BIRZEIT UNIVERSITY
Department of Mechanical and
Mechatronics Engineering

ENMC3361
Sensors and Instrumentation

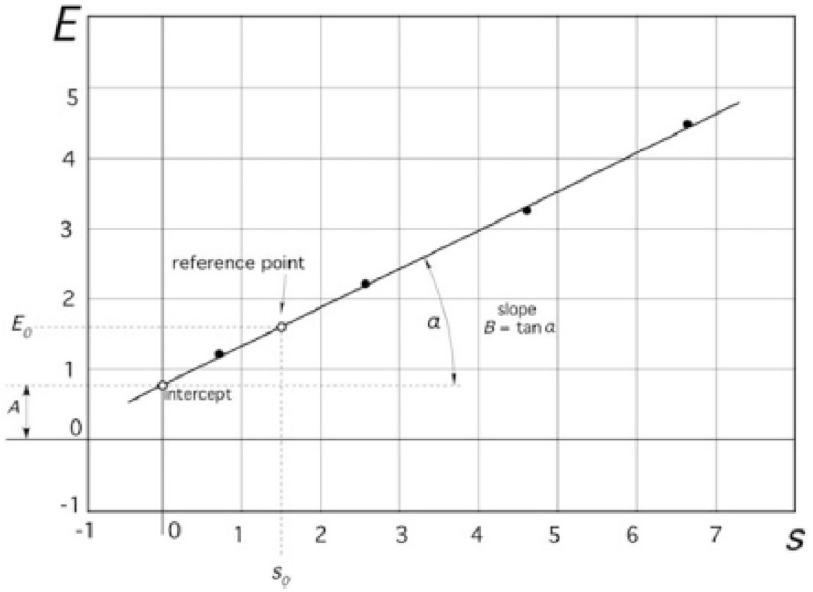
Lecture #22

Ihab Abu Ajamieh, PhD.

Estimating Transfer Function

Linear Regression:

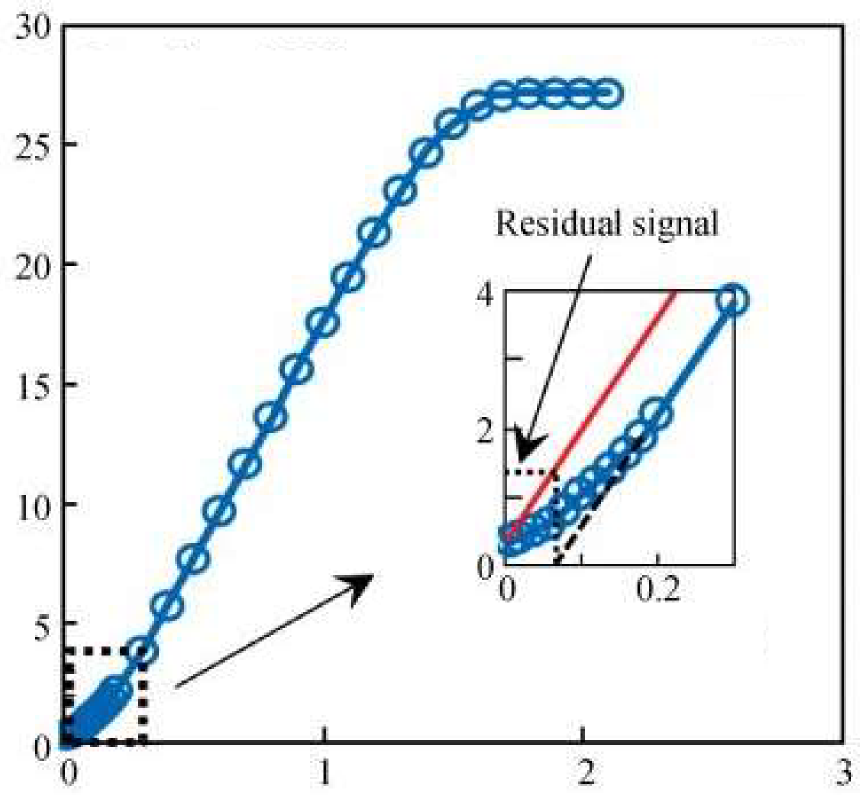
- The simplest and most widely used transfer function is a linear one.
- Usually in sensor calibration 3-5 points are tested along the full range of the sensor (10-90%).
- The line of best fit is determined to minimize standard error (**S**)
- The slope (sensitivity) and intercept (zero offset) is determined.
- Often the intercept (zero offset) must be estimated and can't be actually measured.



Estimating Transfer Function

Non-Linear Function:

- Most sensors are not linear over their entire range.
- Usually at the extremes of the detection range the non-linearity is more predominant.
- A good strategy is to calibrate the sensor over the range that it will be used rather than its entire sensing range.

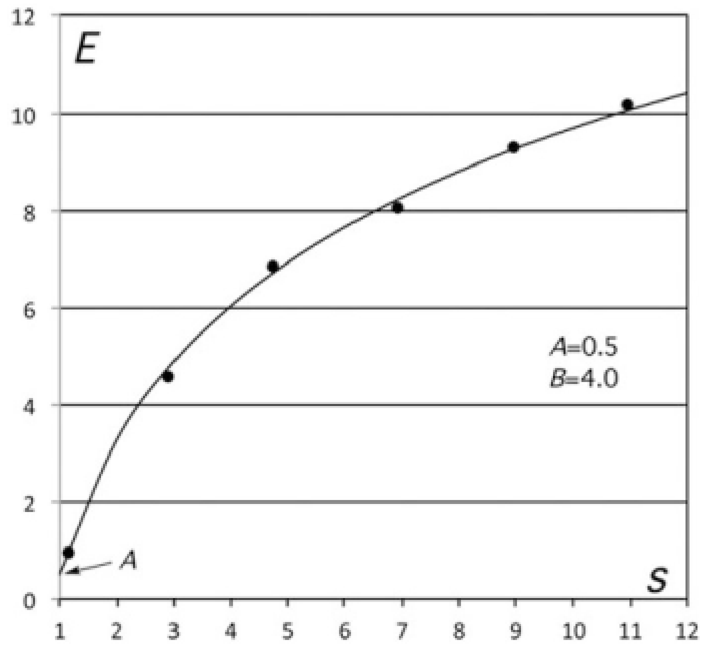


Estimating Transfer Function

Non-Linear Function:

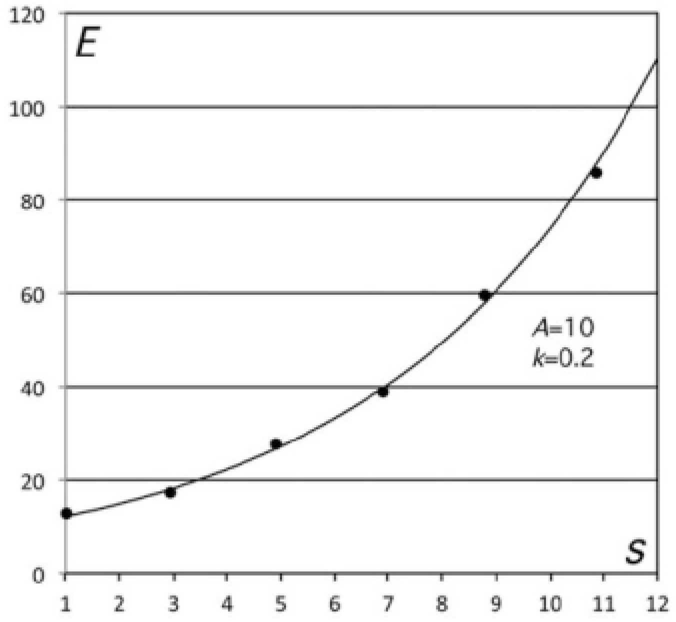
- More complicated functions can be applied such as:

Logarithmic Function



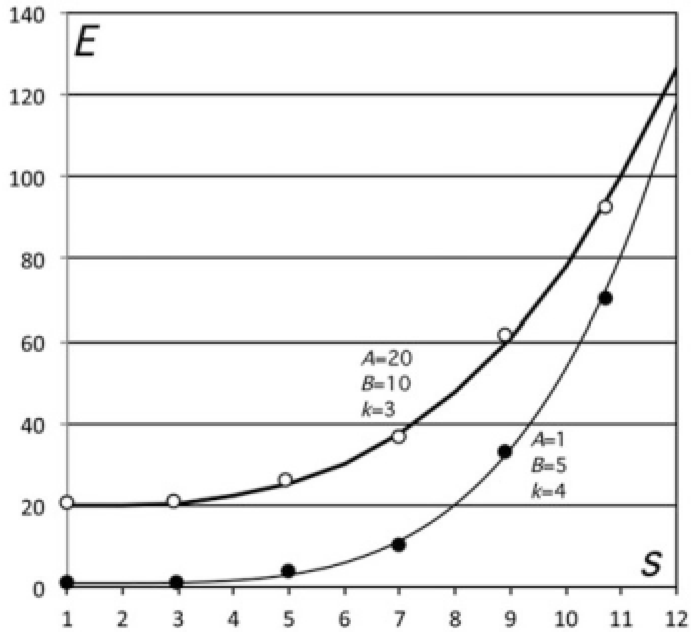
$E = A + B.Ln(X)$

Exponential Function



$E = Ae^{kX}$

Power Function



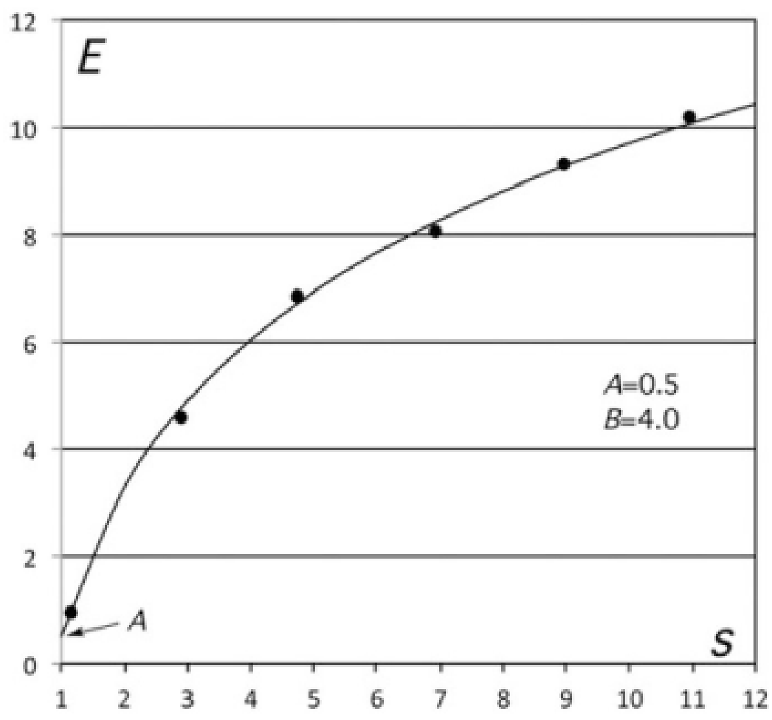
$E = A + BX^k$

Estimating Transfer Function

Non-Linear Function:

- For each transfer function, The inverse transfer function is also required.
  - Transfer Function $E = A + B \ln(X)$
  - Inverse Transfer function $X = e^{(E - A)/B}$
- The three functions provided have only 3 parameters to determine in calibration (A, B, K).
- For these non-linear transfer functions a minimum of 5-8 calibration points are required.

Logarithmic Function



Estimating Transfer Function

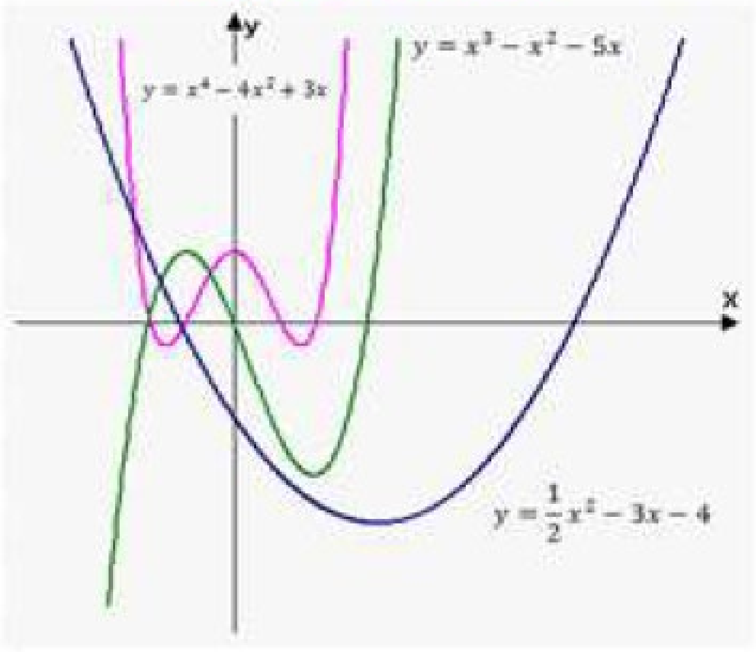
Polynomial Approximation:

