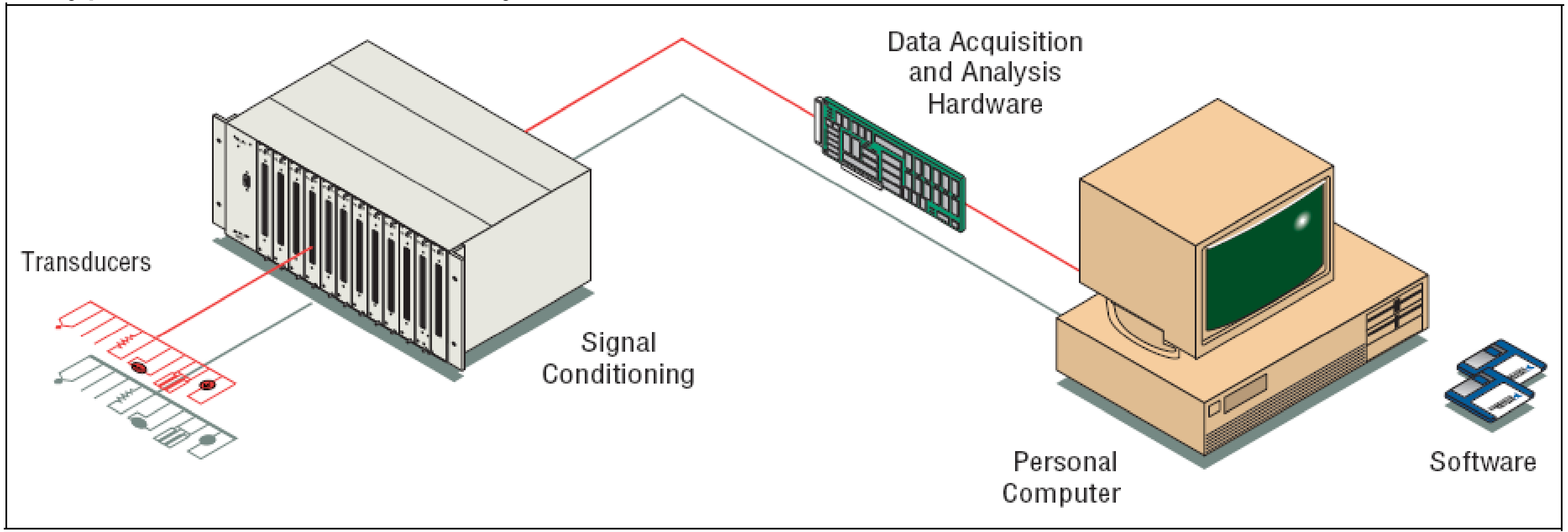
Flow Measurements

- Manometers
- Transducers
- Pitot tubes
- Thermocouples
- Hot wire systems
    a. Anemometers
    b. Probes
        - Simple
        - Slented
        - Cross-wire
- LDA (Laser Doppler Anemometry)
- PIV (Particle Image Velocimetry)

- Data Acquisition System

Data Acquisition (DAQ) Fundamentals

Typical PC-Based DAQ System



Personal computer
Transducers
Signal conditioning
DAQ hardware
Software

http://zone.ni.com/

Data Acquisition (DAQ) Fundamentals

Data acquisition involves gathering signals from measurement sources and digitizing the signal for storage, analysis, and presentation on a PC.

Data acquisition (DAQ) systems come in many different PC technology forms for great flexibility when choosing your system.

Scientists and engineers can choose from PCI (Peripheral Component Interconnect) , PXI, PCI Express, PXI Express, PCMCIA, USB, Wireless and Ethernet data acquisition for test, measurement, and automation applications.

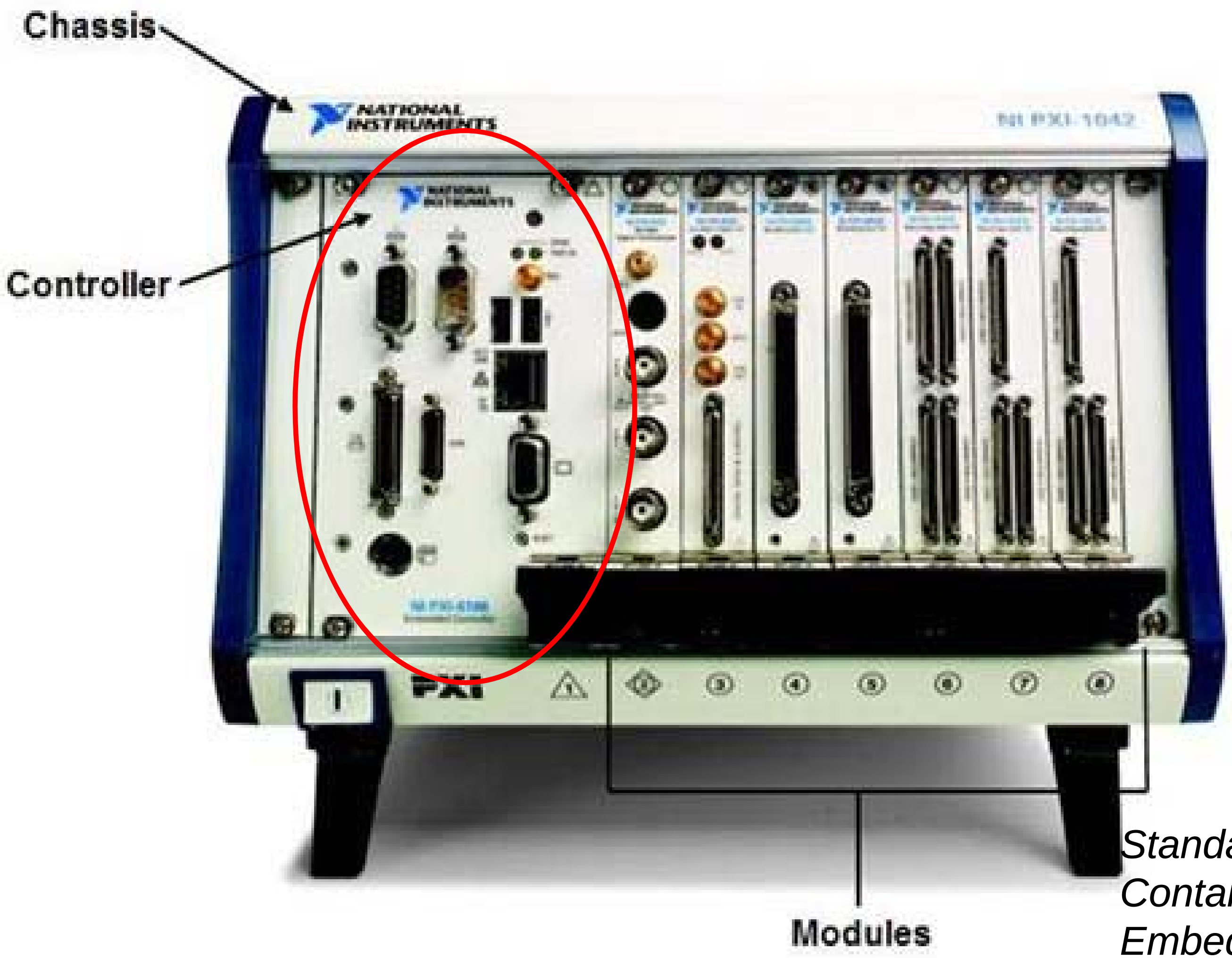
There are five components to be considered when building a basic DAQ system :

- Transducers and sensors
- Signals
- Signal conditioning
- DAQ hardware
- Driver and application software

http://zone.ni.com/devzone/cda/tut/p/id/4811

PXI is the open, PC-based platform for test, measurement, and control

PXI systems are composed of three basic components — chassis, system controller, and peripheral modules



Standard 8-Slot PXI Chassis Containing an Embedded System Controller and Seven Peripheral Modules

A typical DAQ system with National Instruments SCXI signal conditioning accessories

Transducers and sensors

A transducer is a device that converts a physical phenomenon into a measurable electrical signal, such as voltage or current.

The ability of a DAQ system to measure different phenomena depends on the transducers to convert the physical phenomena into signals measurable by the DAQ hardware.

Phenomenon	**Transducer**
Temperature	Thermocouple, RTD, Thermistor
Light	Photo Sensor
Sound	Microphone
Force and Pressure	Strain Gage Piezoelectric Transducer
Position and Displacement	Potentiometer, LVDT, Optical Encoder
Acceleration	Accelerometer
pH	pH Electrode

Signals

The appropriate transducers convert physical phenomena into measurable signals.

However, different signals need to be measured in different ways. For this reason, it is important to understand the different types of signals and their corresponding attributes.

