full-scale input



- For inputs with fixed amplitude
  - Increase gain before ADC
  - Set the correct V_{REF}

MSP432	ATmega328
1.2 V	Av_{cc} (5 V)
1.45 V	1.1 V
2.5 V	Externally Set
Externally Set	



Resolution and Voltage Levels

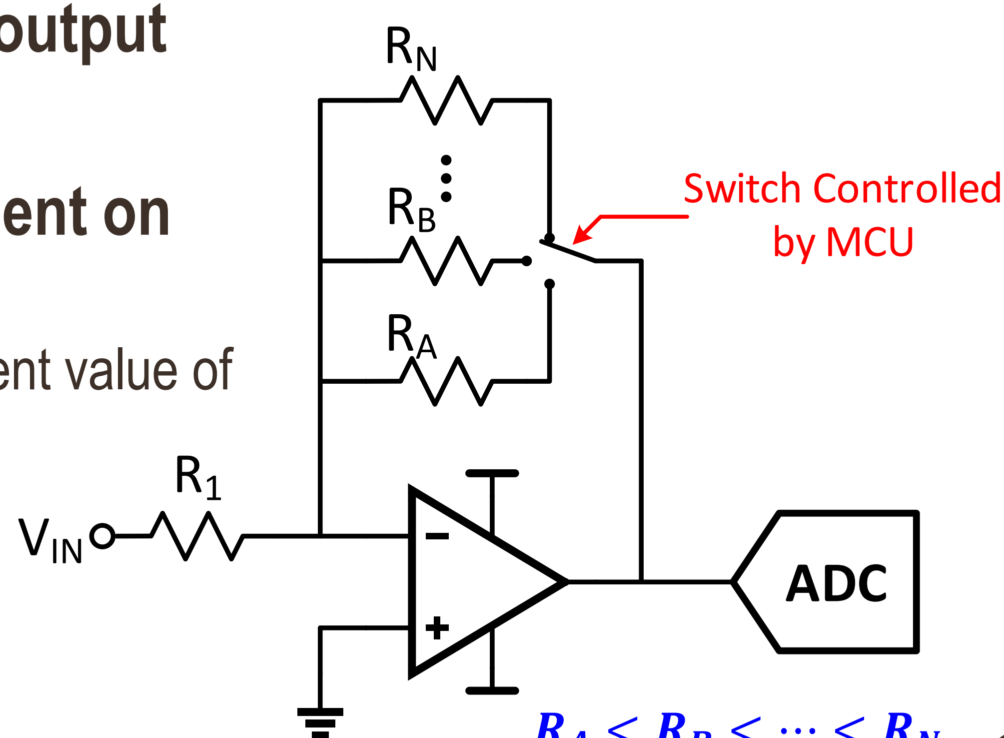
- **For inputs with large dynamic range**
  - Variable gain block will provide best resolution

$D_8 \geq 0b11111xxx$ then decrease gain

$D_8 \leq 0b00000xxx$ then increase gain

$$0.03V_{ref} \leq V_{in}G \leq 0.97V_{ref}$$

- **Gain is controlled by ADC output**
- **ADC output is now dependent on the gain**
  - The MCU must know the current value of gain

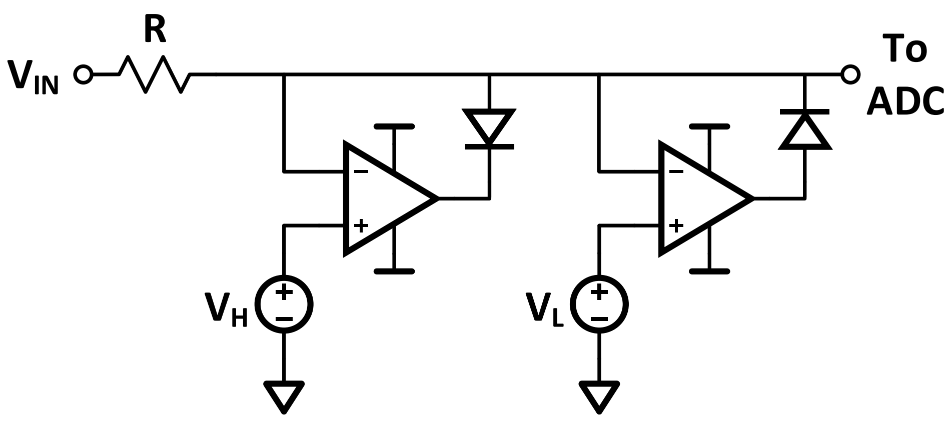


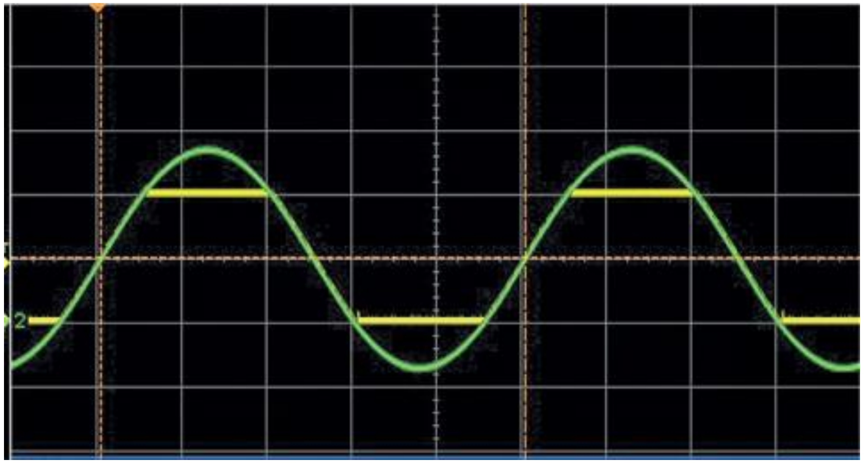
$$G \cdot V_{in} = \frac{V_{ref}}{2^N - 1} D_N$$