- A sensor may have a more complicated transfer function than these basic ones.
- Power series can be used to approximate any transfer function.
- The **n**th order polynomial is:

$$E = a_0 + a_1 X + a_2 X^2 + \ldots a_n X^n$$

- The higher the order the better the fit but the more data points are needed

Logarithmic Function

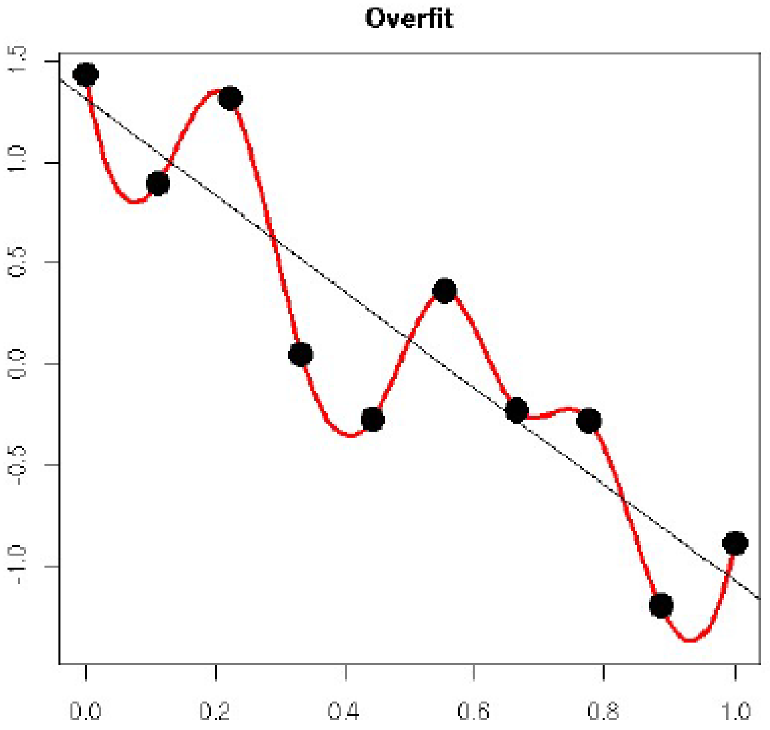


Estimating Transfer Function

Functional Approximation:

Overfitting

- Standard $\mathbf{R^2}$ (coefficient of determination) rewards you with trying to fit a curve to all the data points (noise and signal alike).
- The more complex the curve the higher the $\mathbf{R^2}$ will be.
- $\mathbf{R^2}$ never decreases by increasing the complexity of the transfer function.
- By increasing the complexity you may be "connecting the dots" more than modeling the actual signal.
- The model most aim to ignore the noise and only model the signal



Estimating Transfer Function

Functional Approximation:

Adjusted R^2

- Adjusted $\mathbf{R^2}$ penalizes the score for using more complex functions.

$$R^2_{Adjusted} = 1 - \frac{(1 - R^2)(N - 1)}{N - p - 1}$$

Where:

N is number of samples and **P** is the number of parameters

Parameters	R2	$R^2_{Adjusted}$
2	85.9	84.8
3	**87.4**	**85.9**
4	89.1	82.3
5	89.9	80.7

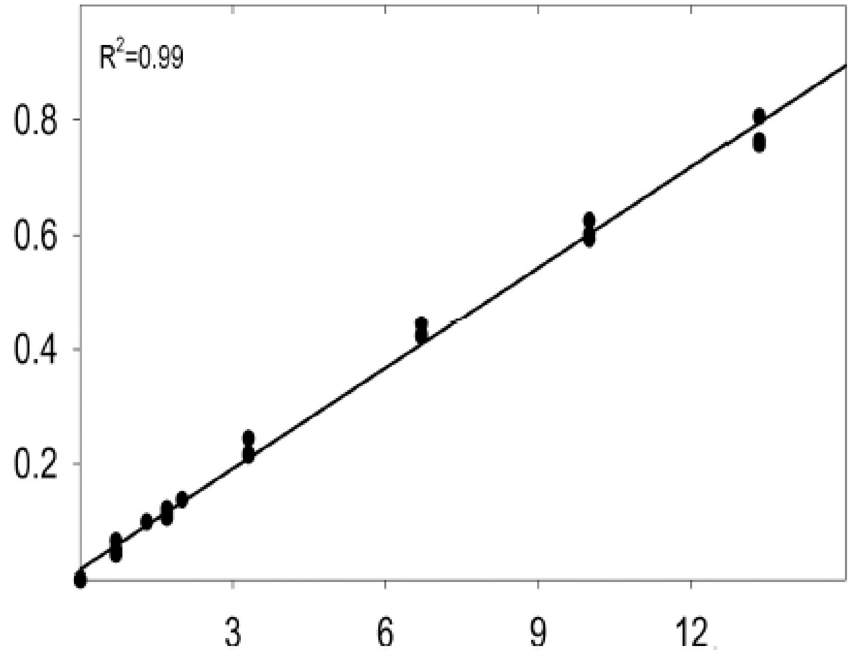
- **P** can also be number of input variables

Estimating Transfer Function

Functional Approximation:

How to avoid overfitting?

- Take multiple samples per calibration point.
- If a large data set is available keep some data for validation.
- Compare the **S** value with data-sheets noise level.
- Try using the most basic transfer function that will yield an acceptable $\mathbf{R^2}$ value.



Estimating Transfer Function

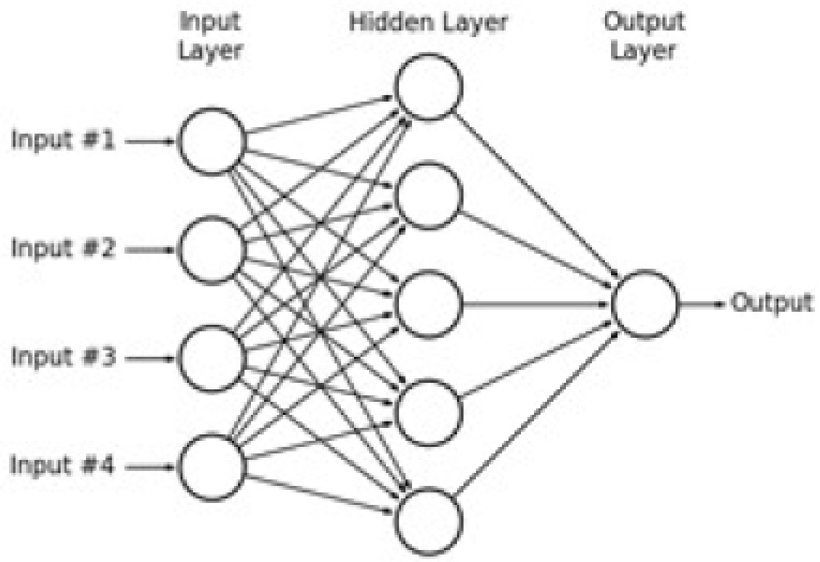
More Complex Approximation:

Neural Network (NN)

- Recent advancements in neural networks and deep learning have created a trend of using NN as a transfer function.

- Things to consider is that NN:

  - Is a black box with no indication of the mathematical model being applied.
  - requires much more data points than the simple regression models (100s if not 1000s).
  - Is computationally expensive

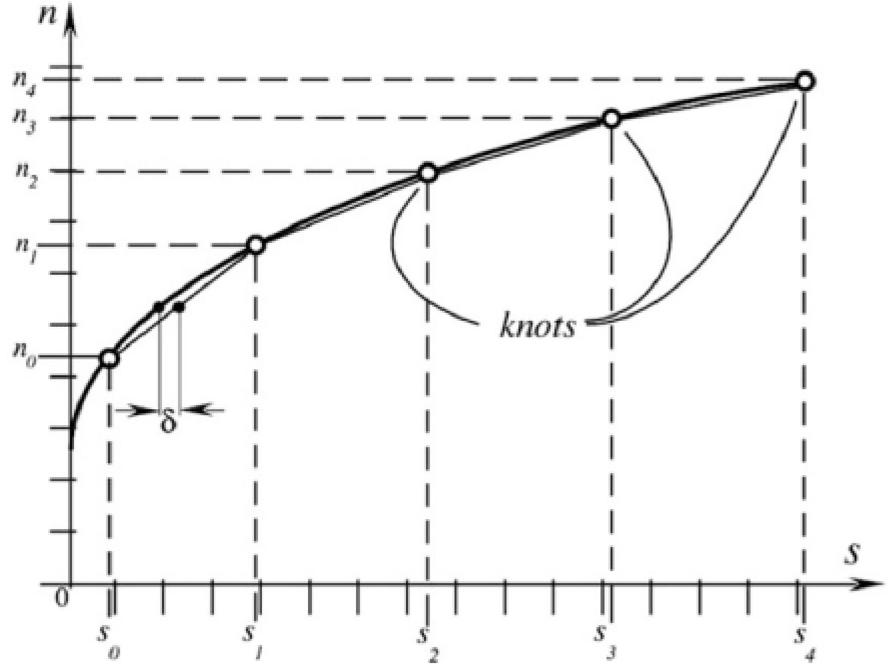


Simple single layer NN
25 parameters to calculate

Estimating Transfer Function

Linear Piecewise Approximation:

- A Non-linear transfer function can be approximated using linear functions over smaller sections.
- The span is divided into sections by knots.
- The greater the non-linearity the closer the knots must be to each other.
- For computing the input stimulus from the sensor reading a linear interpolation should be performed.
- An error of a piecewise approximation is the maximum deviation **δ** of the approximation line from the real curve

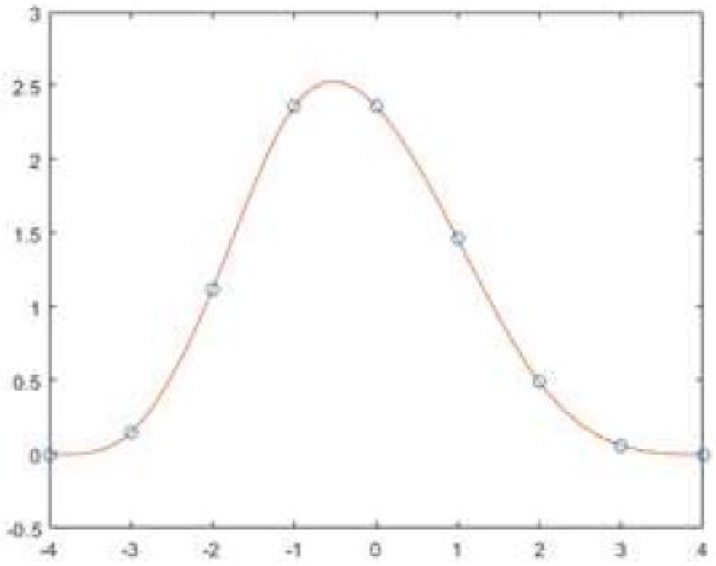


Estimating Transfer Function

Spline Approximation:

Higher order piecewise

- Uses higher-order polynomial (commonly 3rd order) to interpolate between the knots.
- All curves are “stitched” or “glued” together to obtain a smooth combined curve fitting.
- The main advantage over linear piecewise is a continuous sensitivity.
- The disadvantage is the added computational complexity.



Estimating Transfer Function

Sensitivity Review:

- For a linear transfer function, sensitivity is the slope of the line.
- For non-linear transfer functions sensitivity (**Sen**) is a function of the stimuli (**X**).
- For linear piecewise approximation, sensitivity changes at each knot.
- For neural networks, the sensitivity can't be calculated but can be measured using small incremental stimuli change.

Estimating Transfer Function

Multi-Dimensional Transfer Function:

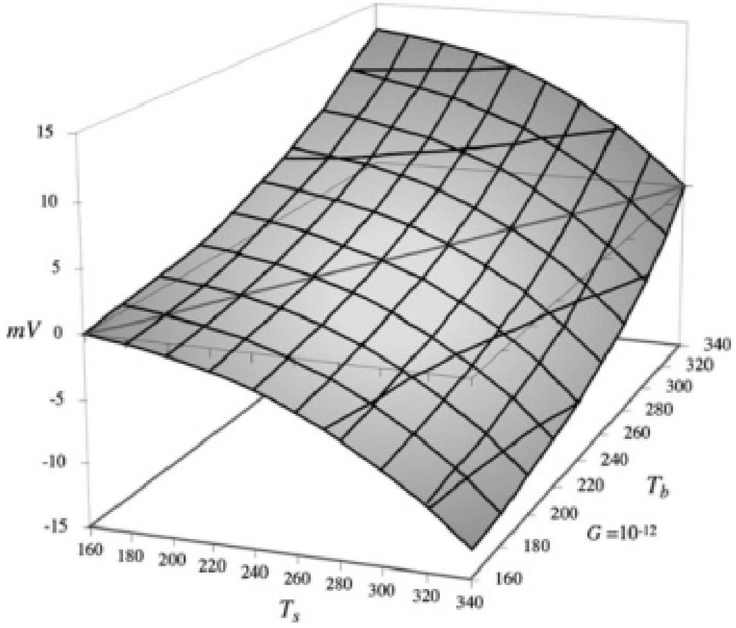
- A sensor transfer function may depend on more than one input variable.

- For example, an infrared thermometer provides a reading that depends on two stimuli.

  - Absolute temperature of the object (**T_b**).
  - Absolute temperature of the senor (T_s)

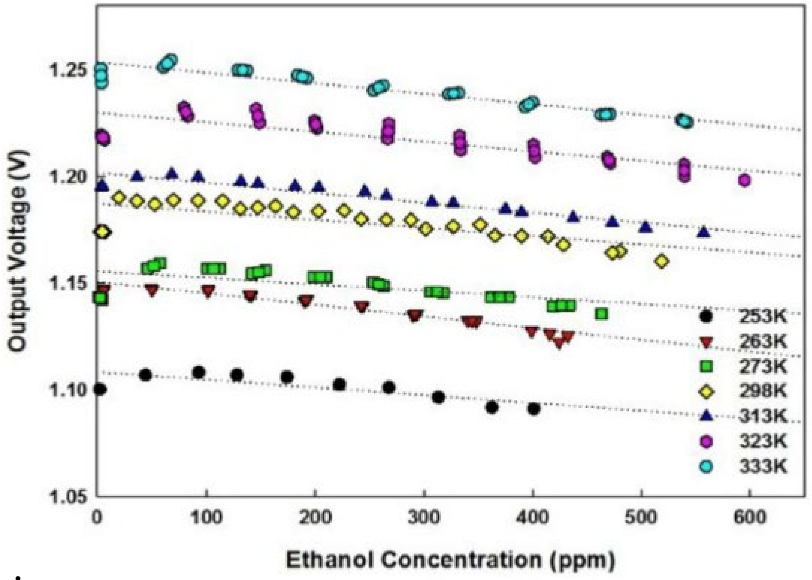
$$V = G(T_b^4 - T_s^4)$$

- Most sensors have cross sensitivity to other stimuli and would benefit from a multi-dimensional transfer function



Estimating Transfer Function

Multi-Dimensional Transfer Function:



- In most practical applications, multi-dimensional calibration is expensive and difficult to achieve.
- These stimuli should be measurable to be used in the transfer function.
- For example:
  - An NDIR sensor used for ethanol measurement has a strong correlation to temperature.
  - 9 point calibration is performed at 7 different temperatures for total of 63 points.
  - Typical calibration takes 5 minutes per point for total of 5 hours and 15 mins!
  - Cost of calibration gas, equipment, and labor would be roughly $918

Estimating Transfer Function

Multi-Dimensional Transfer Function:

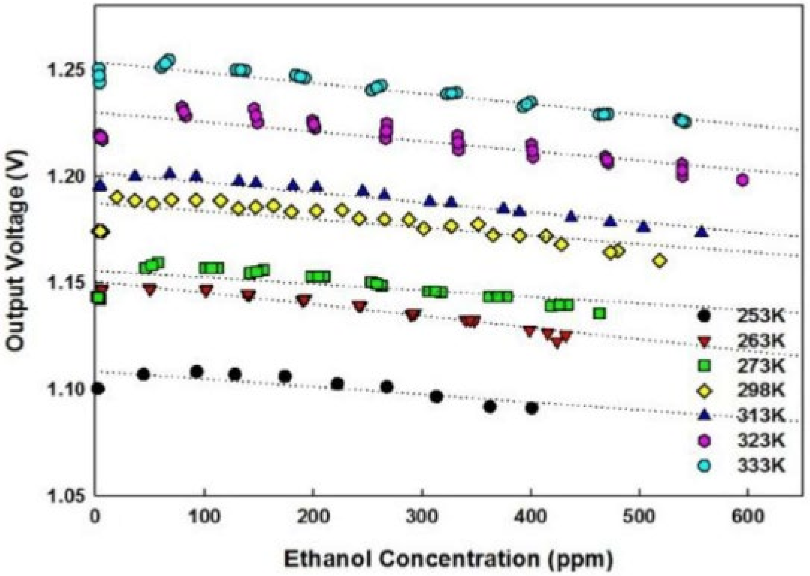
- A common practice is to separate the stimuli into separate transfer functions.