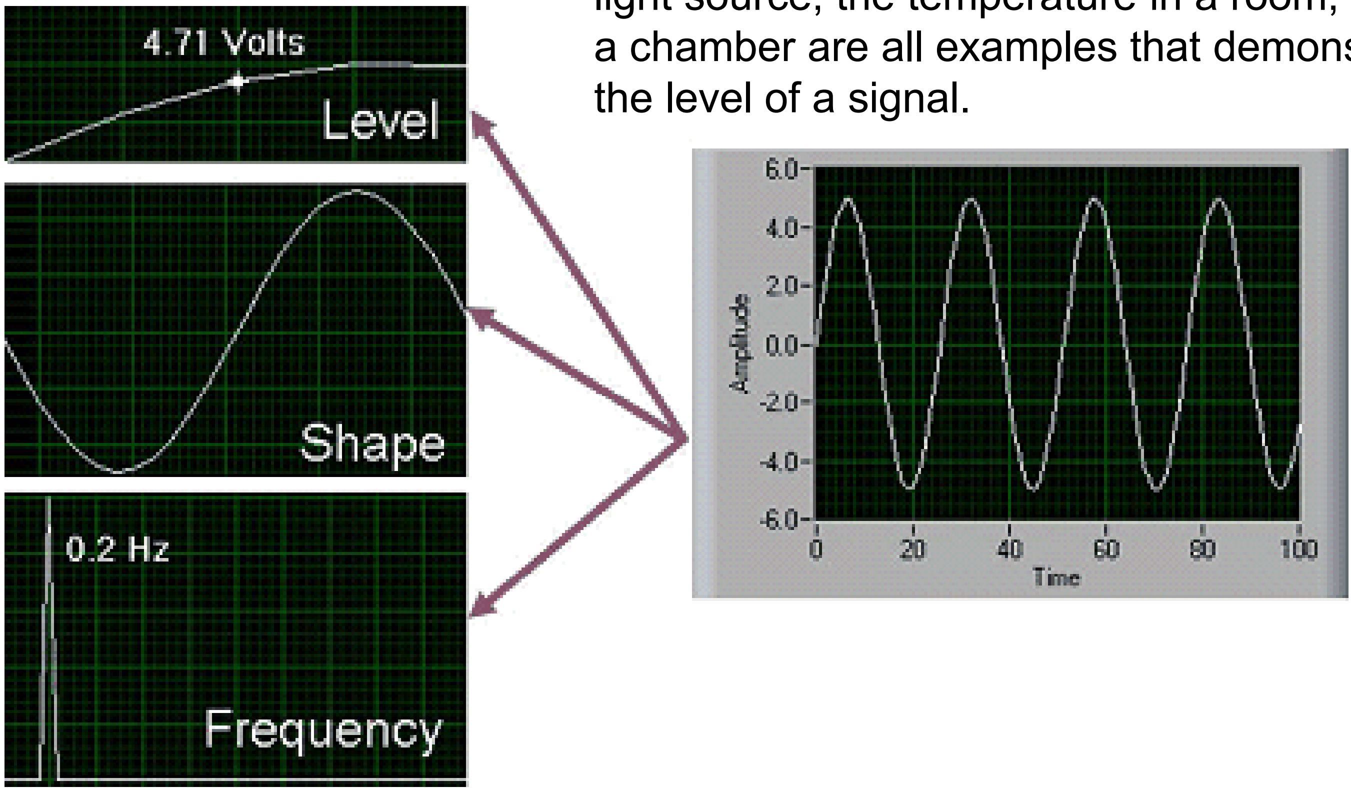
Signals can be categorized into two groups:

- ❑ Analog
- ❑ Digital

Analog Signals

An analog signal can be at any value with respect to time. A few examples of analog signals include voltage, temperature, pressure, sound, and load. The three primary characteristics of an analog signal include level, shape, and frequency

Because analog signals can take on any value, **level** gives vital information about the measured analog signal. The intensity of a light source, the temperature in a room, and the pressure inside a chamber are all examples that demonstrate the importance of the level of a signal.

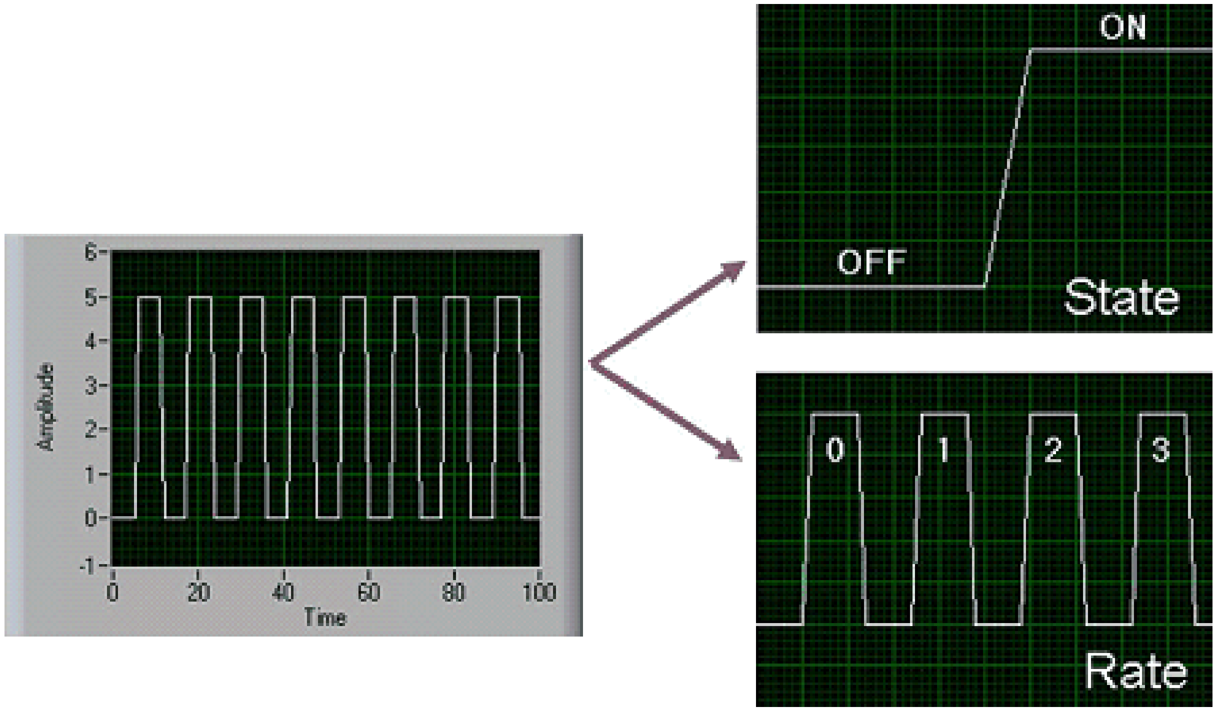


Primary Characteristics of an Analog Signal

Digital Signals

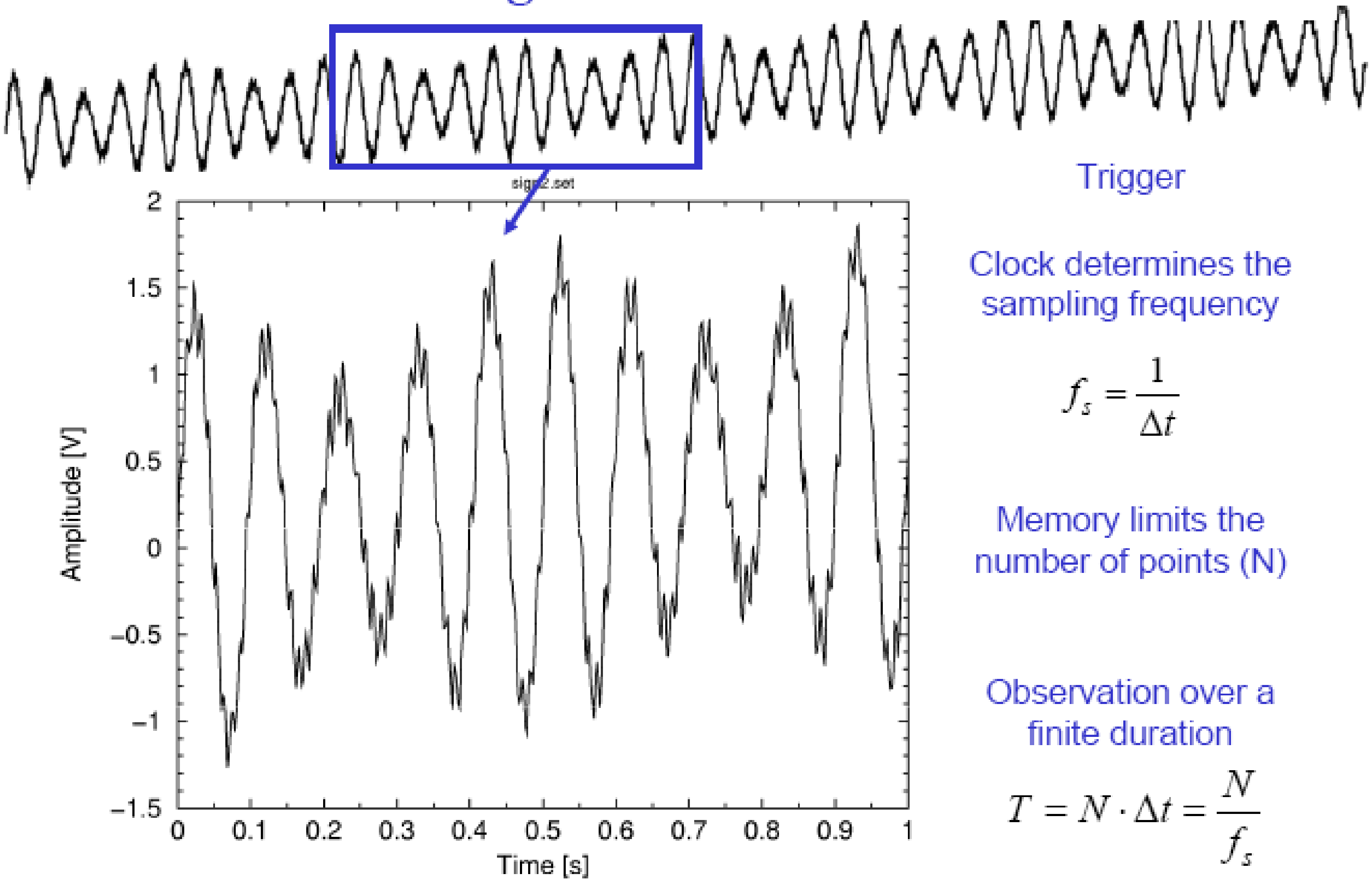
A digital signal cannot take on any value with respect to time.
Instead, a digital signal has two possible levels: high and low.