$R_A < R_B < \cdots < R_N$

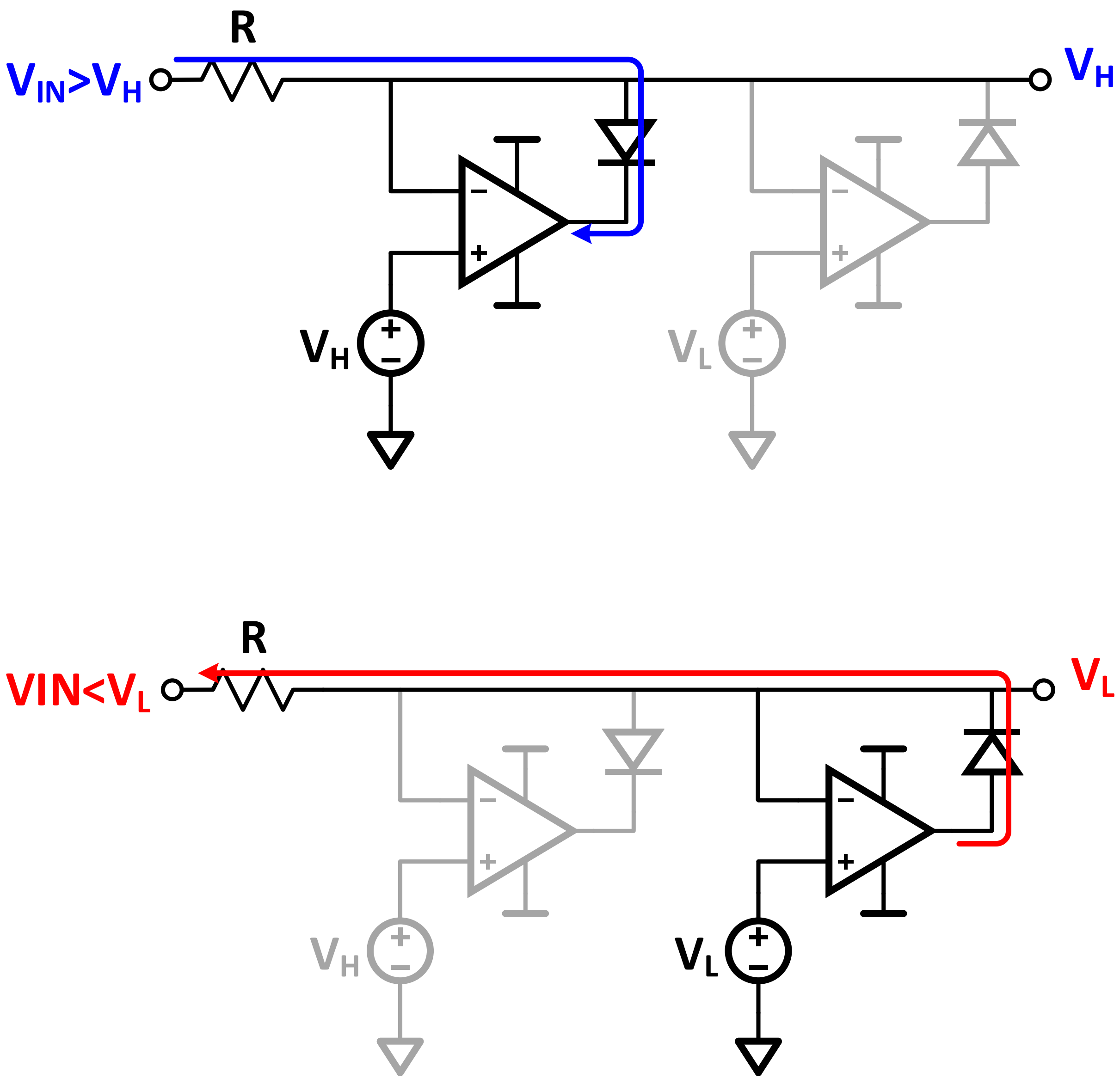
Resolution and Voltage Levels

- **The analog supply voltage may be larger than the ADC supply voltage**
  - This is okay if the analog signal is still within safe operating limits of the ADC
- **During power up or for invalid inputs the analog signal may exceed safe operating voltages for the ADC**
  - You should limit (or clamp) the analog input signal
- **The output is limited to:** $V_L \leq V_{OUT} \leq V_H$
- R **is required to limit the current flowing into the output of the op-amps**