- Assuming that:
  - The sensitivity of the sensor to the gas is constant with temperature.
  - Only the zero offset is temperature dependent.

$$V = A(X) + f(T)$$

Where: **X** is the gas concentration and **T** the sensor temperature

- Notice the larger error at **0** ppm ethanol.



Estimating Transfer Function

Multi-Dimensional Transfer Function:

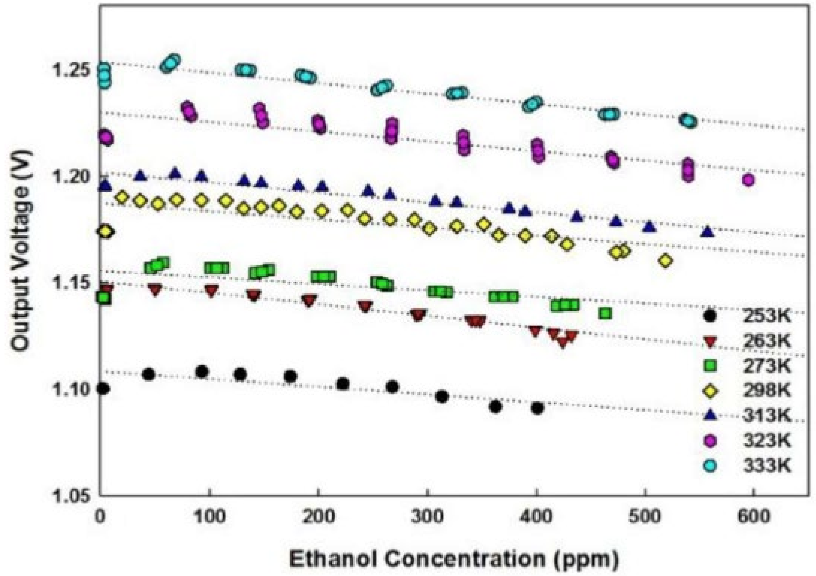
- The zero offset can be approximated with a linear function:

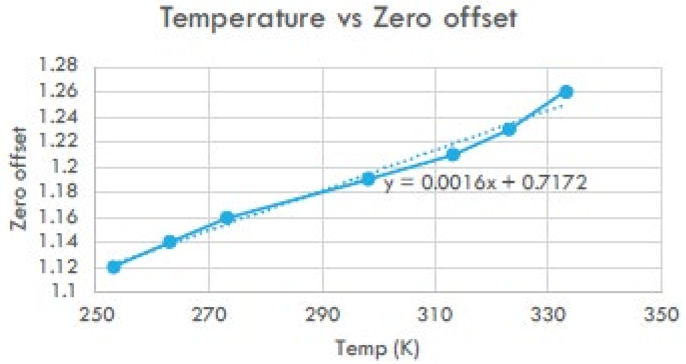
$$V=0.0016T+0.7172$$

- Sensitivity is equal to 0.00004 Volts/ppm.

- Therefore the transfer function can be defined as:

$$V = 0.00004\, X + 0.0016\, T + 0.7172$$





Estimating Transfer Function

Calibration Summary:

Calibration of a sensor can yield:

1. Modifying the transfer function or its approximation to fit the experimental data.
2. Adjustment of the data acquisition system to make the outputs signal fit into a normalized or “ideal” transfer function.
3. Modification (trimming) the sensor’s properties to fit the predetermined transfer function.
4. Creating a sensor specific reference device that can be used to compensate for sensor inaccuracies.

Estimating Transfer Function

Uncertainty:

1. Calibration aims to minimize the error in a sensor by eliminating systematic error.

2. Analog and digital signal processing aims to reduce noise induced errors.

3. Uncertainty remains despite these efforts and is a combination of all errors in the sensor, circuitry, ADC, and ambient variance.

4. Uncertainty can be calculated as the combination of all noise and variance in the system.

$$u_c = \sqrt{u_1^2 + u_2^2 + \cdots + u_i^2 + \cdots + u_n^2}$$

Table 3.4 Uncertainty budget for a thermistor thermometer

Source of uncertainty	Standard uncertainty (°C)
Calibration of sensor	
Reference temperature source	0.03
Coupling between reference and sensor	0.02
Measured errors	
Repeated observations	0.02
Sensor inherent noise	0.01
Amplifier noise	0.005
DVM error	0.005
Sensor aging	0.025
Thermal loss through connecting wires	0.015
Dynamic error due to sensor's inertia	0.005
Transmitted noise	0.02
Misfit of transfer function	0.02
Ambient drifts	
Voltage reference	0.01
Bridge resistors	0.01
Dielectric absorption in A/D capacitor	0.005
Digital resolution	0.01
Combined standard uncertainty	**0.062**

Estimating Transfer Function

Calibration Report:

Calibration Report should have:

- Header to:
  - Identify the equipment being calibrated.
  - Standards being followed or methodology.
  - Date, conditions, etc.
- Summary of parameters determined in calibration.

Certificate of Calibration

Date of Issue: January 7, 2020 Date of Calibration: January 1, 2020

Certificate Number: CC01072020-01 Serial #: SL111901

Device: SL50 – Scentinal

Device Description: Compact Air Quality and Odor Monitoring Station

Conditions: T: 21.5°C ± 2°C

Scentinal calibration is conducted in accordance to USEPA methodology EPA-454/B-17-001 and this instrument is traceable back to USEPA Standards.

Calibration Values

Sensor	Zero Offset Voltage (mVolts)	Sensitivity(mVolts/PPM)	Max Detection (PPM)
O3 – LC	596.191	2818.93	0.5
SO2 - LC	583.301	2963.93	1
NO2 – LC	605.859	813.88	1
NMHC	0.000	1.00	25
H2S - LC	533.350	960.34	3
CO – LC	530.933	22.30	100

The End of Lecture #22

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Sensors and Instrumentation

Lecture #23

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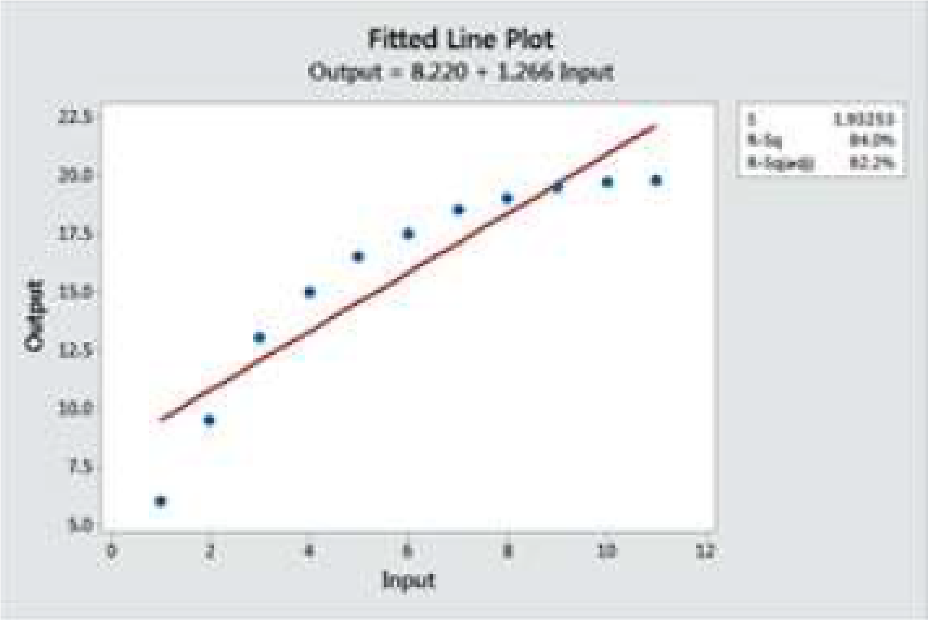
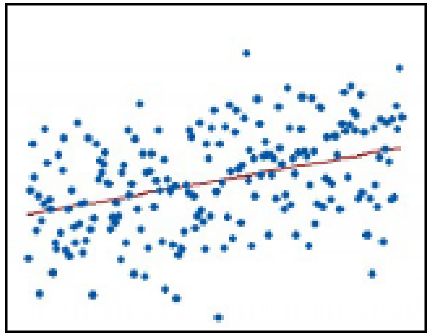
Calibration

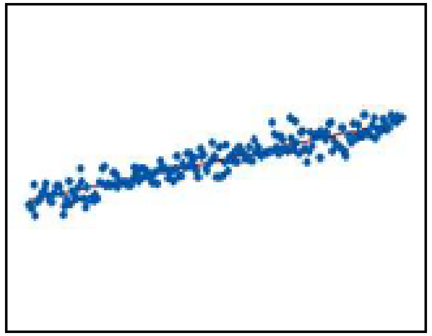
Transfer Function:

Functional Approximation: From Lec. #21

- In general, it is better to start with a model and only use more complex ones if required.
- The more complex the model, the larger the data set is required during calibration.
- To test the validity of the model, a number of metrics can be calculated:
  - Standard error of the regression (***S***).
  - $\mathbf{R^2}$.
  - Adjusted $\mathbf{R^2}$.







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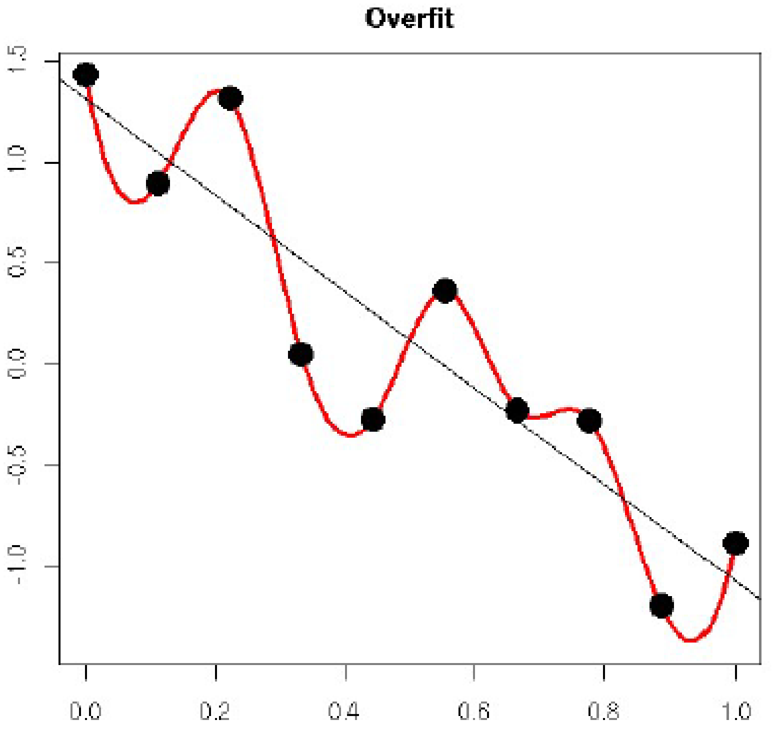

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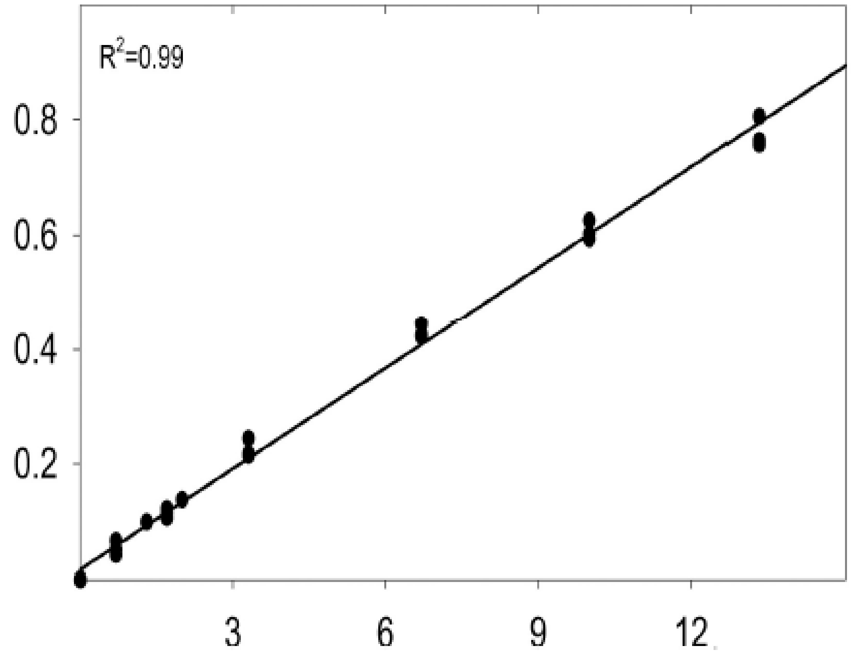