Digital signals generally conform to certain specifications that define characteristics of the signal. Digital signals are commonly referred to as transistor-to-transistor logic (TTL). TTL specifications indicate a digital signal to be low when the level falls within 0 to 0.8 V, and the signal is high between 2 to 5 V.



The useful information that can be measured from a digital signal includes the **state** (on or off, high or low) and the **rate** of a digital how the digital signal changes state with respect to time

Observing over a Finite Duration



Trigger

Clock determines the sampling frequency

$$f_s = \frac{1}{\Delta t}$$

Memory limits the number of points (N)

Observation over a finite duration

$$T = N \cdot \Delta t = \frac{N}{f_s}$$

Signal Conditioning

Sometimes transducers generate signals too difficult or too dangerous to measure directly with a DAQ device.
For instance, when dealing with high voltages, noisy environments, extreme high and low signals, or simultaneous signal measurement, signal conditioning is essential for an effective DAQ system. Signal conditioning maximizes the accuracy of a system, allows sensors to operate properly, and guarantees safety.

Signal conditioning accessories can be used in a variety of applications including:

❑**Amplification**
❑**Attenuation**
❑**Isolation** (The system being monitored may contain high-voltage transients that could damage the computer without signal conditioning)
❑**Bridge completion**
❑**Simultaneous sampling**
❑**Sensor excitation**
❑**Multiplexing** (A common technique for measuring several signals with a single measuring device is multiplexing.)