Resolution and Voltage Levels



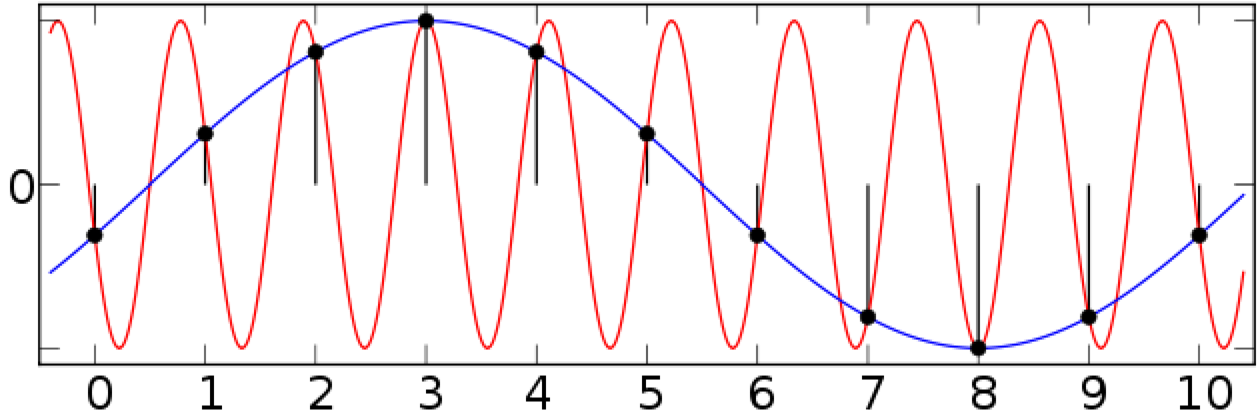
Sampling

ADC Sampling Rate

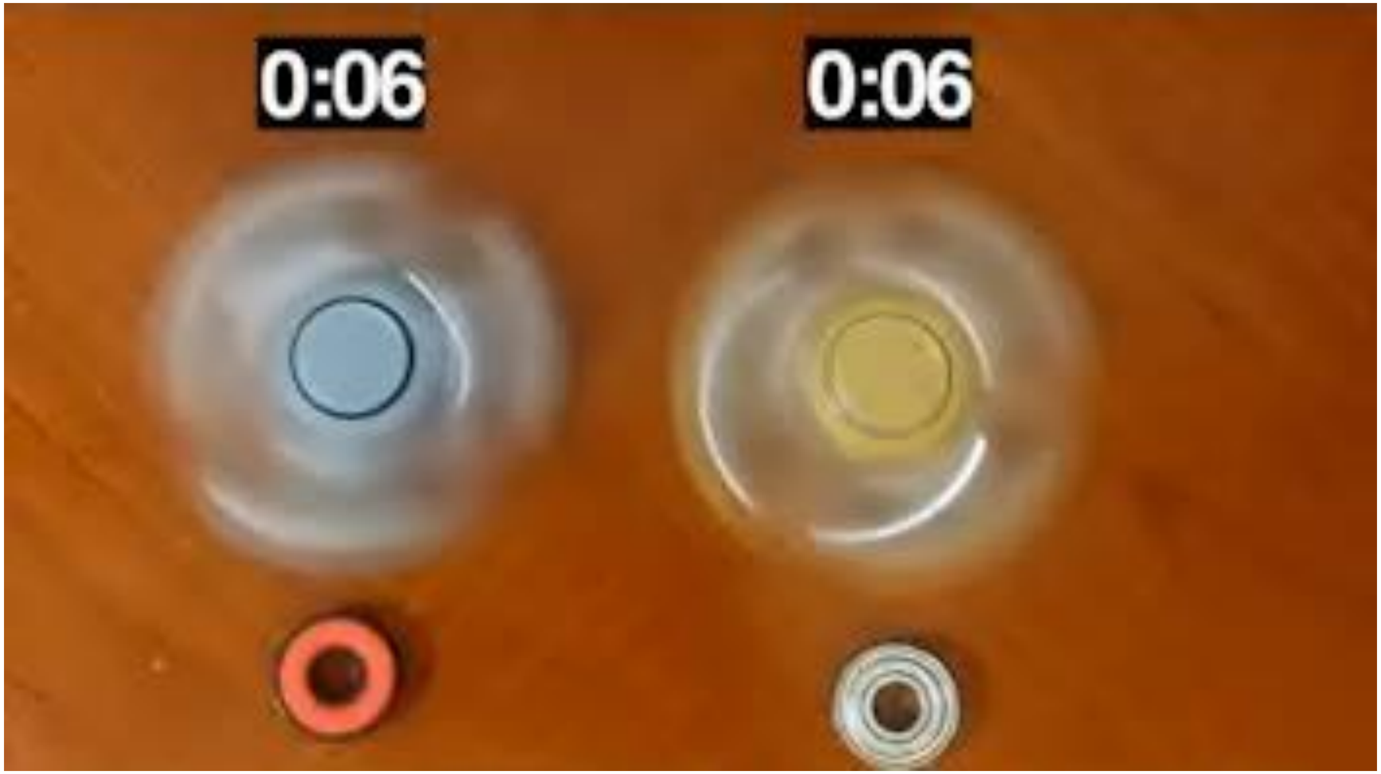
- One of the most important characteristics of the ADC is the sampling rate

The sampling rate must be at least twice the highest frequency of interest

- If the sampling rate is too low you will get <u>aliasing</u>
- Aliasing is an effect that causes signals with different frequencies to become indistinguishable



ADC Sampling Rate



Video taken from: https://www.youtube.com/watch?v=vLL-T4Z_TNo

ADC Sampling Rate

- Sweep the frequency of a sinusoidal signal from $20\ Hz$ to $15\ kHz$

- Sine wave sampled at $f_S = 44.1\ kHz$
  - No aliasing

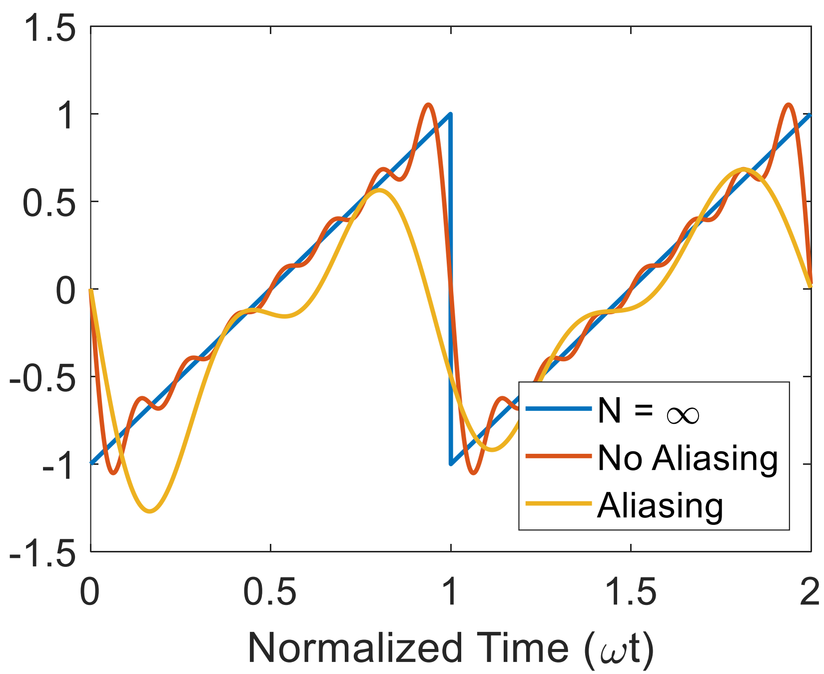
- Sine wave sampled at $f_s = 10\ kHz$
  - Aliasing at high frequencies