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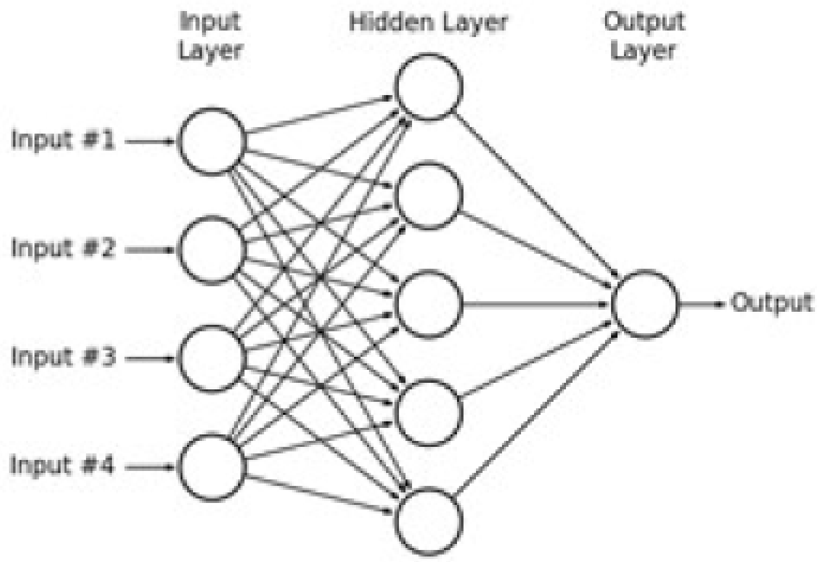

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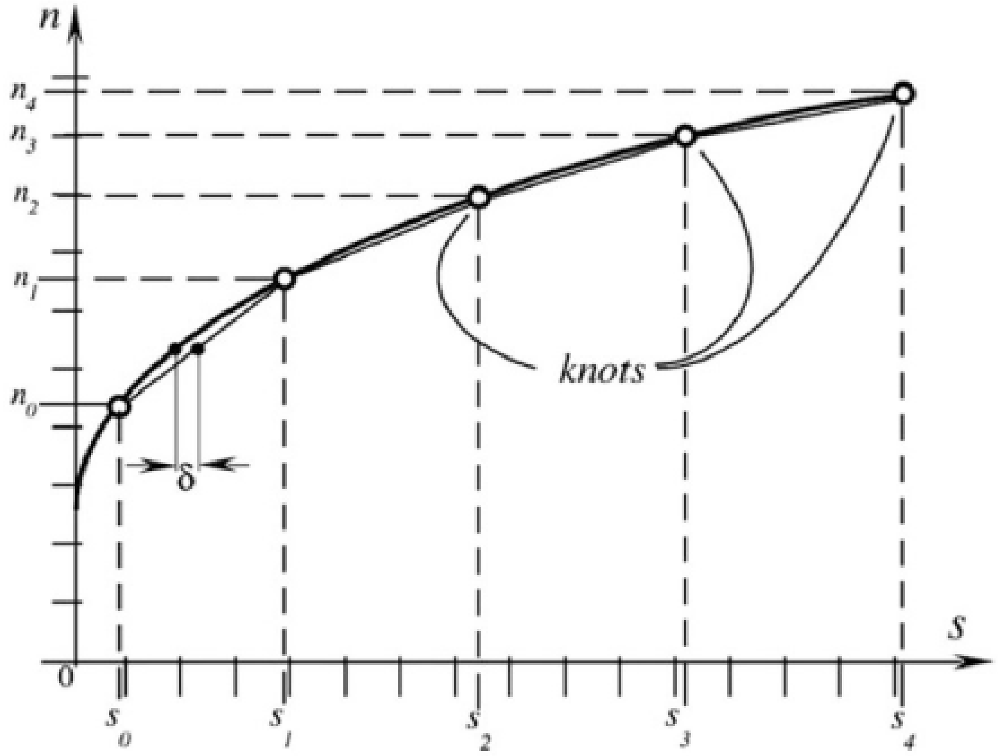

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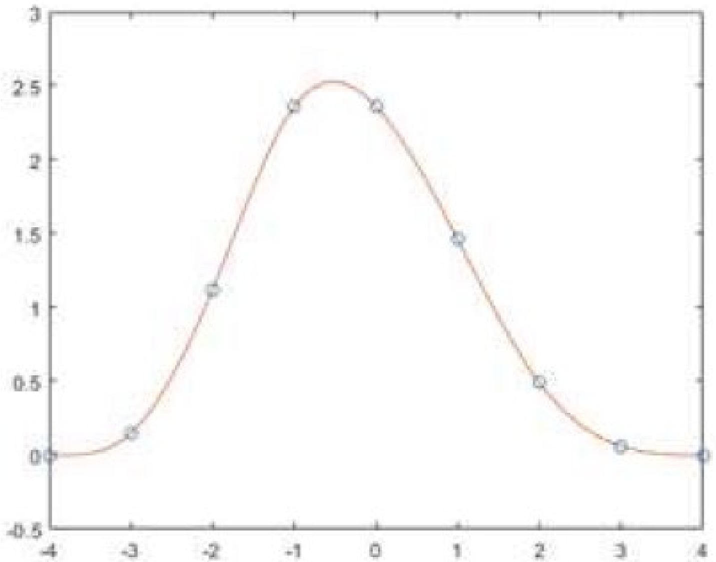

Estimating Transfer Function

Multi-Dimensional Transfer Function:

- A sensor transfer function may depend on more than one input variable.
- For example, an infrared thermometer provides a reading that depends on two stimuli.
    - Absolute temperature of the object (**T_b**).
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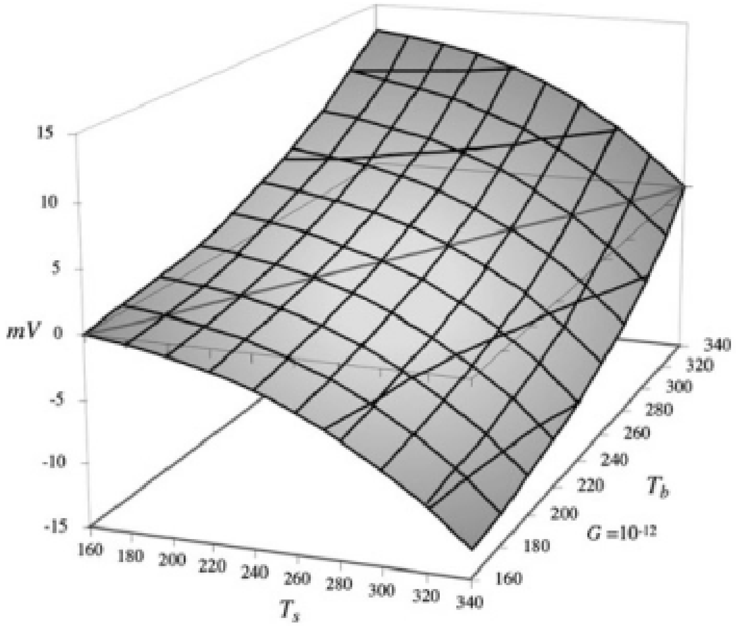
$$V = G(T_b^4 - T_s^4)$$



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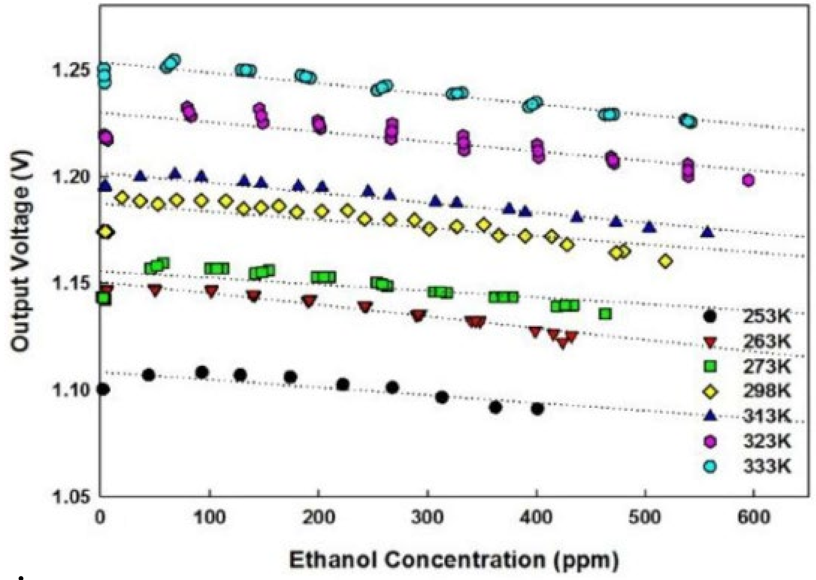

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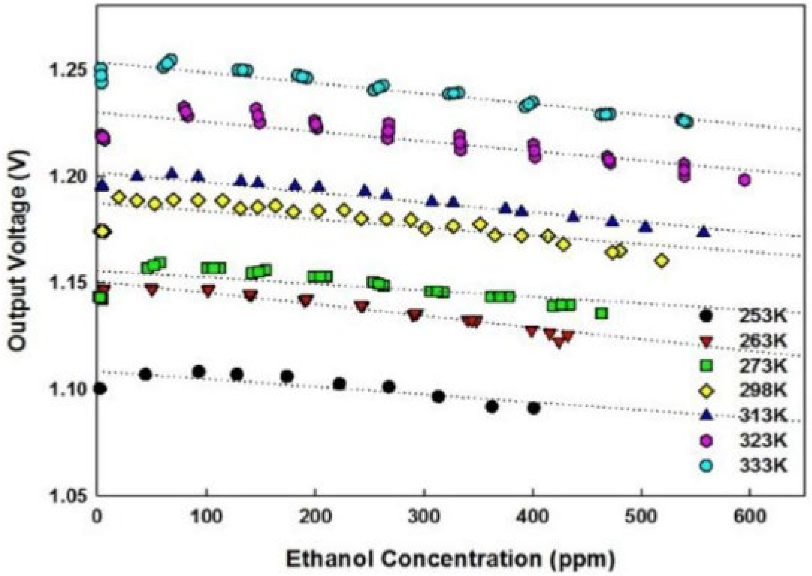

Estimating Transfer Function

Multi-Dimensional Transfer Function:

- The zero offset can be approximated with a linear function:

$$V=0.0016T+0.7172$$

- Sensitivity is equal to 0.00004 Volts/ppm.

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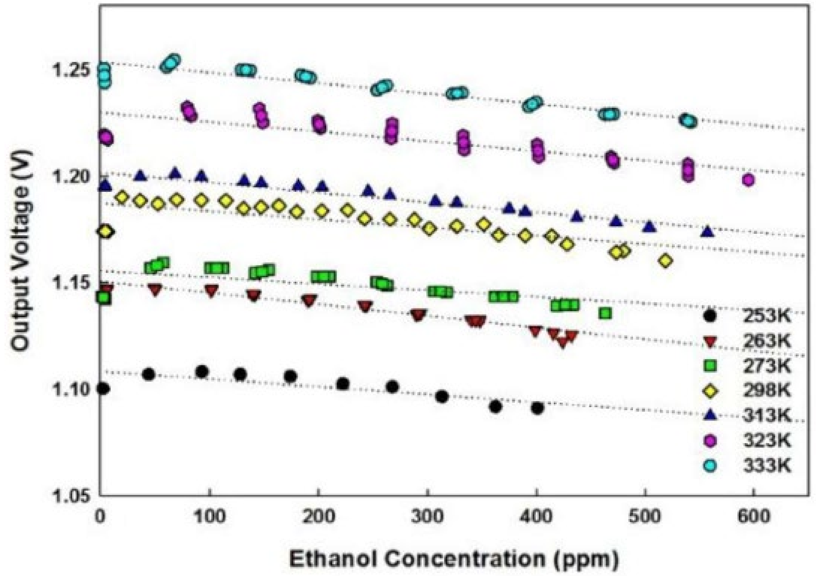
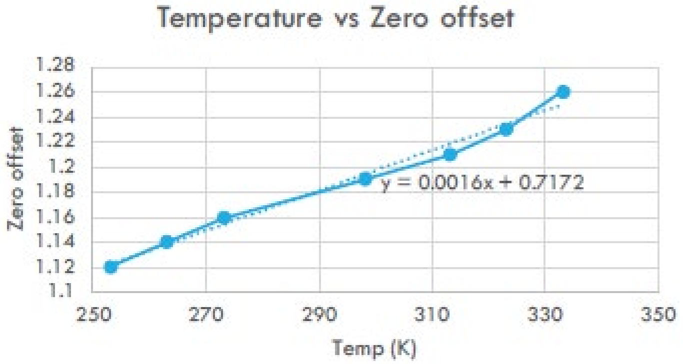
$$V = 0.00004\ X + 0.0016\ T + 0.7172$$





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The End of Lecture #23

ENMC3361
Sensors and Instrumentation

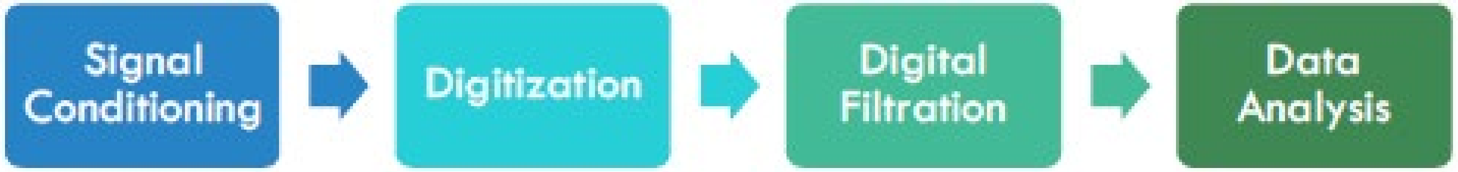
Lecture #24

Ihab Abu Ajamieh, PhD.