Modular Signal Conditioning Systems

Wi-Fi & Ethernet DAQ

2

SCXI

SCC

Compact FieldPoint

Integrated Signal Conditioning Devices

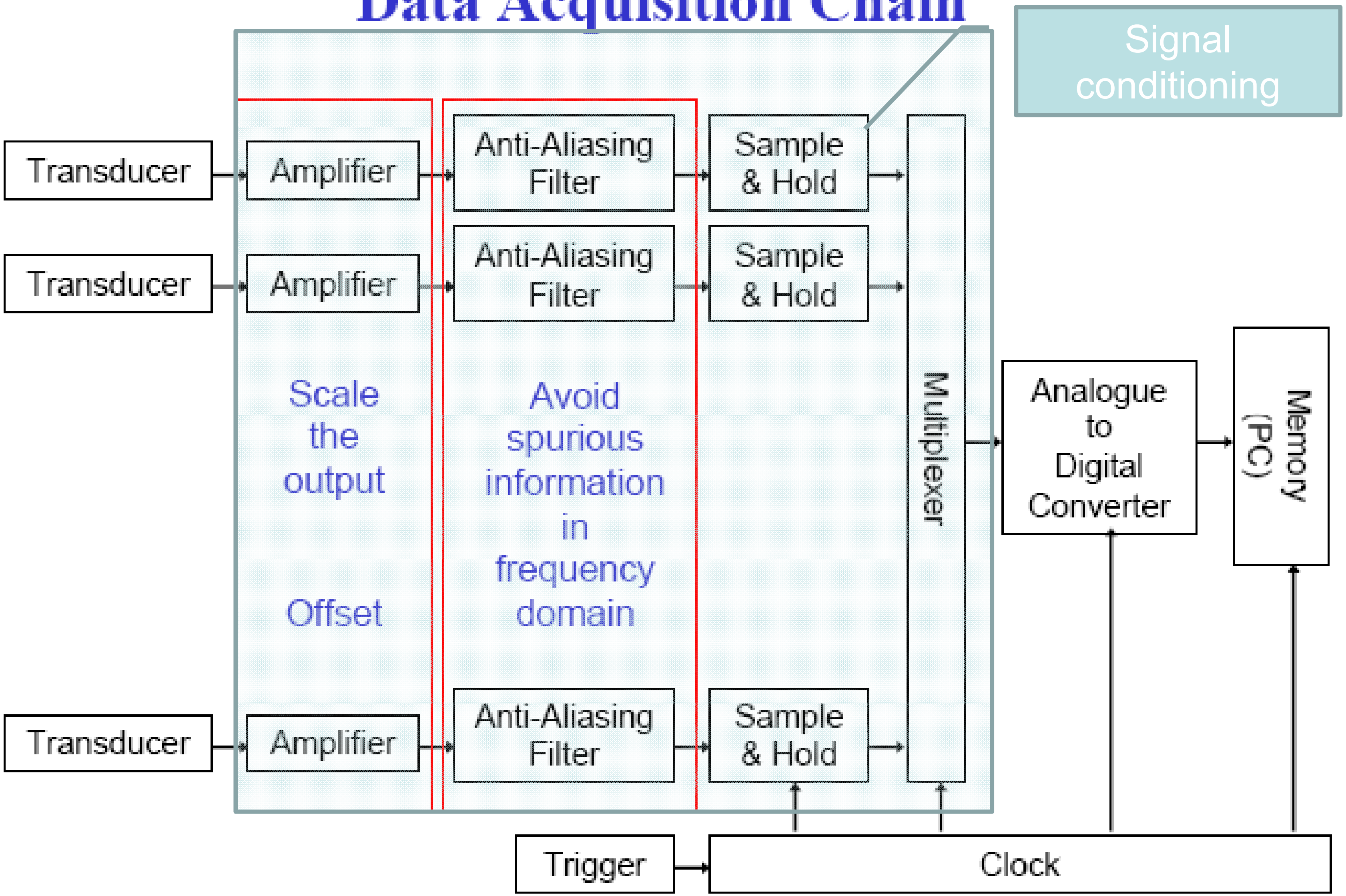
PXI Instruments

SC Series

USB-9200 Series

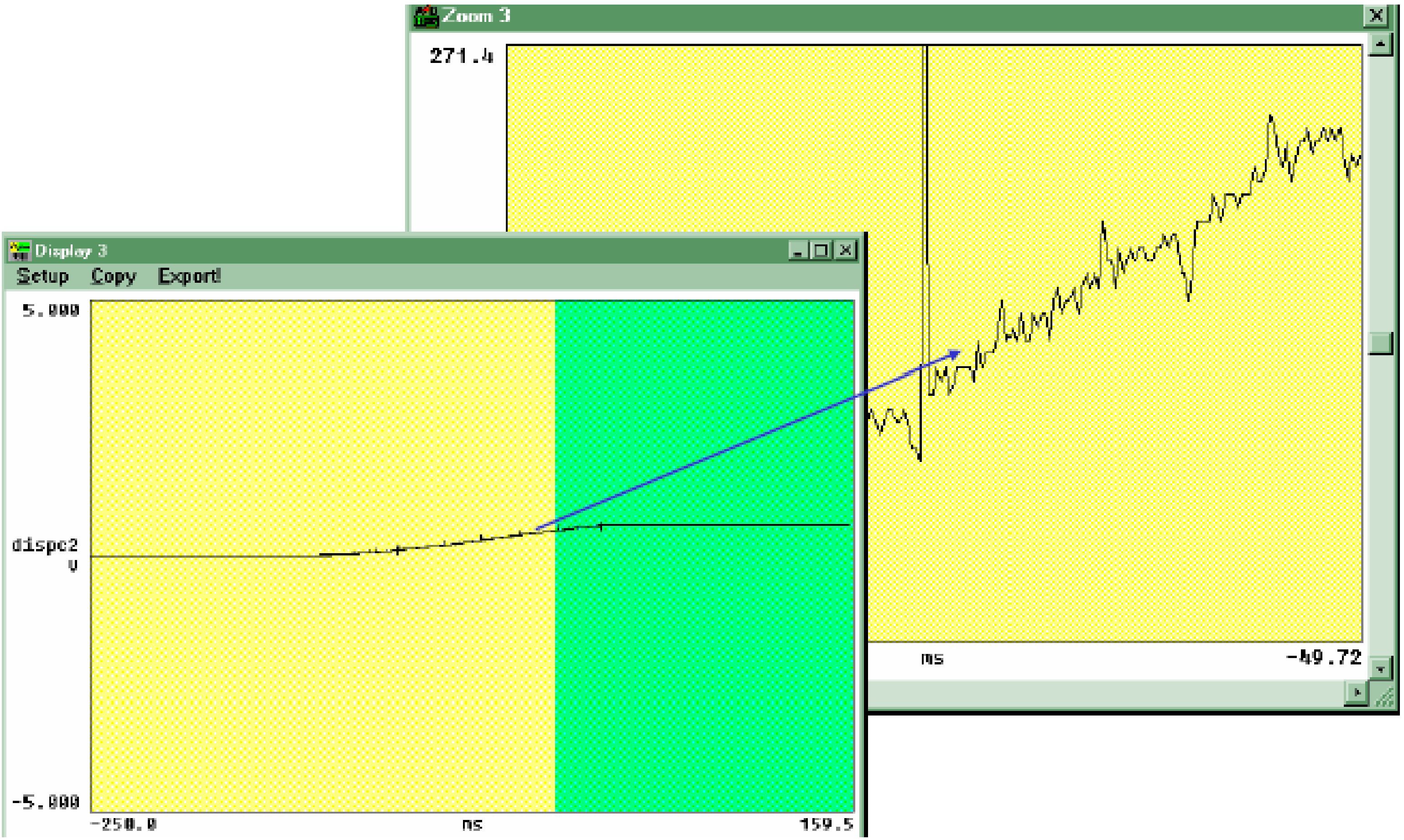
Wi-Fi & Ethernet DAQ

Data Acquisition Chain



Example for Need of Amplifiers

Amplification – The most common type of signal conditioning is amplification. Low-level thermocouple signals, for example, should be amplified to increase the resolution and reduce noise. For the highest possible accuracy, the signal should be amplified so that themaximum voltage range of the conditioned signal equals the maximum input range of the A/D Converter.



DAQ Hardware

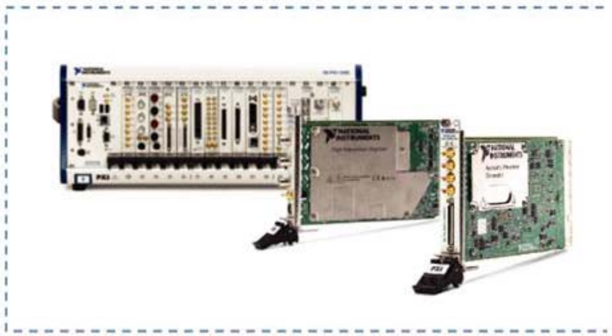
DAQ hardware acts as the interface between the computer and the outside world. It primarily functions as a device that digitizes incoming analog signals so that the computer can interpret them. Other data acquisition functionality includes:

· Analog Input/Output
· Digital Input/Output
· Counter/Timers
· Multifunction - a combination of analog, digital, and counter operations on a single device

NI Wi-Fi Data Acquisition

Distributed

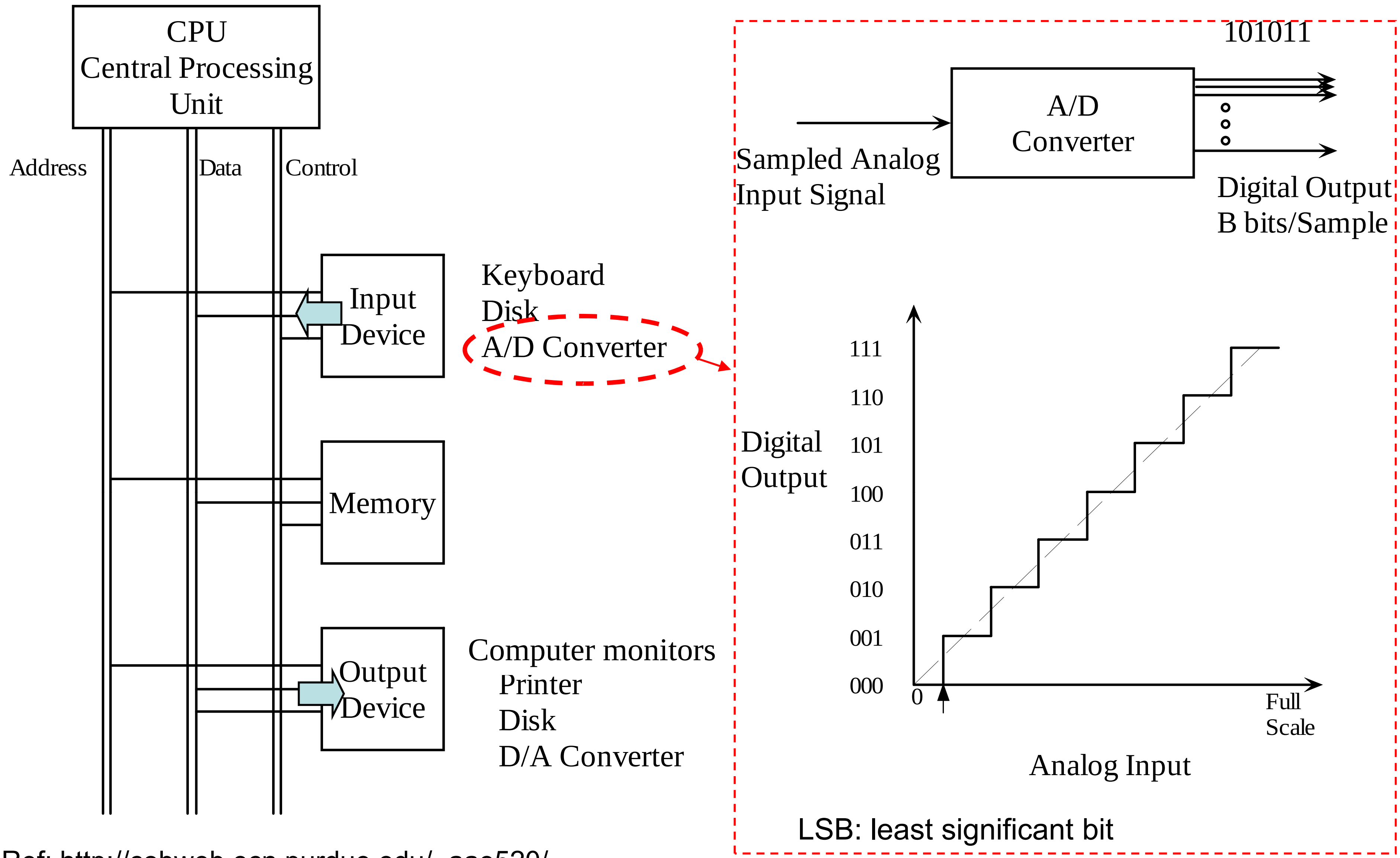
Desktop



PXI: Rugged and Modular

Portable

Computer

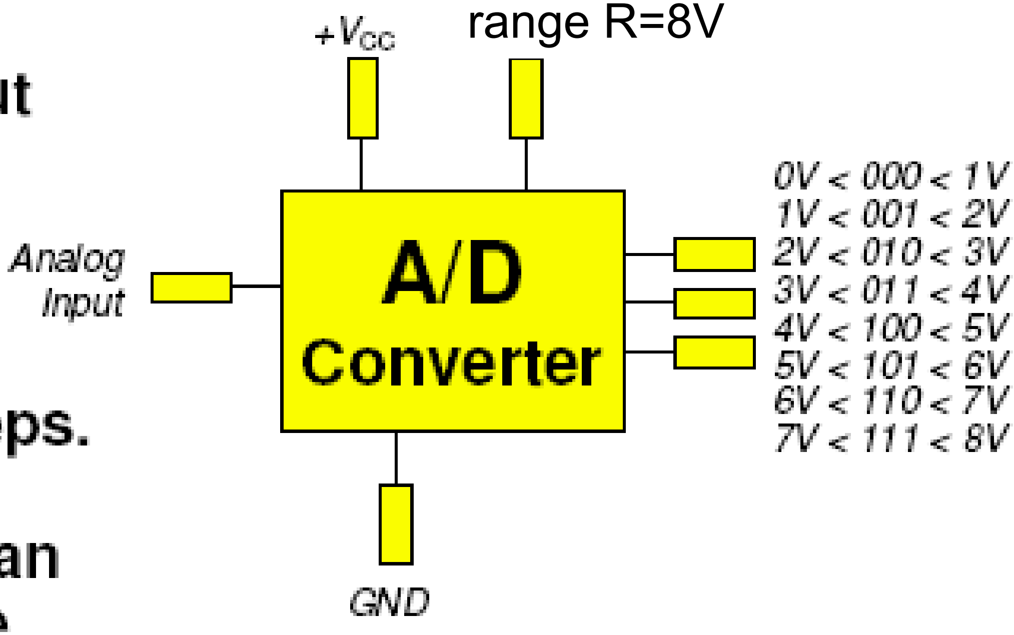


Ref: http://cobweb.ecn.purdue.edu/~aae520/

What, Exactly, Does An Analog-to-Digital Converter Do?

- For a 3-bit ADC, there are 8 $=2^3$ possible output codes.
- In this example, if the input voltage is 5.5V and the reference is 8V, then the output will be 101.
- More bits give better resolution and smaller steps.
- A lower reference voltage gives smaller steps, but can be at the expense of noise.