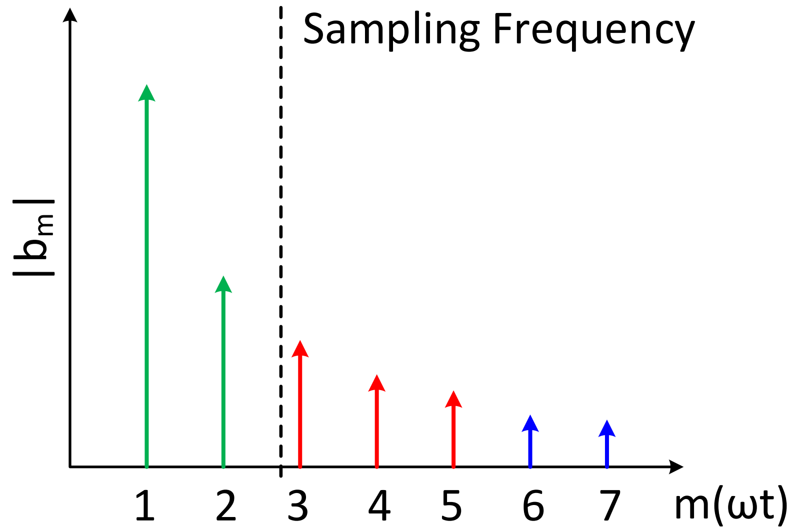
- Saw tooth wave sampled with $f_S = 30\ kHz$
  - Why is there still aliasing at high frequencies?

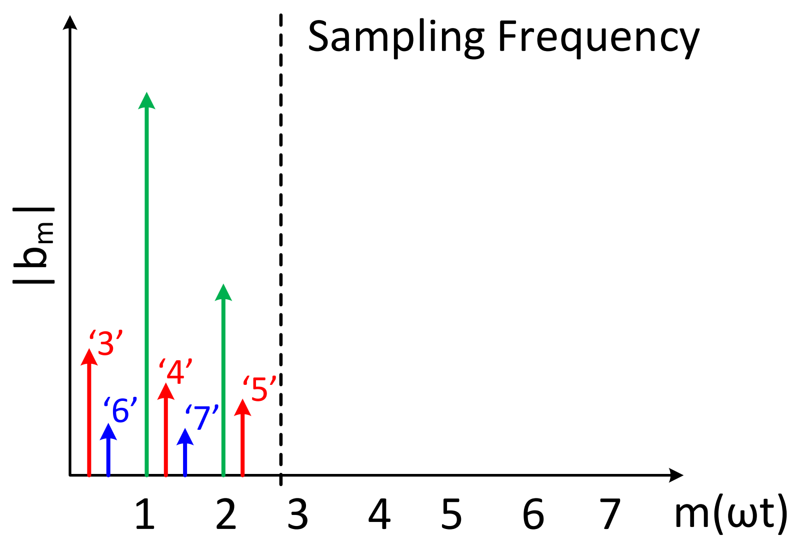
ADC Sampling Rate

- The Fourier series expansion for the Saw tooth wave:

$$f(t) = -\frac{2}{\pi}\sum_{m=1}^{\infty}\frac{\sin(m\omega t)}{m}$$

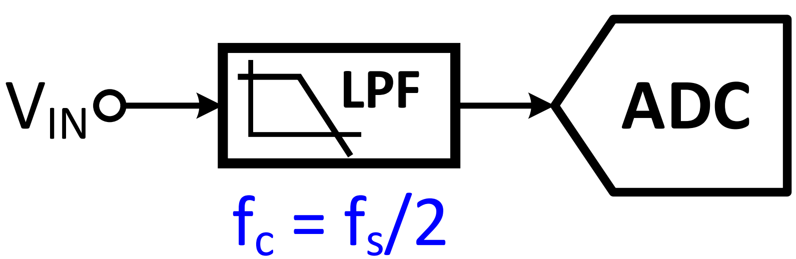


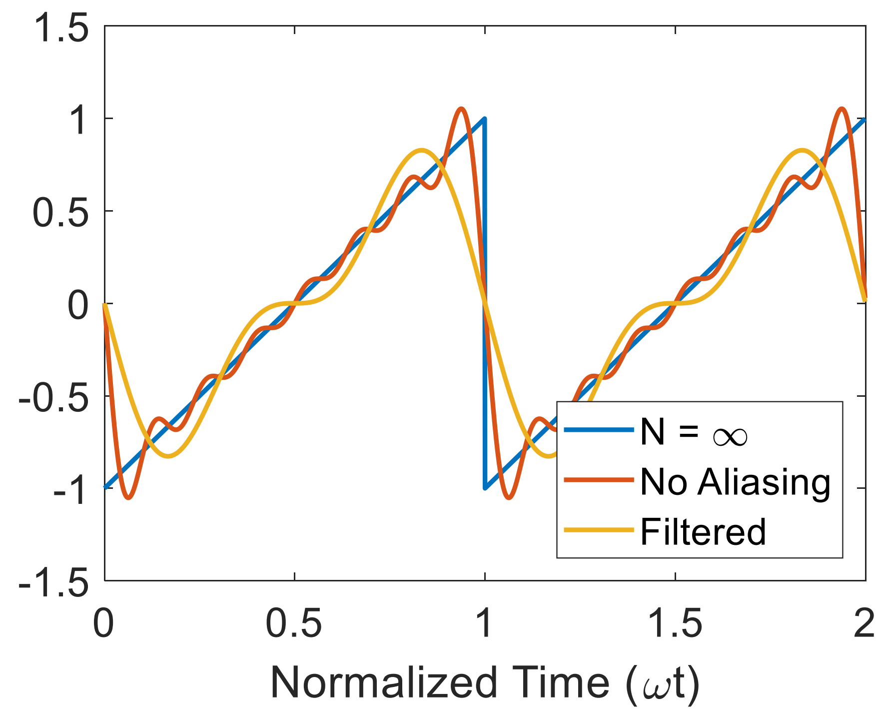




ADC Sampling Rate

- When choosing a sampling rate you must know something about the frequency content of your signal
- An anti-aliasing filter should be used to limit the bandwidth



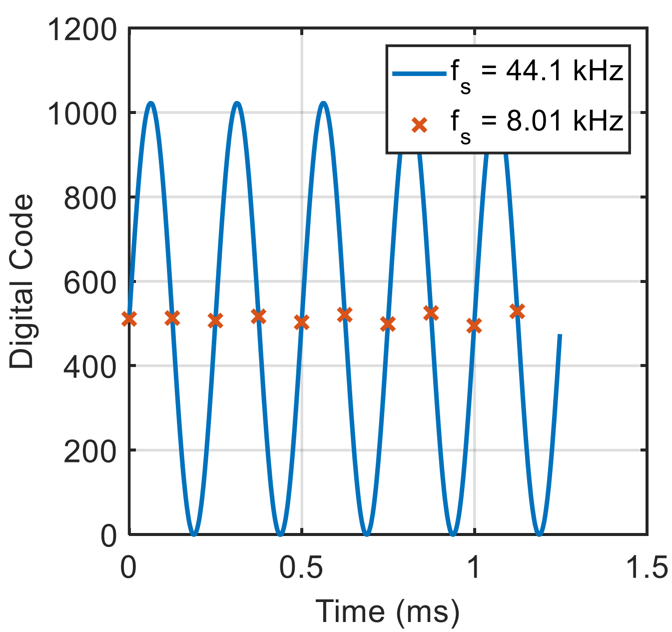


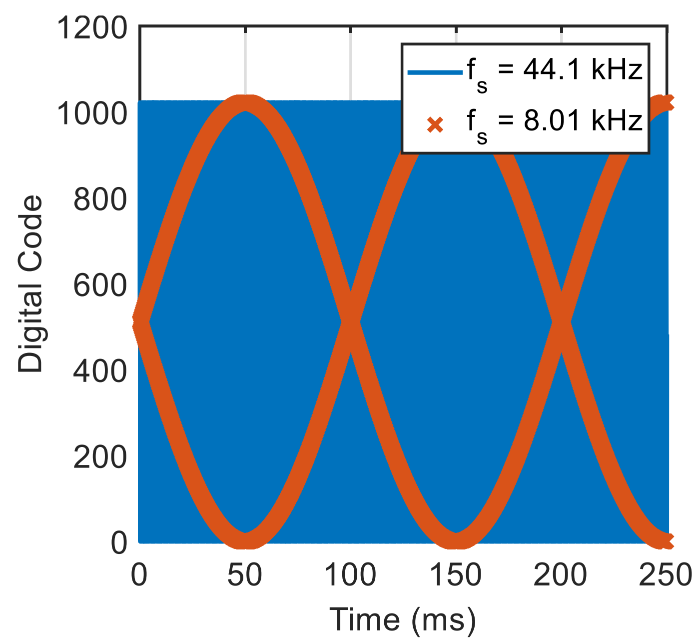
ADC Sampling Rate

- Often you will need to sample signals very close to the Nyquist rate

- Care must be taken when using low sampling rates

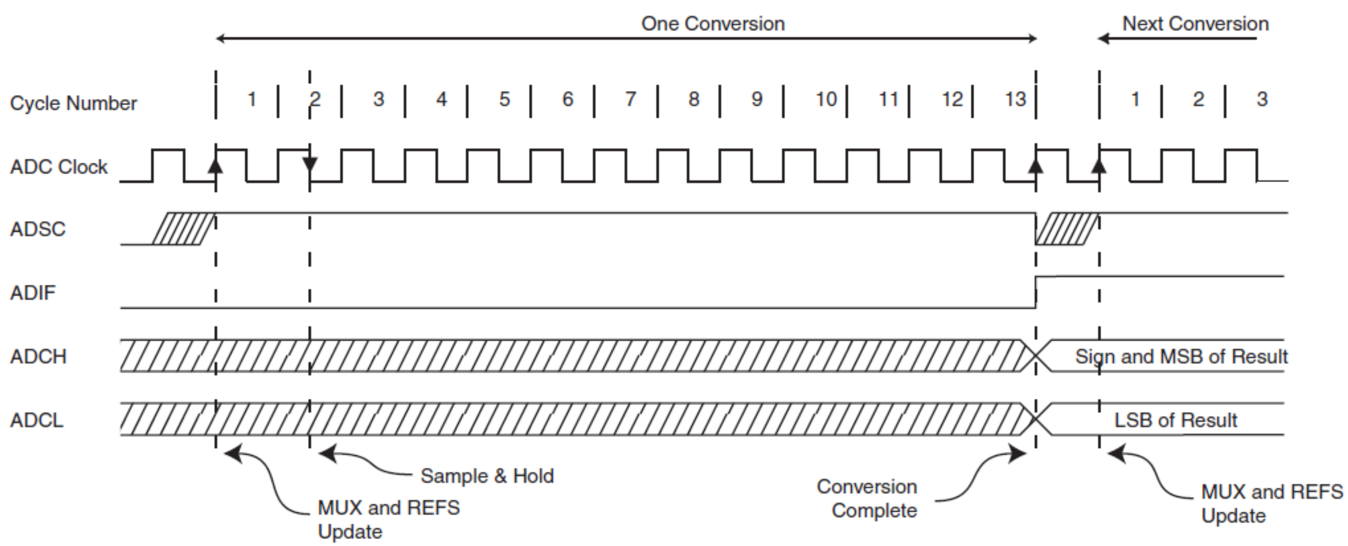
$$V_{in}(t) = sin\left(8\pi \times 10^3 t\right)$$