Signal Conditioning and Digitizing

Signal Processing:

- Signal from a sensor is often either too weak, or too noisy, or it contains undesirable components.
- To be used the signal must undergo conditioning and digitization.

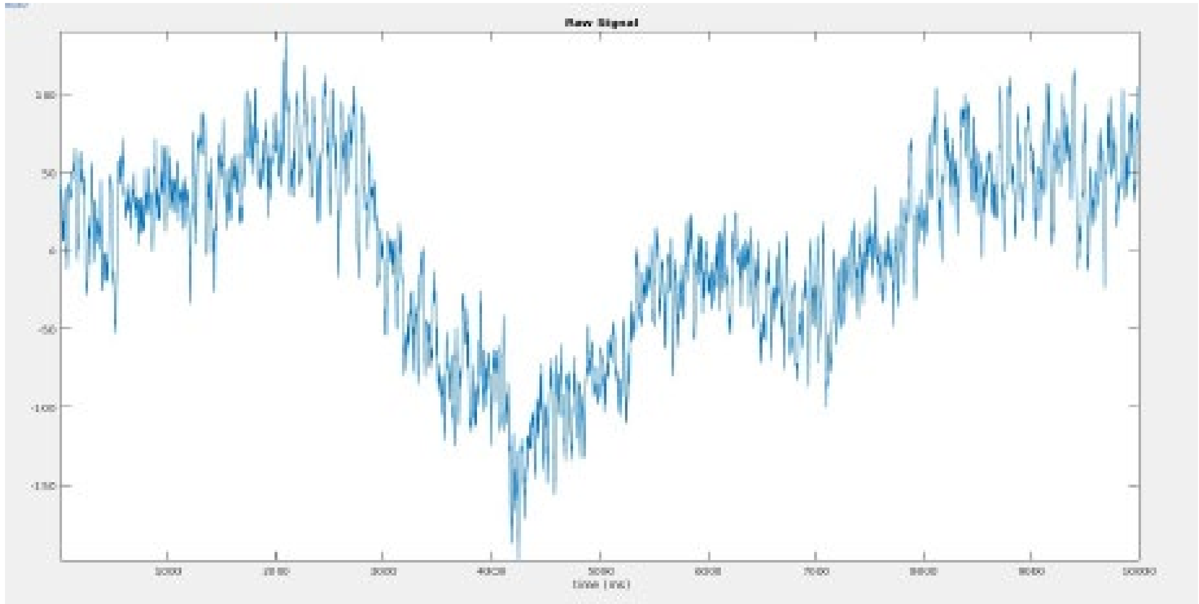


Signal Conditioning and Digitizing

Signal Conditioning:

- Signal conditioning is the manipulation of an analog signal in such a way that it meets the requirements of the next stage for further processing.

- It involves:
  - Amplification.
  - Level shifting.
  - Analog filtering.



Signal Conditioning

Amplification:

- The amplification circuit has two functions:
  - Attenuate the signal.
  - Provide high input impedance.
- In sensing, a specific type of amplifier is used and called the Instrumentation Amplifier.
- Instrumentation amplifier provides:
  - Low DC offset.
  - Low drift
  - Low noise
  - High input impedance
  - High open-loop gain

Signal Conditioning

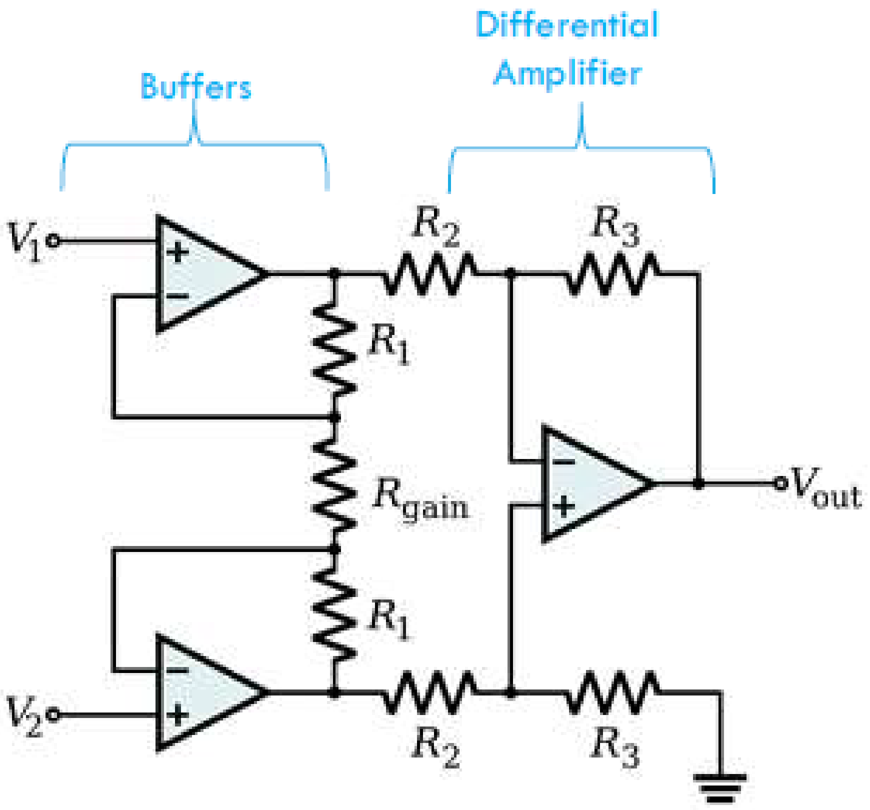
Instrumentation Amplifier:

- Instrumentation amplifier are a form of differential amplifier.
- The gain can be calculated as:

  $$A = V_{out}/(V_2 - V_1)$$

  $$A = (1 + 2R_1/R_{gain}) \times R_3/R_2$$

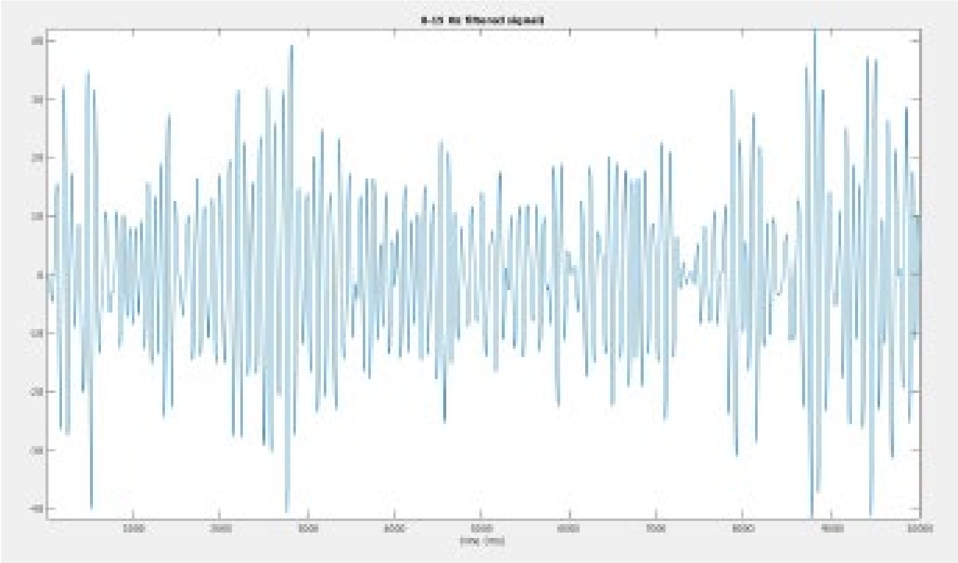
- The standard differential amplifier has input resistance of $2R_2$.
- The other two op amps act as buffers to increase input resistance



Signal Conditioning

Analog Filters:

- Undesired noise can be removed before digitization to:
  - Reduce the required sampling rate.
  - Reduce load on the micro-controller
- The noise is differentiated from the signal based on frequency

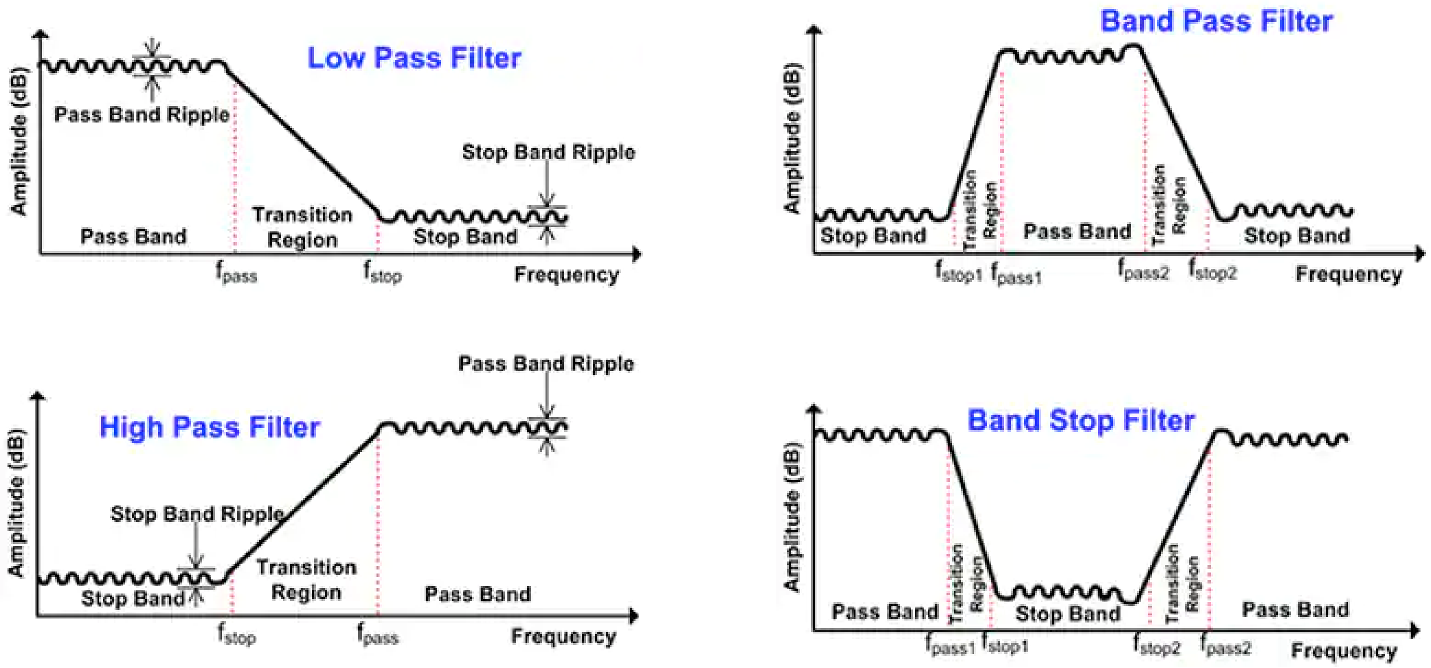


Signal Conditioning

Analog Filters:

➢ Filters are classified according to their frequency response:

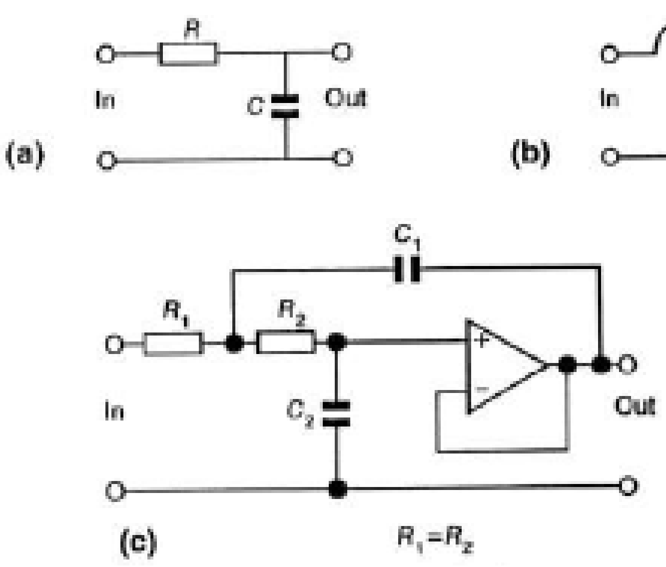
- Low-pass filter
- High-pass filter
- Band-pass filter
- Band-stop (Notch)



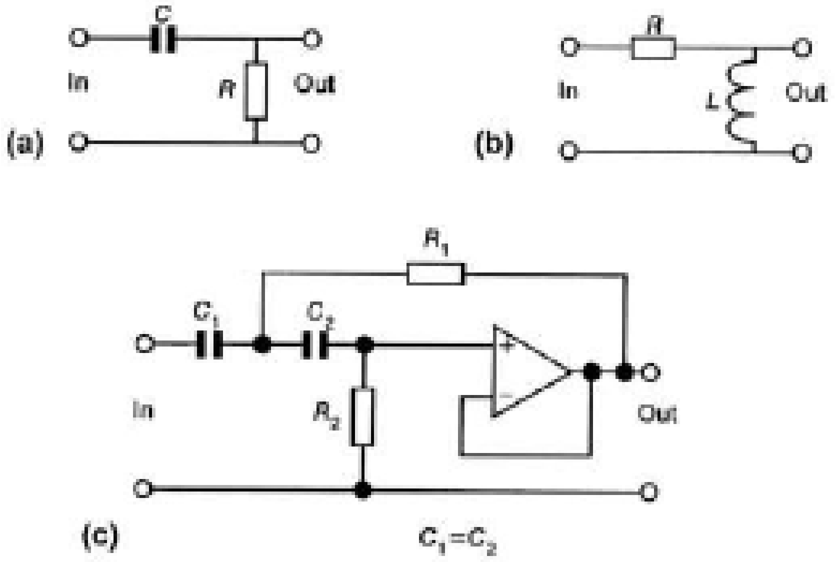
Signal Conditioning

Analog Filters:

Low pass filters



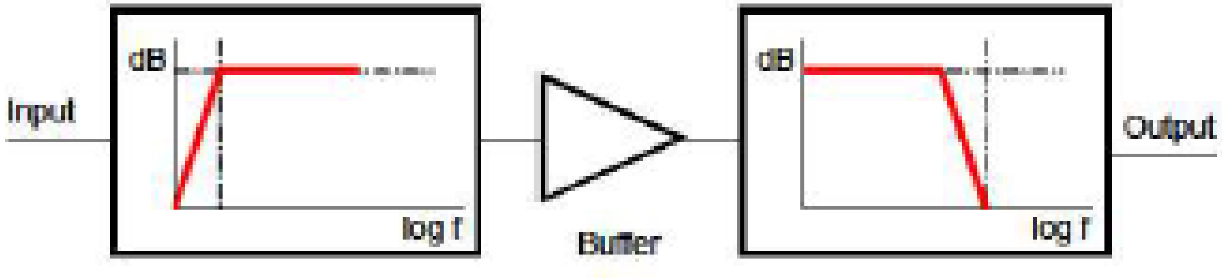
High pass filters



Signal Conditioning

Analog Filters:

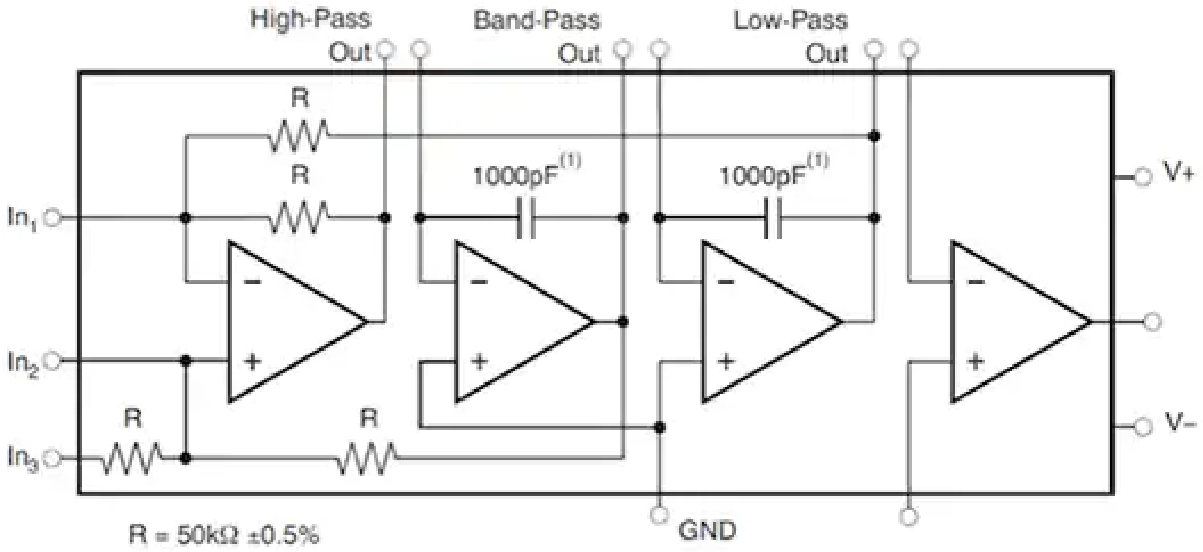
- A band Pass filter is simply a high pass filter followed by a low pass filter:
  - Corner frequency of low-pass must then be higher than the high pass filter



Signal Conditioning

Analog Filters:

- Universal Active Filter:
  - Consists of one amplifier and two integrators
  - High-pass, low-pass and band-pass in the same IC
  - It can be configured based on requirement to provide inverting or non inverting amplification with various filter characteristics and gains



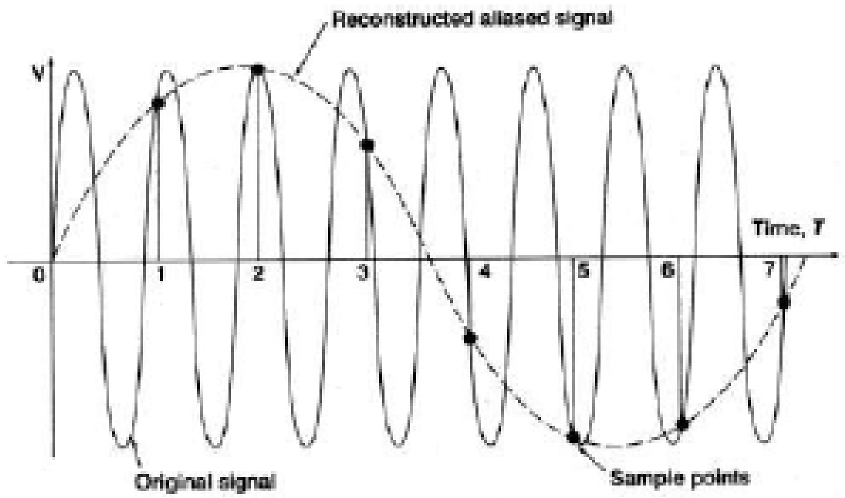
ANTI-ALIASING

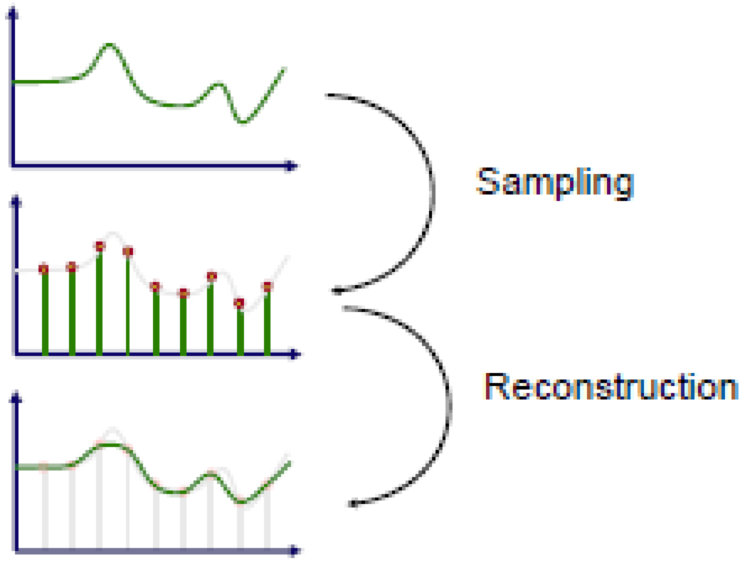
Signal Conditioning

Anti-Aliasing:

➢ The sampling theorem:

- A continuous signal can be represented by a set of instantaneous measurements which are made at equally-spaced times
- The reconstructed signal can be different than the original signal.
- This distortion is called **aliasing**





Signal Conditioning

Anti-Aliasing:

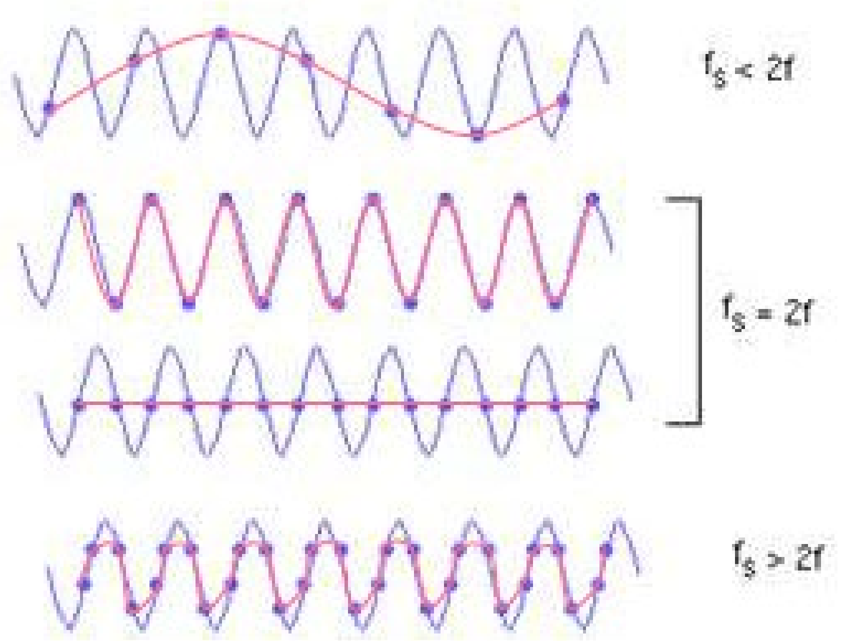
- Spatial vs Temporal Aliasing:

Signal Conditioning

Anti-Aliasing:

- The sampling theorem:
  - If the sampling frequency is 2 times the signal frequency the distortion is minimal.
  - Sampling rate must be higher than the Nyquist rate:

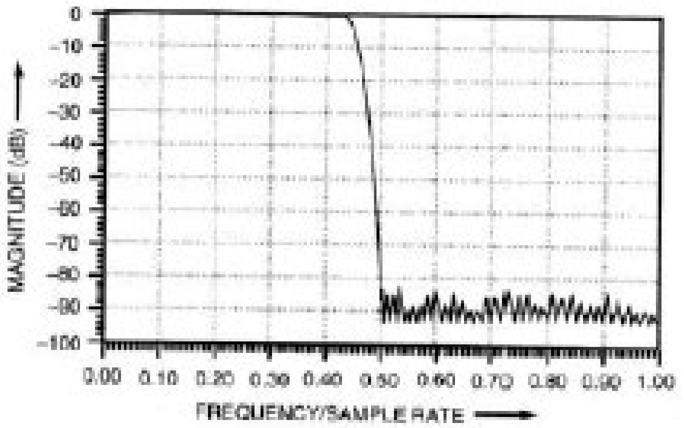
$$f_s = 2f_{max}$$

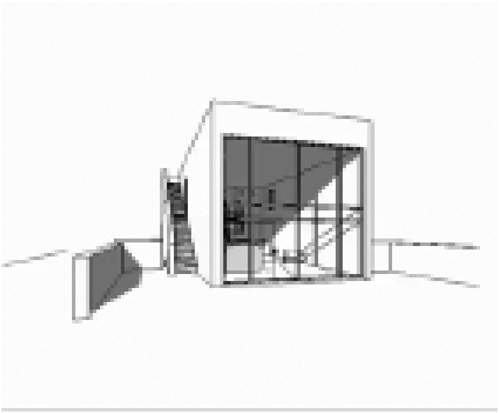


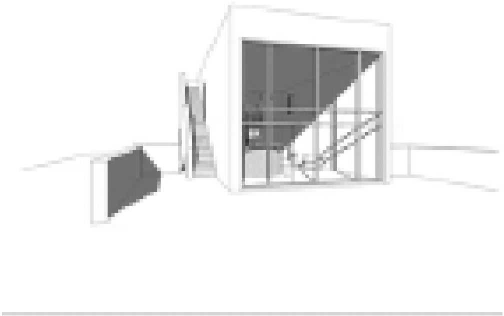
Signal Conditioning

Anti-Aliasing:

- To eliminate aliasing (temporal):
  - Use a Digital to Analog Converter (DAC) with frequency 2x the signal frequency.
  - Filter out any frequency above 2FS – Anti-aliasing low pass filter:







The End of Lecture #24

ENMC3361

Sensors and Instrumentation

Lecture #25

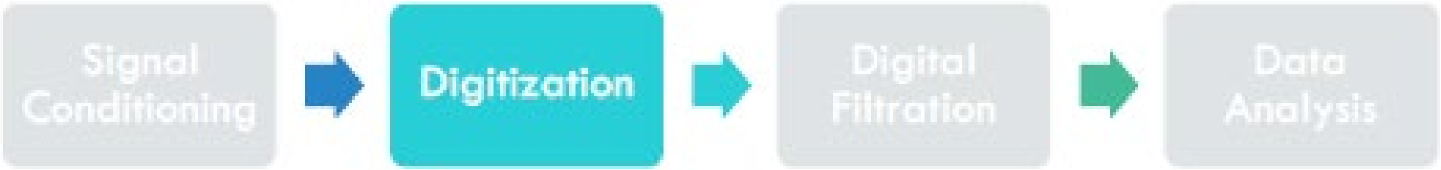
Ihab Abu Ajamieh, PhD.

DIGITIZATION

Digitization

Digitization:

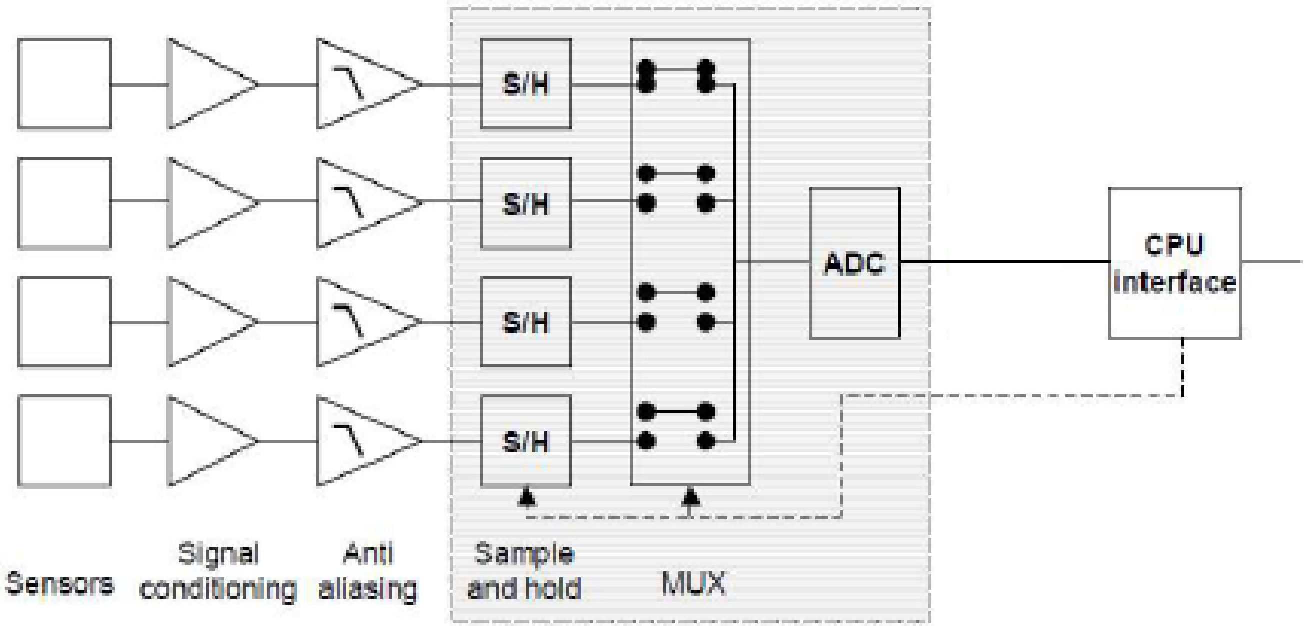
- Once the signal has undergone analog filtration and anti-aliasing, it can be converted to a digital signal