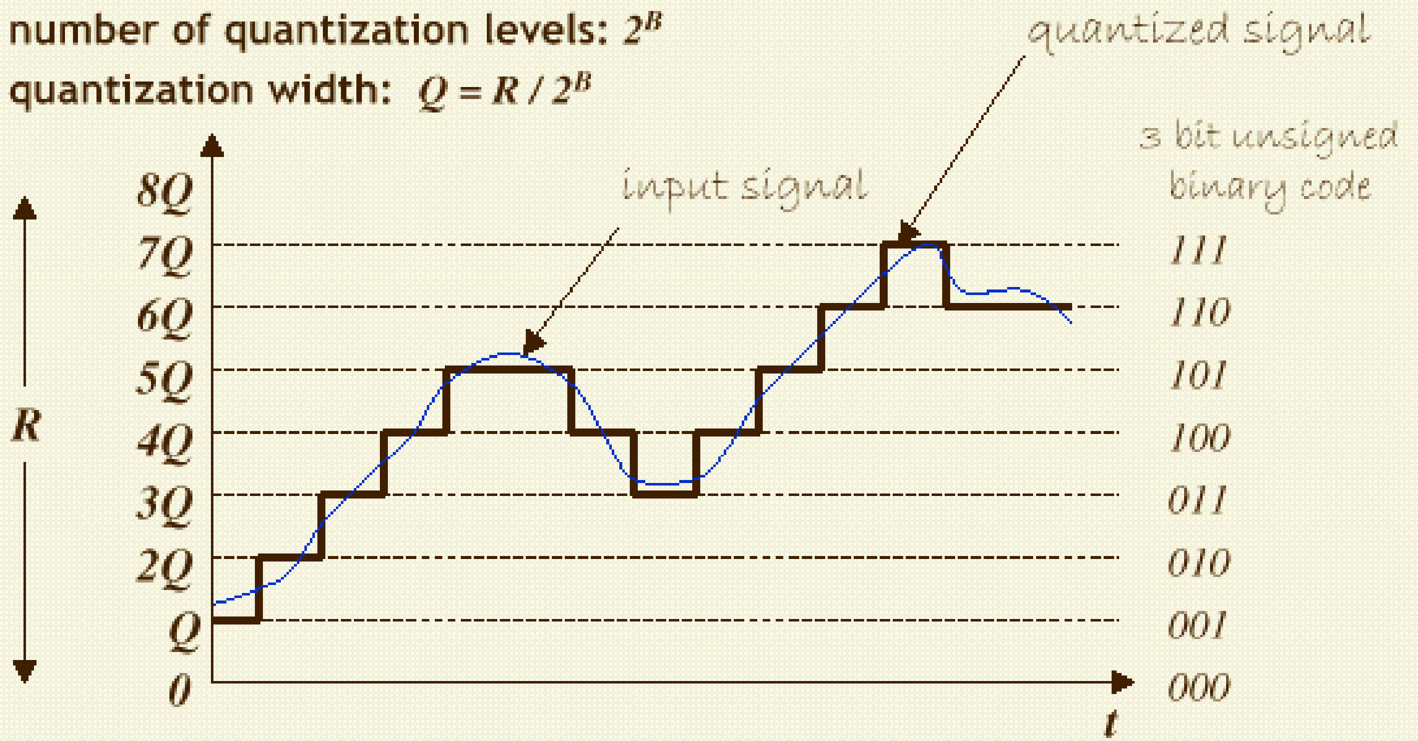
Full scale voltage range R=8V



A/D converter

Key parameters for an A/D converter

- full-scale voltage range: R
- number of bits: B
- number of quantization levels: 2^B
- quantization width: $Q = R / 2^B$



Dynamic Response of Measurement Systems

A **static measurement** of a physical quantity is performed when the quantity is not changing in time.

The deflection of a beam under a constant load would be a static deflection.

However, if the beam were set in vibration, the deflection would vary with time (**dynamic measurement**).

Zeroth-, First- and Second-Order Systems:

A system may be described in terms of a general variable x(t) written in differential equation form as:

$$a_n \frac{d^n x}{dt^n} + a_{n-1} \frac{d^{n-1} x}{dt^{n-1}} + \cdots + a_1 \frac{dx}{dt} + a_0 x = F(t)$$

where F(t) is some forcing function imposed on the system.

The order of the system is designed by the order of the differential equation.

A zeroth-order system would be governed by:

$$a_0 x = F(t)$$

A first-order system is governed by:

$$a_1 \frac{dx}{dt} + a_0 x = F(t)$$

A second-order system is governed by:

$$a_2 \frac{d^2x}{dt^2} + a_1 \frac{dx}{dt} + a_0 x = F(t)$$

The zeroth order system indicates that the system variable x(t) will follow the input forcing function F(t) instantly by some constant value:

$$x = \frac{1}{a_0} F(t)$$

The constant $1/a_0$ is called the ***static sensitivity*** of the system.

The first order system may be expressed as:

$$\frac{a_1}{a_0}\frac{dx}{dt} + x = \frac{F(t)}{a_0}$$

The $\tau = a_1/a_0$ has the dimension of time and is usually called the **time constant** of the system.

For step input : F(t)=0 at t=0

F(t)=A for t>0

Along with the initial condition $x=x_0$ at t=0

<u>The solution to the first order system is:</u>

$$x(t) = \underbrace{\frac{A}{a_0}}_{\substack{\text{Steady state response} \\ (\text{call } x_\infty)}} + \underbrace{\left(x_0 - \frac{A}{a_0}\right)e^{-t/\tau}}_{\text{Transient response of the system}}$$

where $\tau = \frac{a_1}{a_0}$

The same solution can be written in dimensionless forms as:

$$\frac{x(t) - x_\infty}{x_0 - x_\infty} = e^{-t/\tau}$$

The **rise time** is the time required to achieve a response of 90 percent of the step input.

This requires:

$$e^{-t/\tau} = 0.1$$

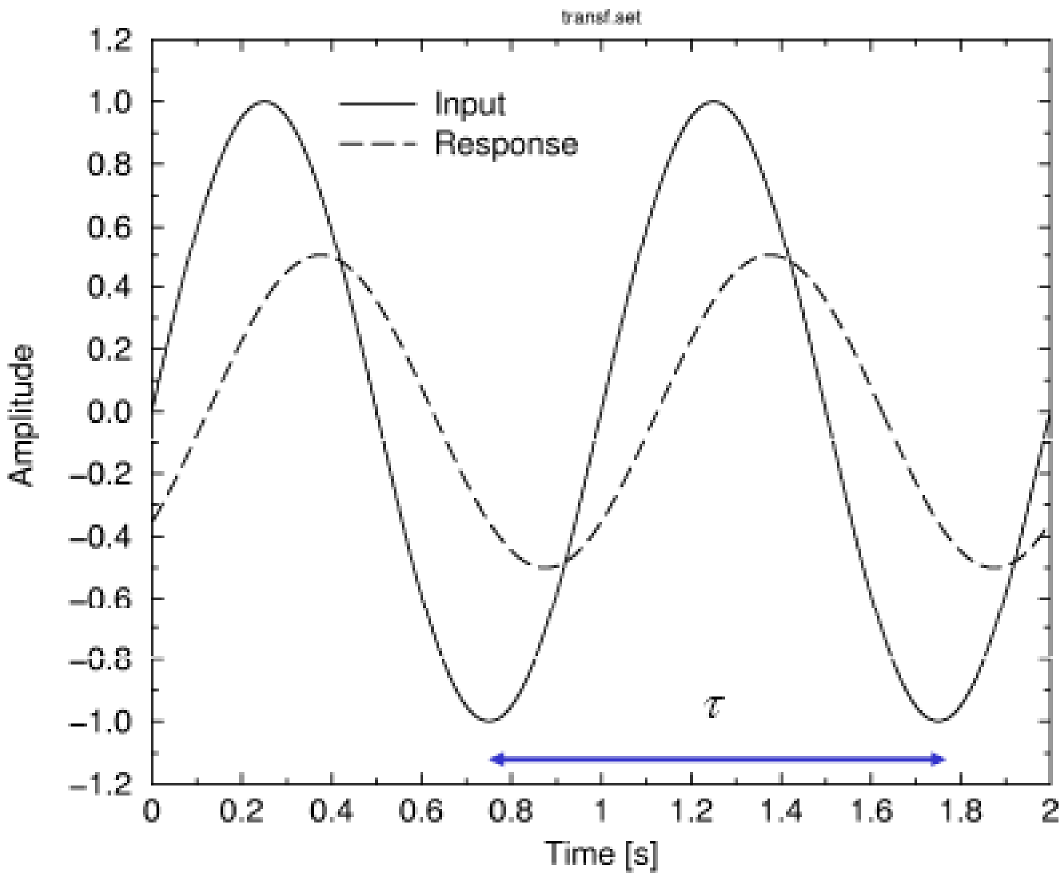
or

$$t = 2.303\ \tau$$

Transfer Function

Input → Response

$$F(t) \longrightarrow \boxed{\text{System } H(\omega)} \longrightarrow x(t)$$



$$g = \frac{A_{out}}{A_{in}}$$

$$g[dB] = 20\log_{10}(g)$$

$$\varphi[rad] = \frac{t_{in} - t_{out}}{\tau}.2\pi$$

$$g = \frac{\sqrt{2}}{2}$$

$$g[dB] = -3dB$$

$$\varphi[rad] = \frac{-\pi}{4}$$

http://cobweb.ecn.purdue.edu/~aae520/

Dynamic Response of Measurement Systems

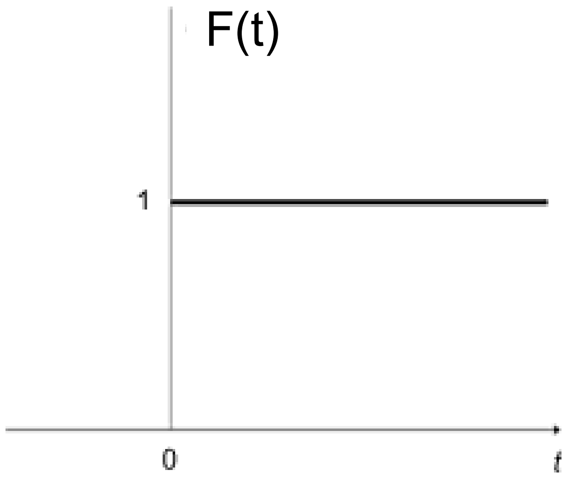
Zero Order System:

Output signal

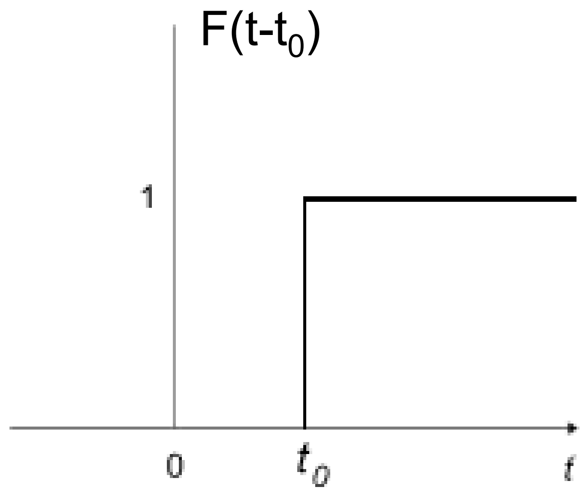
Input signal

$$x(t) = K \cdot F(t)$$

Input signal examples:

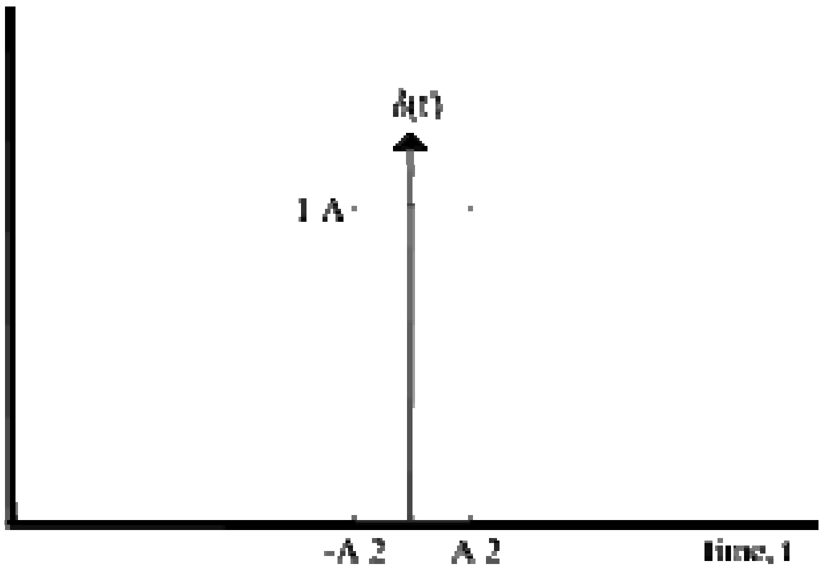


Unit step function
(Heaviside function)



Shifted unit step function

Input signal examples:



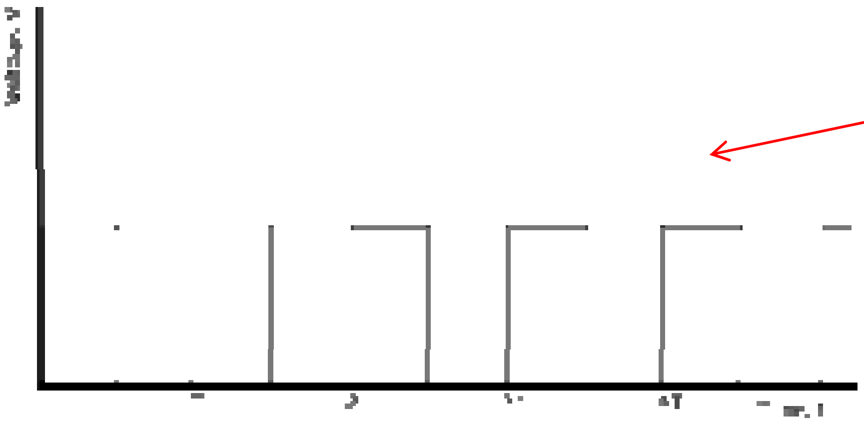
$$\int_{-\infty}^{\infty} \delta(t)dt = 1$$

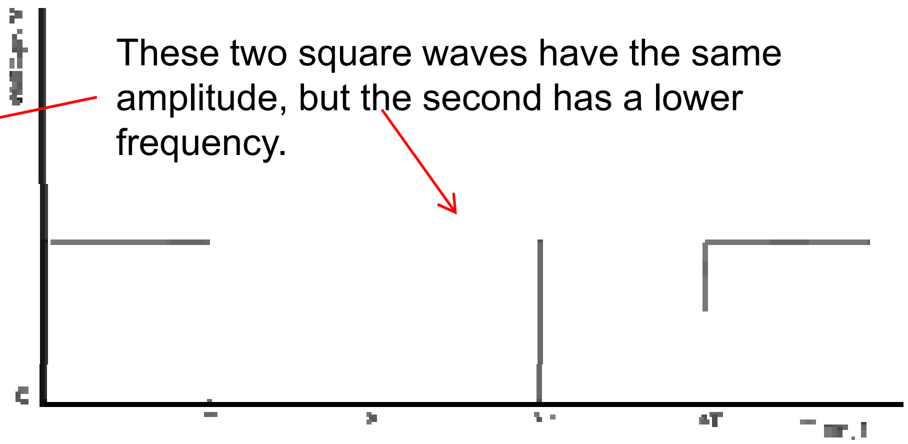
Impulse function (Dirac delta function)

Input signal examples:

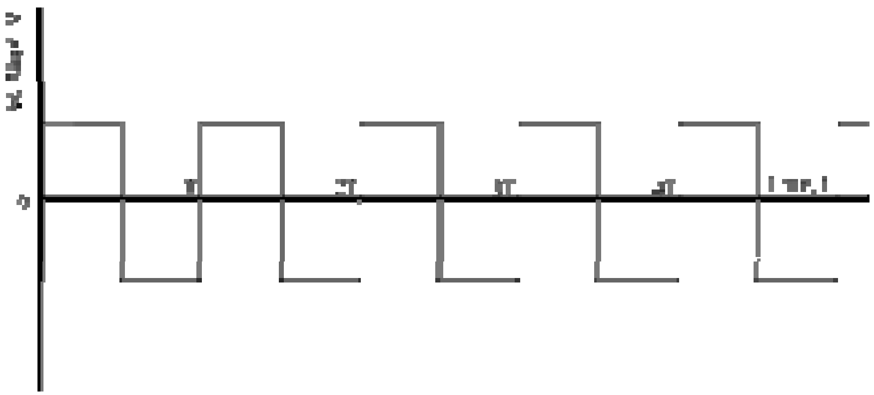
Square Wave: A square wave is a series of rectangular pulses.

some examples of square waves:





These two square waves have the same amplitude, but the second has a lower frequency.