ADC Sampling Rate

- So how do we control the sampling rate?
- Default Arduino ADC clock rate is $f_{ADC} = 125\ kHz$
- Normal conversion requires 13 clock cycles or $104\ \mu s$
  - Maximum sampling rate is 9,615 Hz
- The actual sampling rate depends on your implementation



ADC Sampling Rate

- The serial monitor is a very useful debugging tool for Arduino
- It is common to embed the ADC conversion function into the main loop
- Takes approximately 284 μs to execute this loop
- Actual sampling rate is **3,521 Hz**!

<u>Sample Arduino Code</u>

```
int analogPin = 3;
int val = 0;

void setup() {
     Serial.begin(9600);
}

void loop() {
    val = analogRead(analogPin);
    Serial.print(“Value is: “);
    Serial.println(val);
}
```

ADC Sampling Rate

- A much better way is to use timers and interrupts
- Sampling rate is now tightly controlled by the timer
- Sampling rate is still limited by other code and resolution of timer

Sample Arduino Code

```
#include “TimerOne.h”

int analogPin = 3;
int val = 0;

void setup() {
   Timer1.initialize(1000);
   Timer1.attachInterrupt(callback);
}

void callback() {
   val = analogRead(analogPin);
}

void loop() {
   // Do something with val
}
```

Common Applications

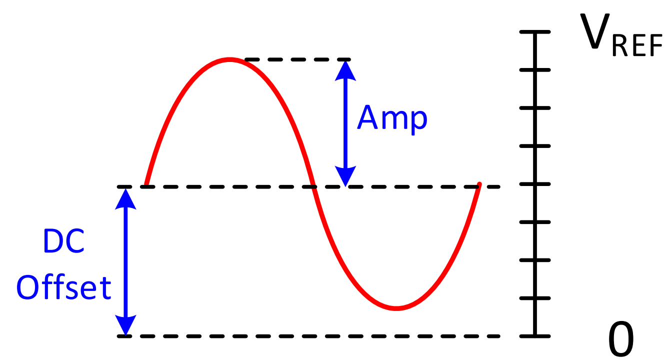
Measuring Amplitude

- Measuring the amplitude of an unknown AC signal with respect to ground

$$V(t) = V_{DC} + Asin(\omega t + \theta)$$

$$v[n] = v_{DC} + Asin\left(2\pi \frac{f}{f_S} n + \theta\right)$$

- A common method for finding amplitude is to find the maximum value of $v[n]$
  - Do not forget the DC offset