Digitization

Digitization:

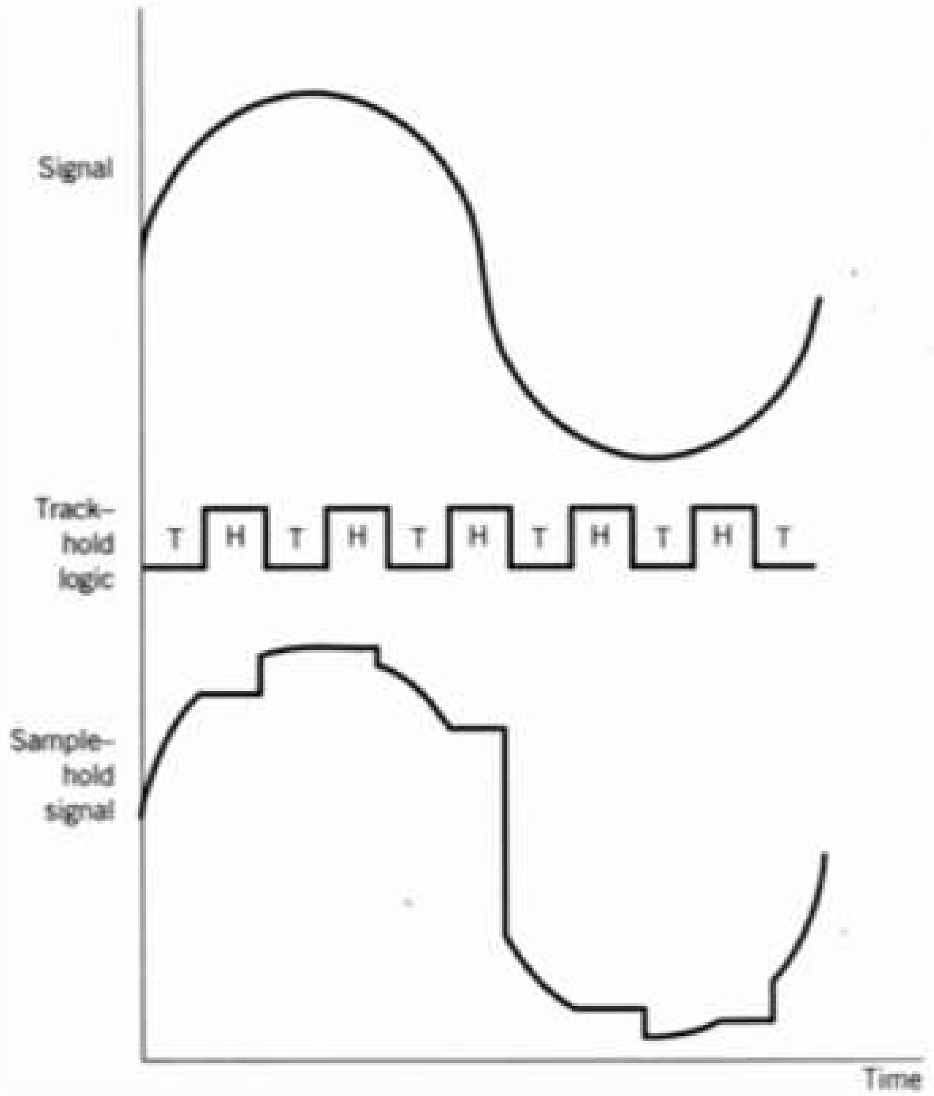
- Digitization consists of:
  - Sample and hold circuit
  - Multiplexor
  - Analog to Digital Converter



Digitization

Sample and Hold (S/H) Circuits:

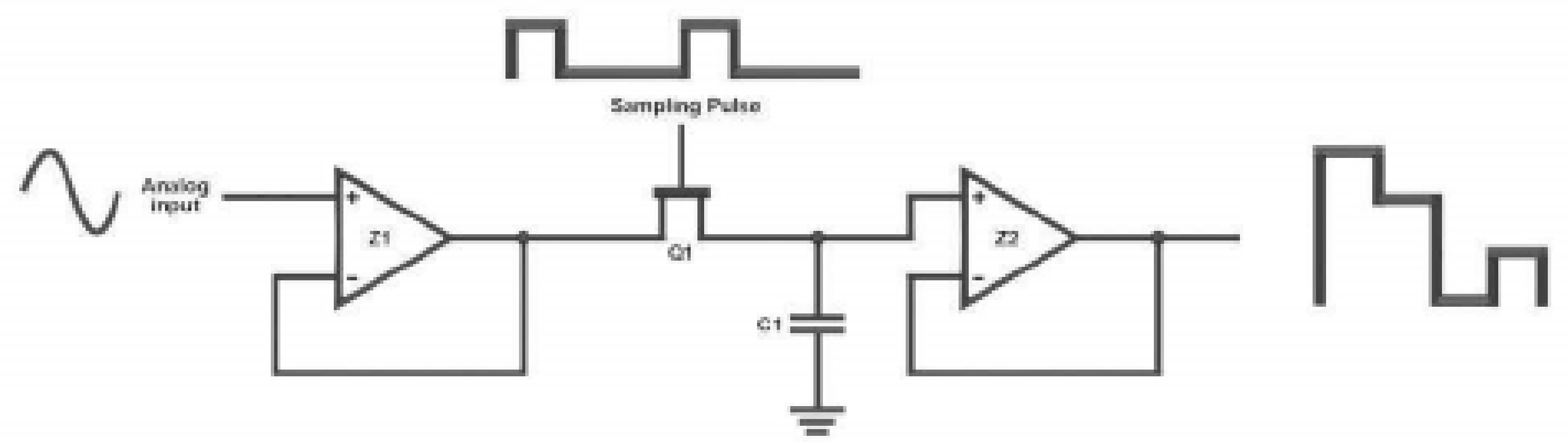
- S/H circuits sample an input continuously and hold/freeze the signal when commanded:
  - Sample mode: The output follows the input.
  - Hold mode: The output is held constant until sample mode is resumed
  - Analog to Digital Converter



Digitization

Sample and Hold (S/H) Circuits:

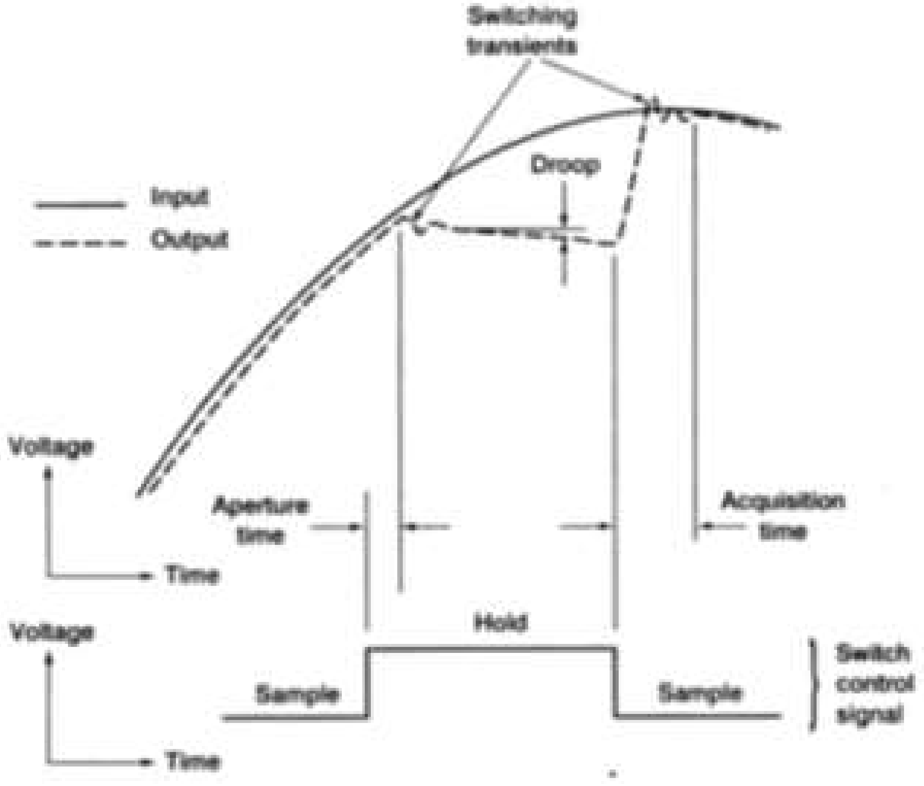
- Composed of:
  - Voltage follower op-amp circuit (Z1).
  - Metal Oxide Semiconductor Field Effect Transistor - MOSFET switch (Q1).
  - Capacitor (C1).
  - High impedance op-amp to minimize discharge of capacitor



Digitization

Sample and Hold (S/H) Circuits:

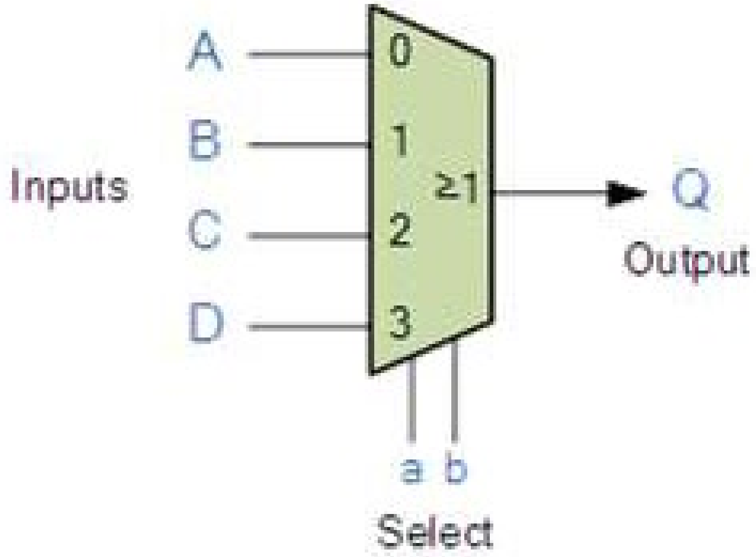
- Some important parameters to consider when selecting a S/H circuit:
  - Aperture time: time required for the switch to open (~50ns).
  - Droop: capacitor discharge (~1mV/ms).
  - Acquisition time: switch operation plus capacitor charging time.

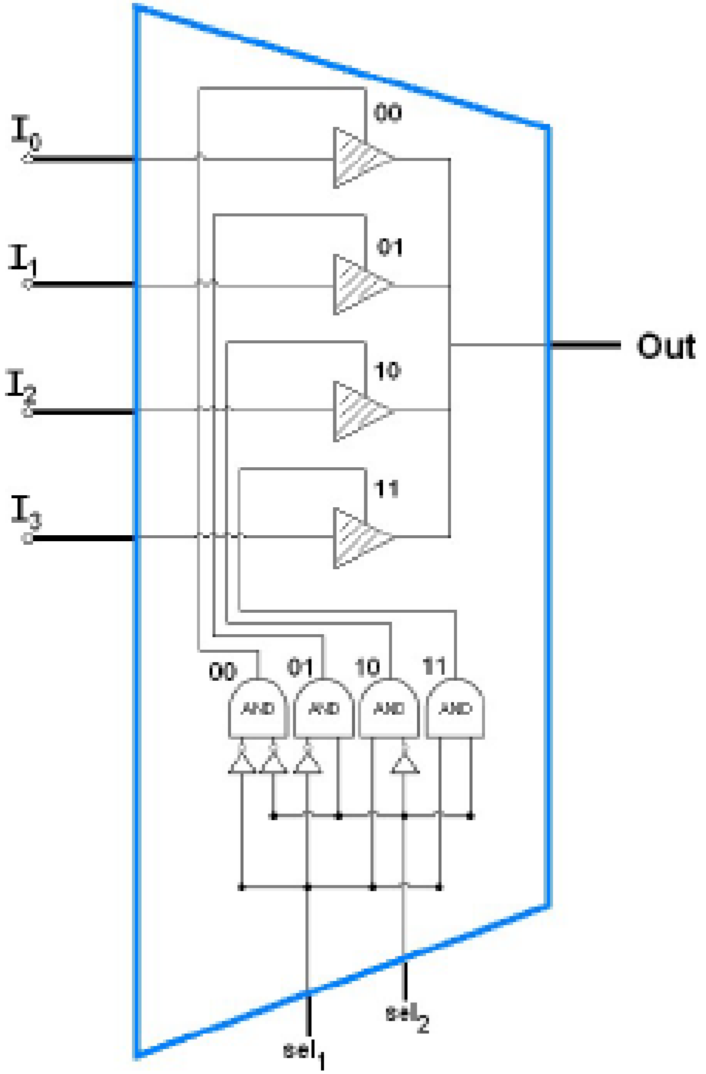


Digitization

Multiplexor:

- A multiplexer allows multiple inputs to be sampled by a single digitizer.
- Can be for analog or digital signal.