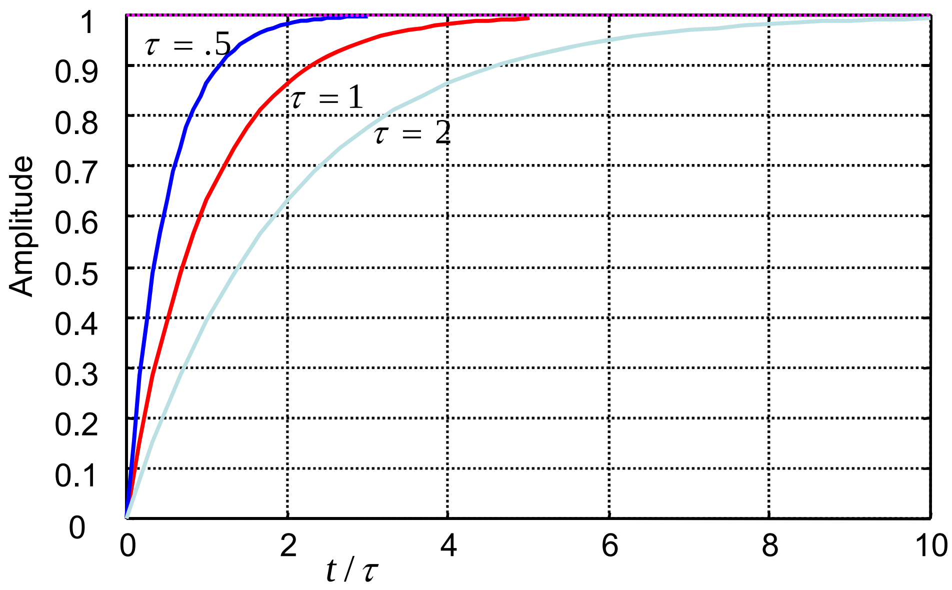


Dynamic Response of Measurement Systems

First Order System $\tau \dfrac{dx}{dt} + x = K \cdot F(t)$

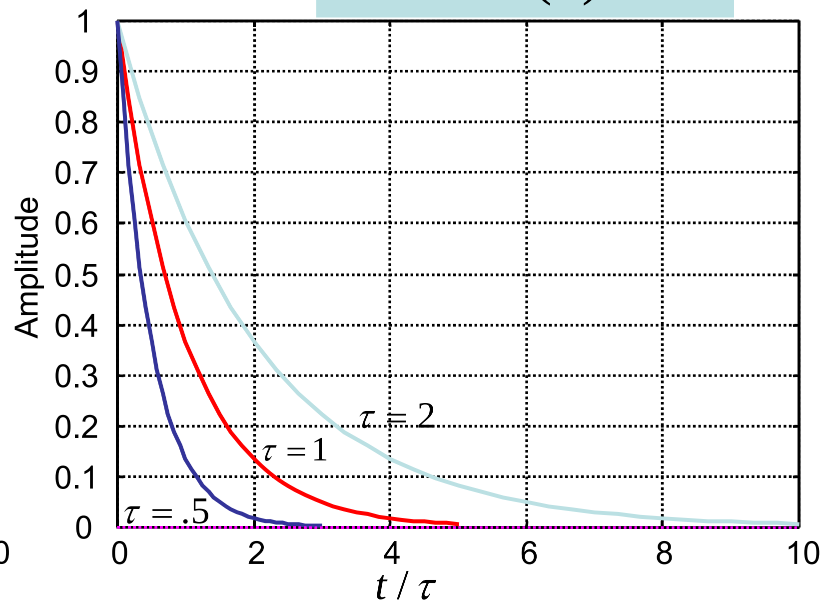
Step response
- First Order System

$$x = K \cdot F(0) \cdot (1 - e^{-t/\tau})$$



Impulse response –
First Order System

$$x = K \cdot F(0) \cdot e^{-t/\tau}$$



Dynamic Response of Measurement Systems

First Order System
Sinusoidal Response

Input

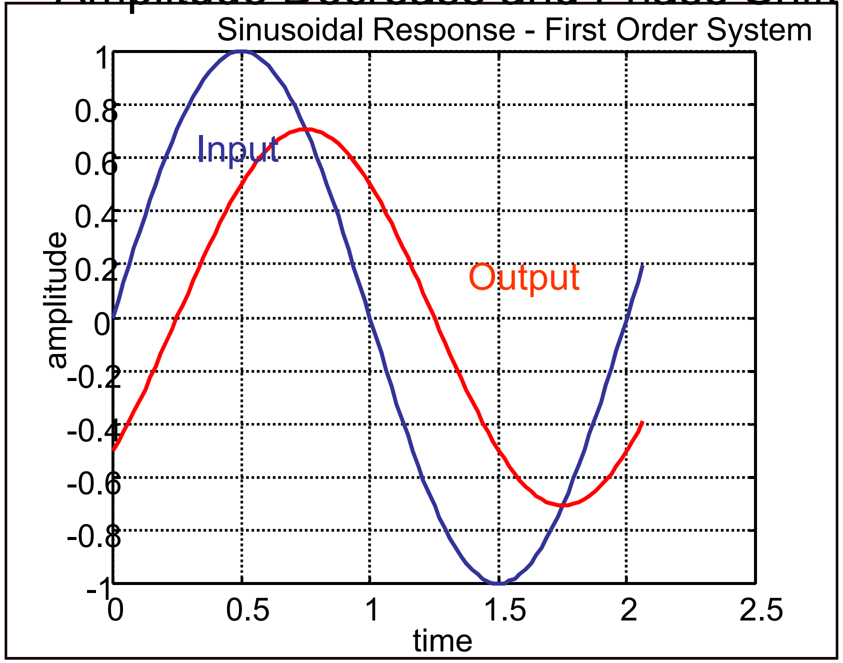
$$F(t) = F(0)\sin(\omega t)$$

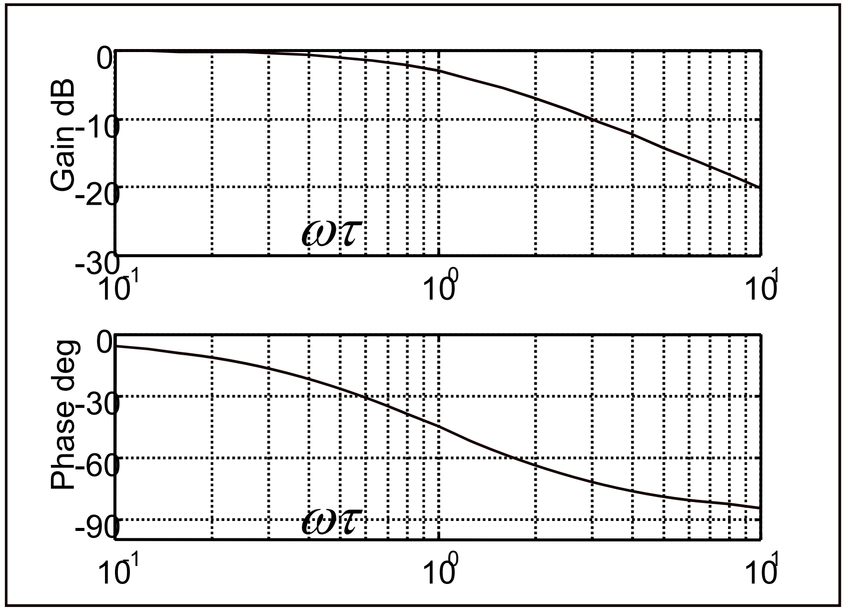
Output

$$x = \frac{K \cdot F(0)}{\sqrt{1+\omega^2\tau^2}}\sin(\omega t + \Phi)$$

$$\Phi = \tan^{-1}(-\omega\tau)$$

Amplitude Decrease and Phase Shift





Bode Plot

Dynamic Response of Measurement Systems

Second Order System

$$\frac{d^2x}{dt^2} + 2\zeta\omega_n \frac{dx}{dt} + \omega_n^2 x = K\omega_n^2 F(t)$$

ω_n - natural frequency

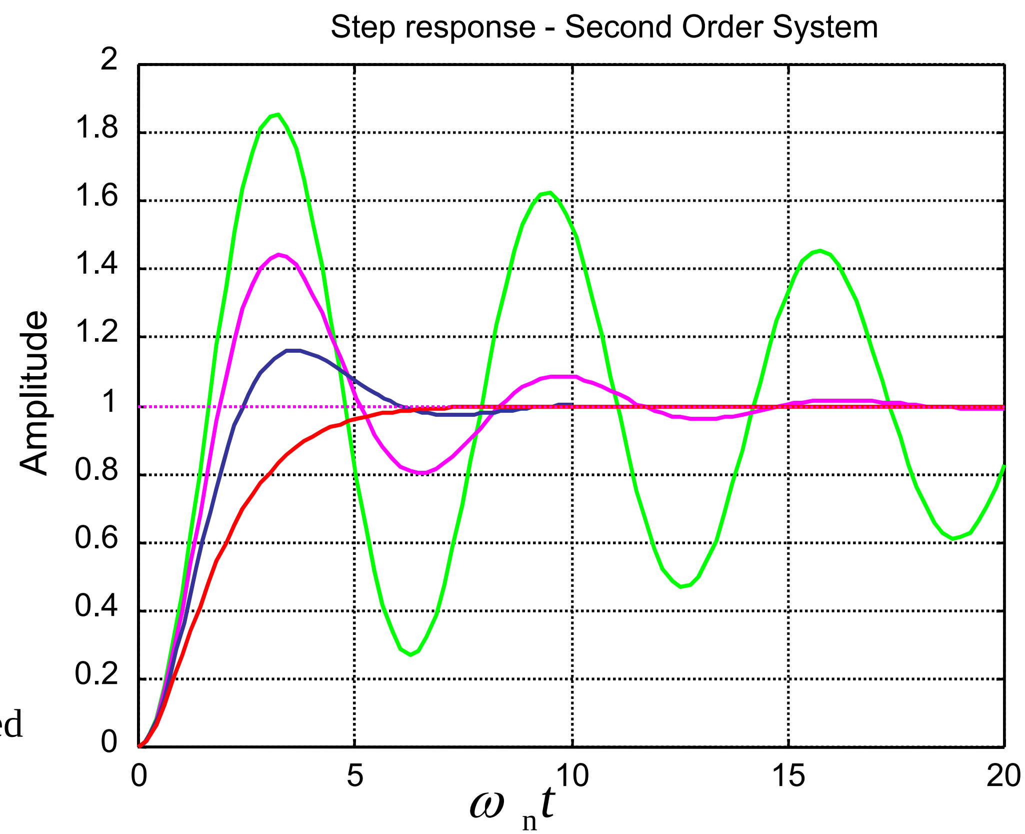
ζ - damping factor

$\zeta = 1$ - critical damping - no oscillations

$\zeta = .7$ - for fastest response

5% overshoot

System comes to 5% of static value in half the time for critically damped systems