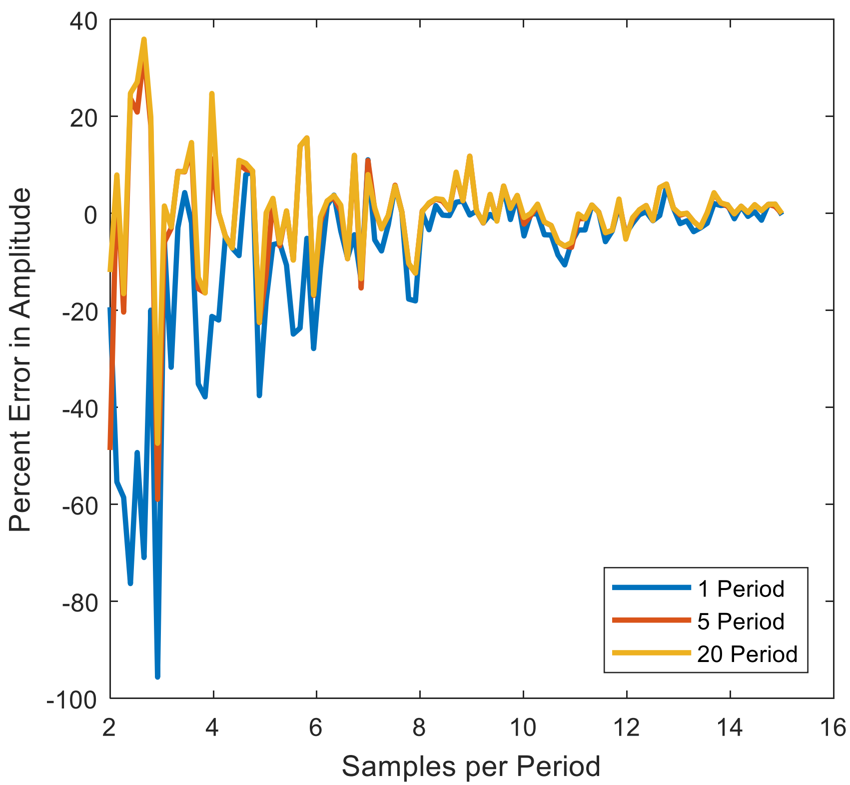


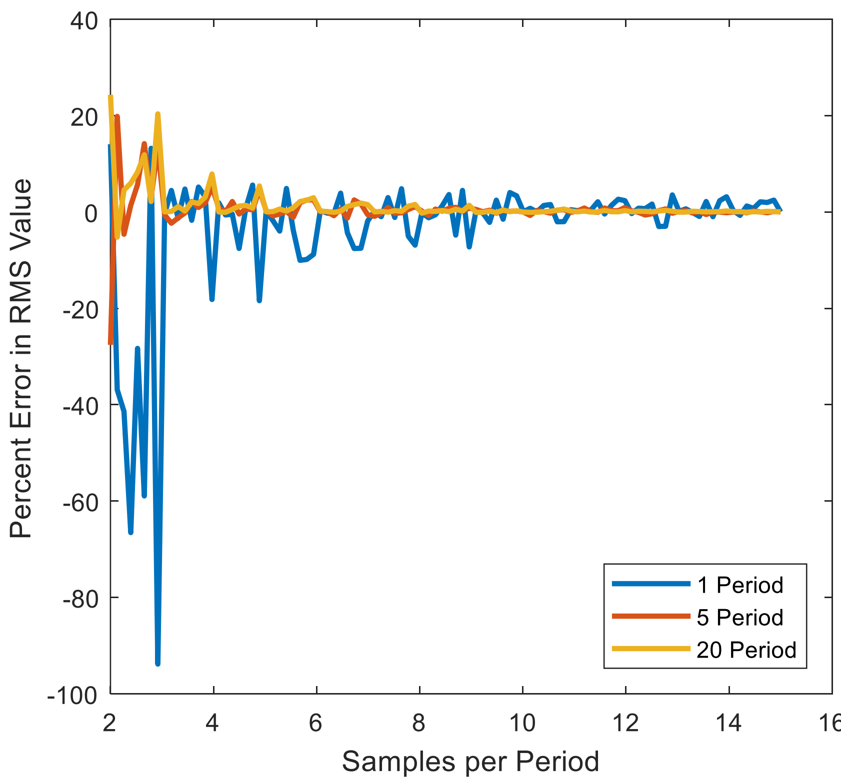
- Does sampling rate matter?

Measuring Amplitude

- Accuracy can be improved by taking at least 5 samples per period
- Measuring RMS voltage is a bit more accurate