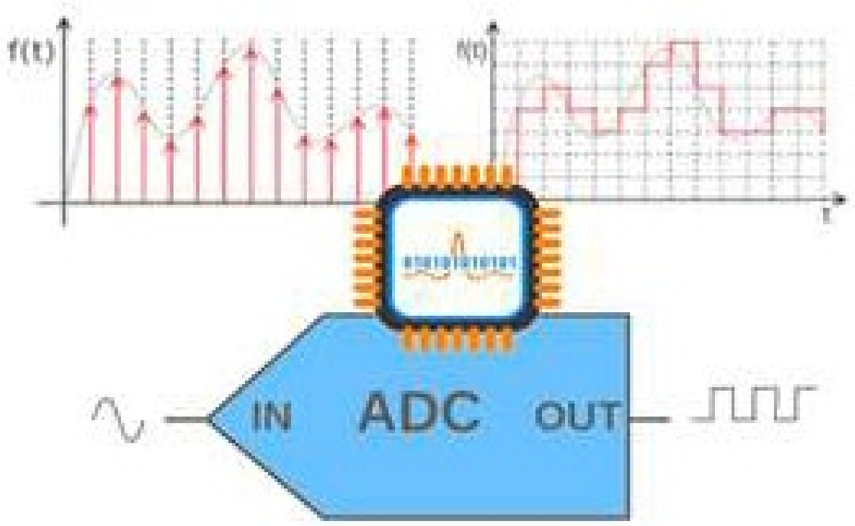


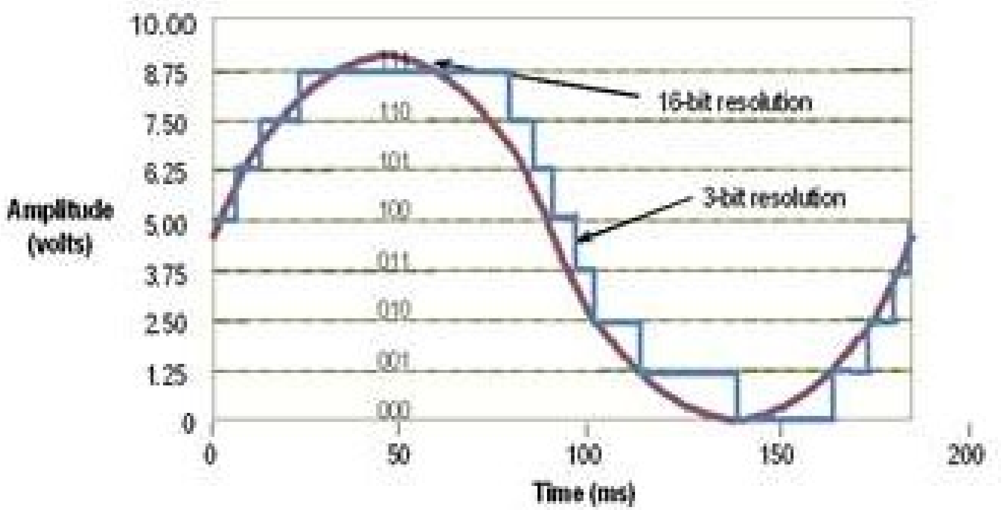


Digitization

Analog to Digital Converter (ADC):

- Most important parameters are:
  - Sampling rate.
  - Signal to noise ratio.
- The SNR of an ADC is affected by:
  - Resolution
  - Linearity
  - Accuracy
  - Aliasing





Digitization

Analog to Digital Converter (ADC):

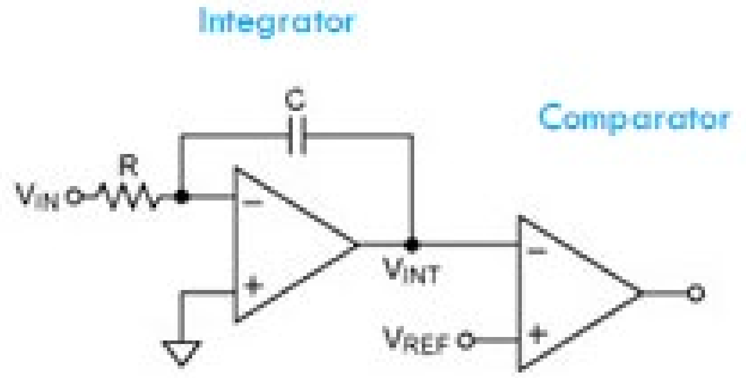
- Architectures:
  1. Single Slope/ramp ADC consists of :
  2. Dual Slope
  3. Successive approximation
  4. Parallel/Flash.

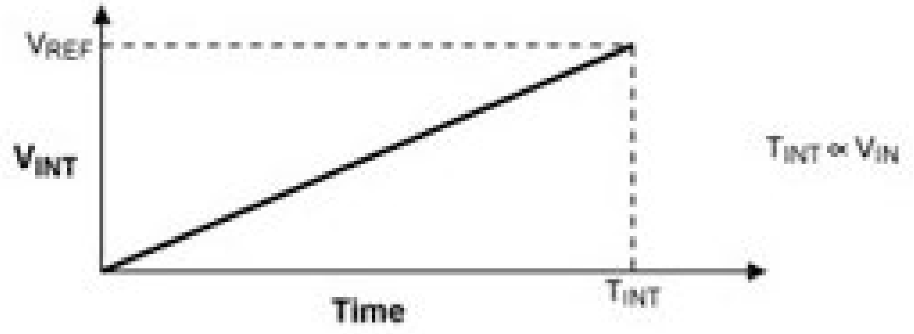
Digitization

Analog to Digital Converter (ADC):

➢ Architectures:

1. Single Slope/ramp ADC consists of :
   - Integrator
   - Comparator



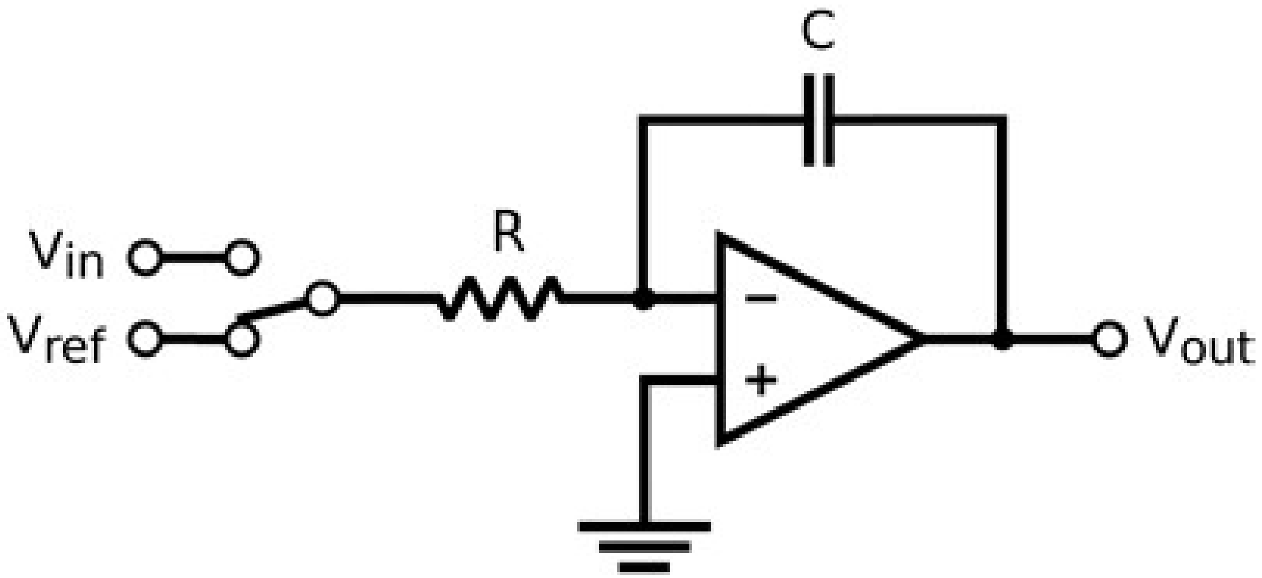


Digitization

Analog to Digital Converter (ADC):

- Architectures:
  2. Dual Slope ADC:

     The integrator generates two different ramps, one with the known analog input voltage V_{in} and another with a known reference voltage V_{ref}



Digitization

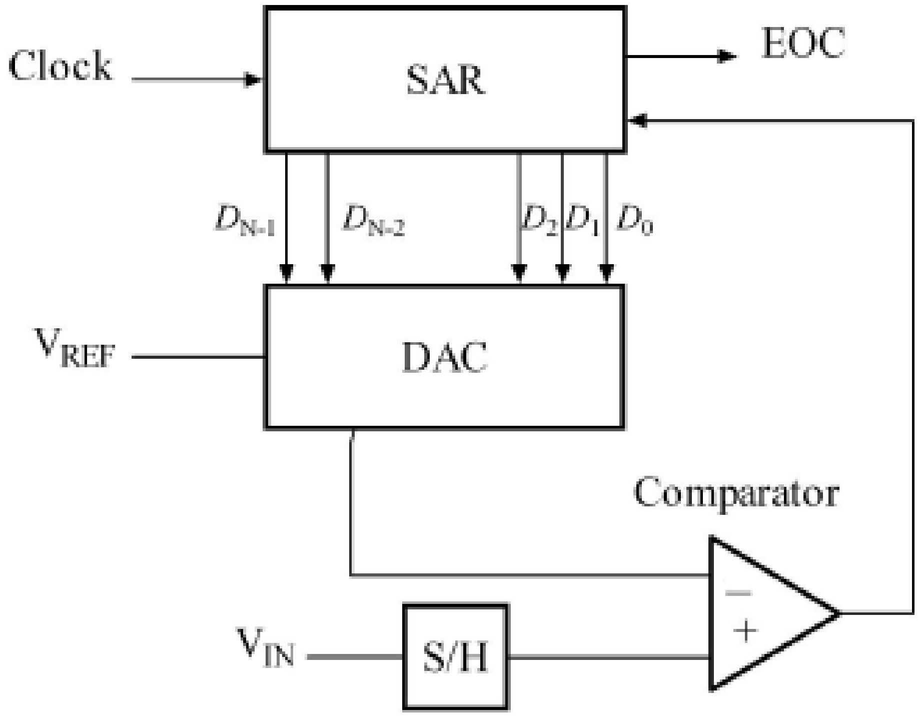
Analog to Digital Converter (ADC):

- Architectures:

  3. Successive Approximation ADC:

     Components:

     - SAR: Successive Approximation Register.
     - DAC: Digital to Analog converter
     - Comparator
     - S/H: sample and hold circuit



* EOC – end of conversion (output)

Digitization

Analog to Digital Converter (ADC):

- Architectures:

4. Flash/Parallel ADC:

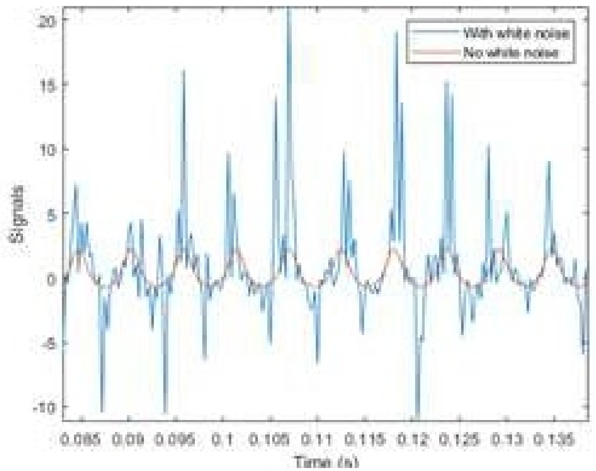
   Uses a linear voltage divider with a comparator at each point.

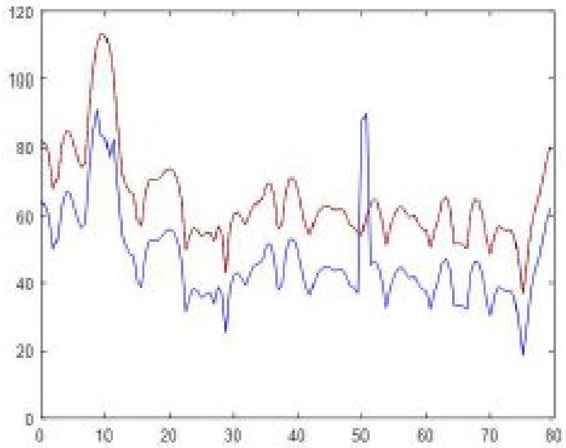
   - Extremely fast conversion.
   - Does not need a S/H circuit.

Digital Signal Processing

Digital Filters:

- Digital filtering is a subset of digital signal processing.
- Digital filters are used to:
  - Remove unwanted random noise
  - Remove fixed error (offsets)
  - Remove the unwanted effects of random external effects

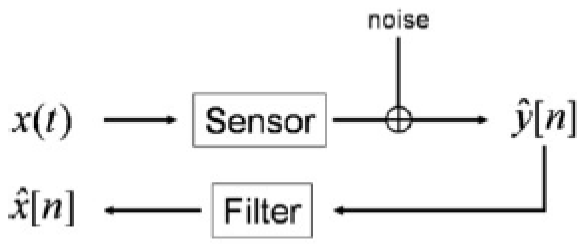


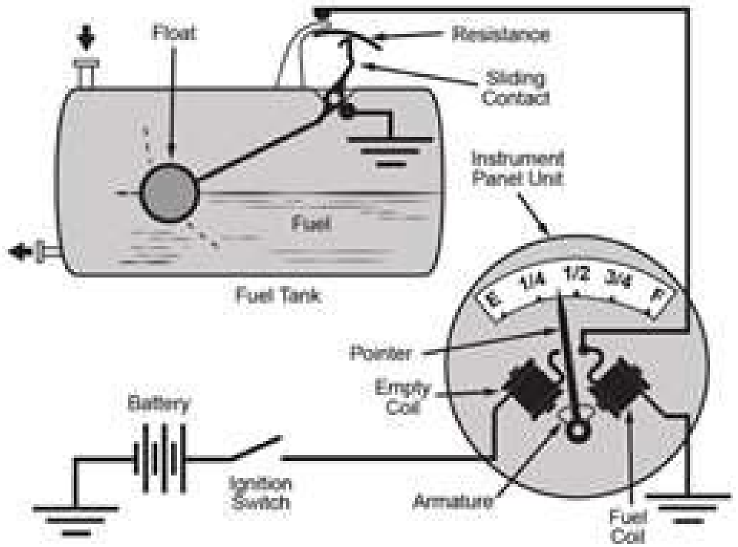


Digital Signal Processing

Digital Filters:

- Scope:
  - digital filters for signal from a sensor measuring a physical parameter





Digital Signal Processing

Digital Filters:

Implementation of digital filters:

- Digital filters can be realized through the use of:
  - Microprocessor + filtering software
  - Digital Signal Processor (DSP) chip
  - Application-specific integrated circuit (ASIC)

The End of Lecture #25