$$RMS\{v[n]\} = \sqrt{\frac{1}{N}\sum_{n}(v[n] - V_{DC})^2}$$

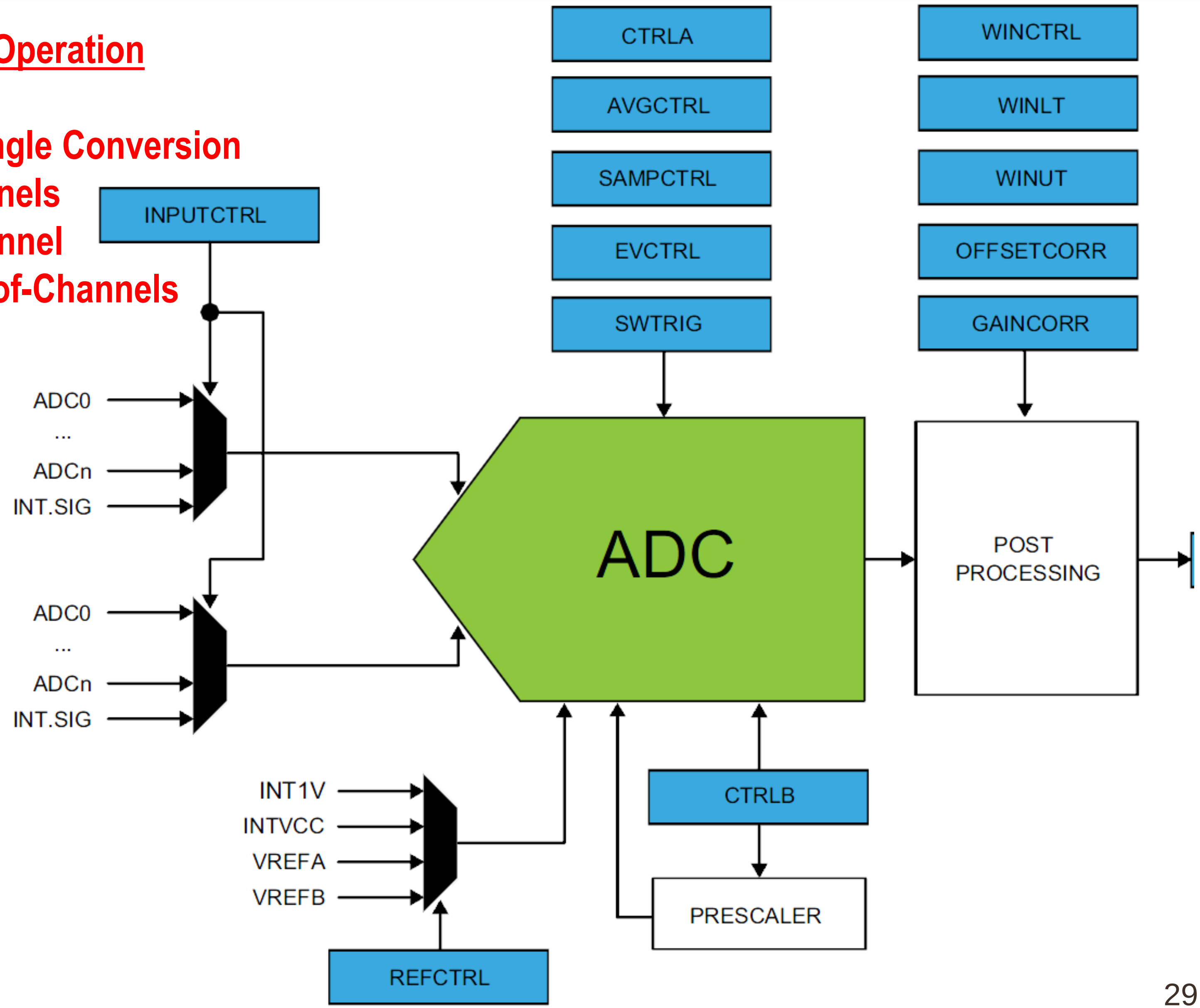




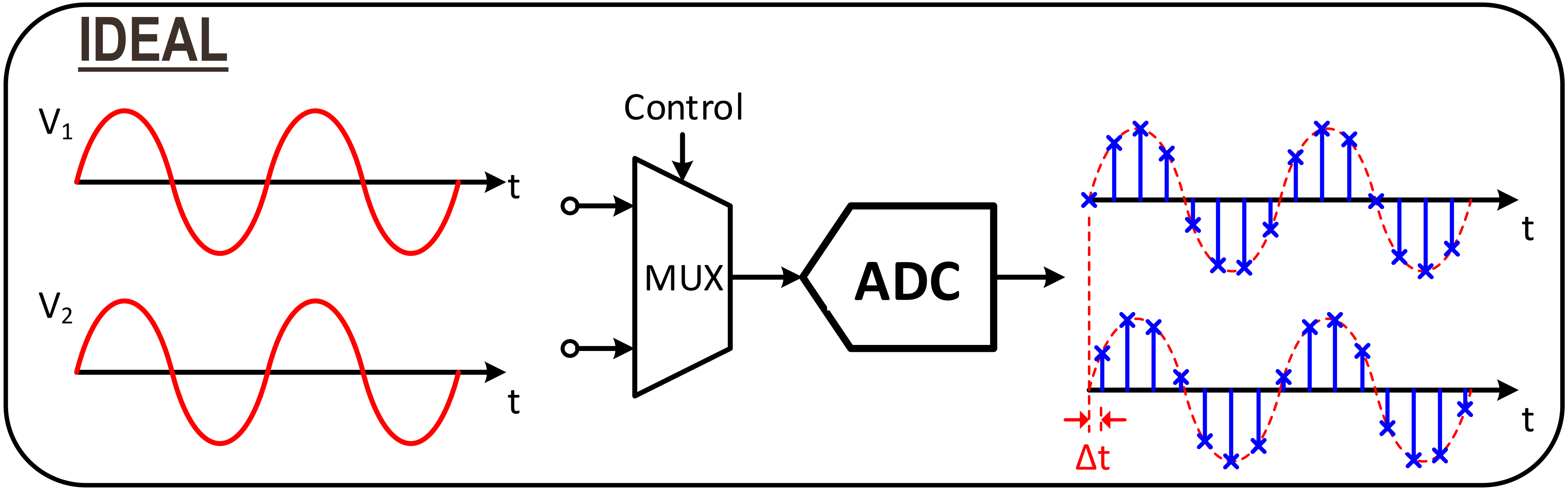
Digitizing Multiple Signal Sources

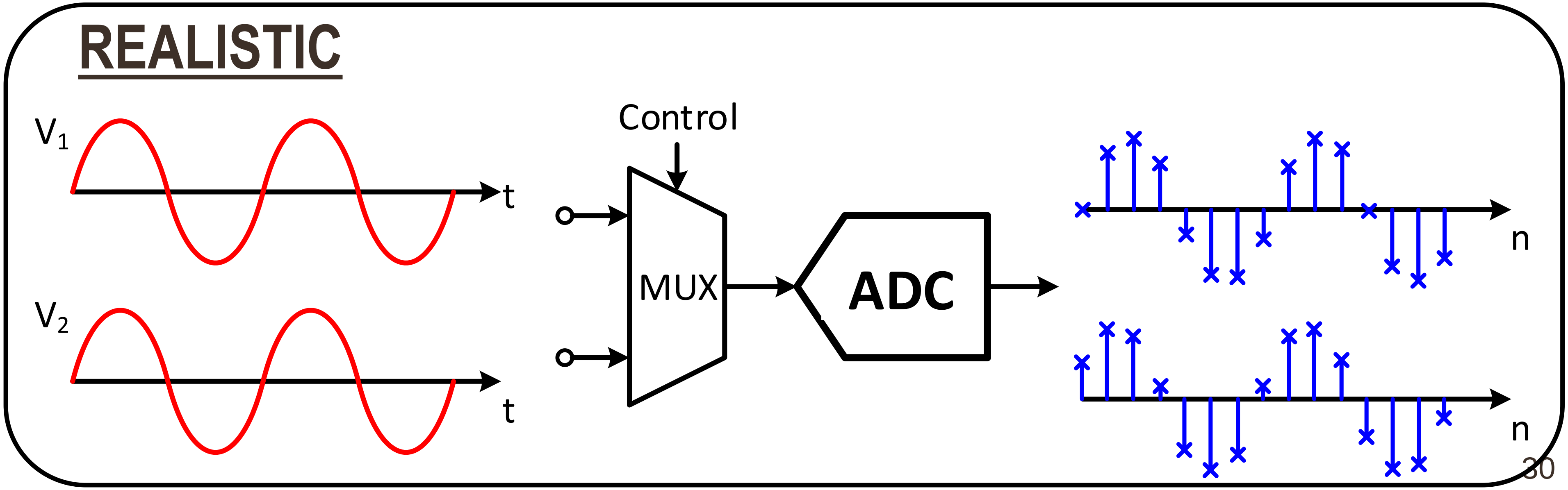
Four Modes of Operation

1. Single-Channel Single Conversion
2. Sequence-of-Channels
3. Repeat Single-Channel
4. Repeat Sequence-of-Channels



Digitizing Multiple Signal Sources





Summary

- **Make sure that your analog input signal is within the valid range of the ADC**
- **For maximum resolution, you want the input signal to be close to V_{ref}**
  - Variable amplification may be necessary
- **Make sure that you are sampling above the Nyquist rate**
  - Watch out where you place your conversion enable code
- **You should always low-pass filter your input signal before digitization**
  - Avoid unwanted aliasing
  - Minimize noise contribution from any gain blocks

Thank You