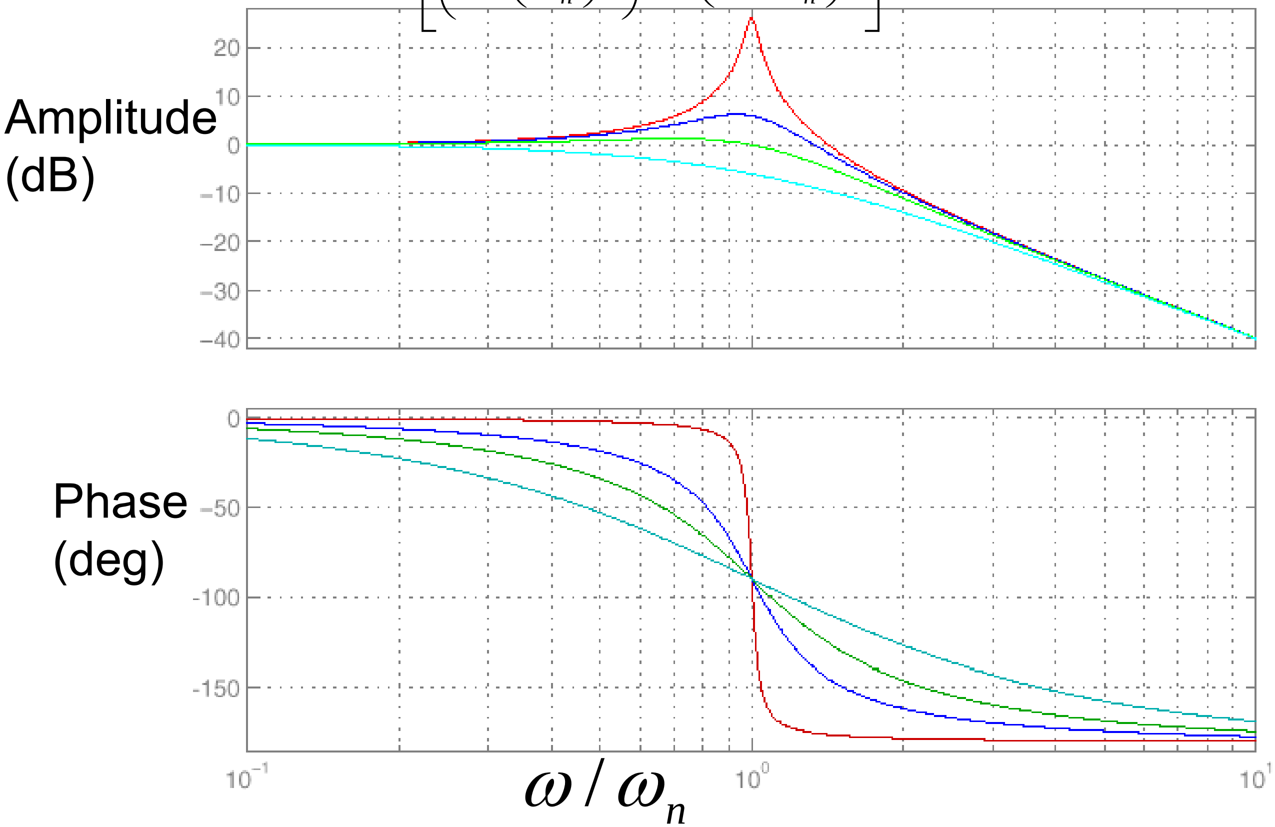
Dynamic Response of Measurement Systems

Second Order System - Sinusoidal Response

$$F = F(0)\sin(\omega t)$$

$$x = \frac{K \cdot F(0)}{\left[\left(1-\left(\frac{\omega}{\omega_n}\right)^2\right)^2 + \left(2\zeta\frac{\omega}{\omega_n}\right)^2\right]}\sin(\omega t+\phi)$$

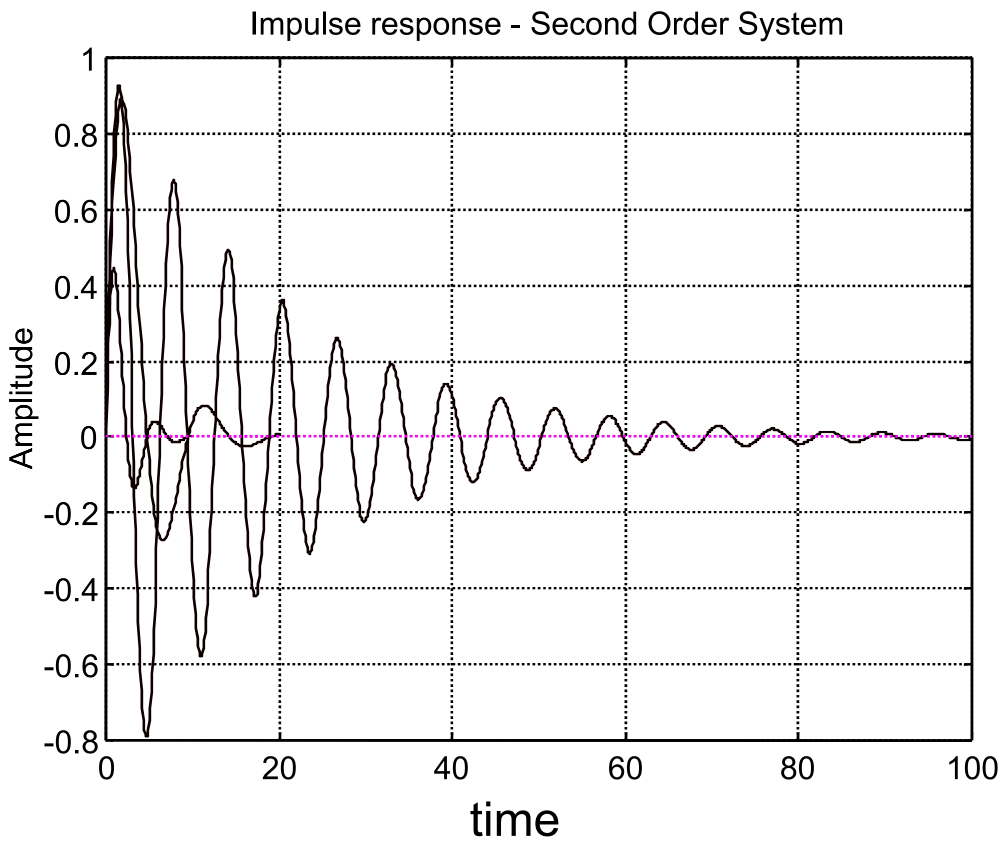
$$\phi = \tan^{-1}\left(-\frac{2\zeta\frac{\omega}{\omega_n}}{1-\left(\frac{\omega}{\omega_n}\right)^2}\right)$$



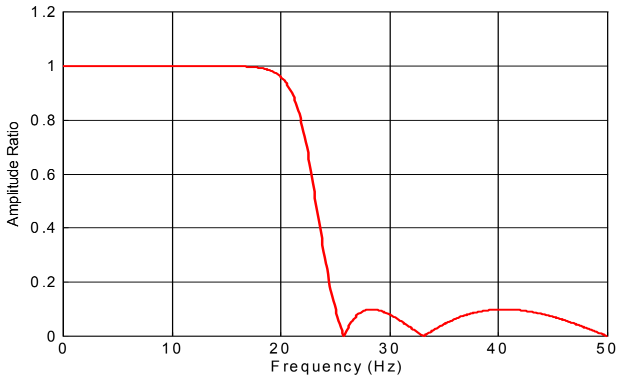
Dynamic Response of Measurement Systems

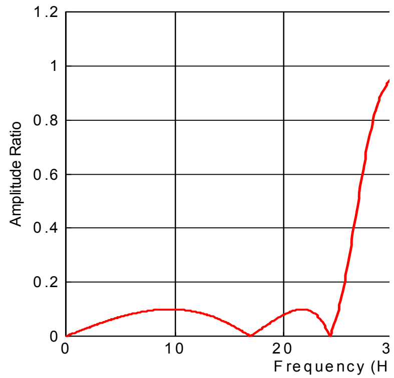
Second Order System - Impulse Response

$$x = K \cdot F(0) \cdot e^{-\zeta\omega_n t} \sin(\sqrt{1-\zeta^2}\,\omega_n t + \phi)$$



Filters





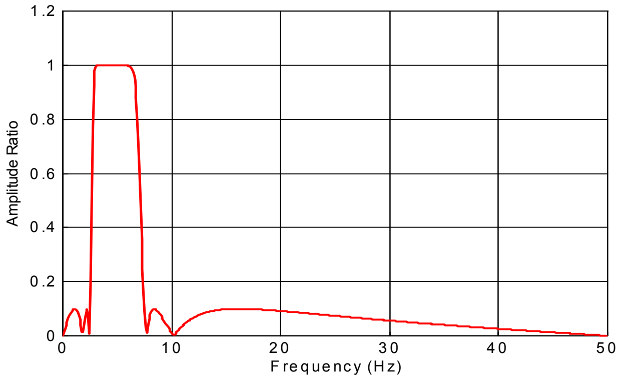
Low Pass Filter

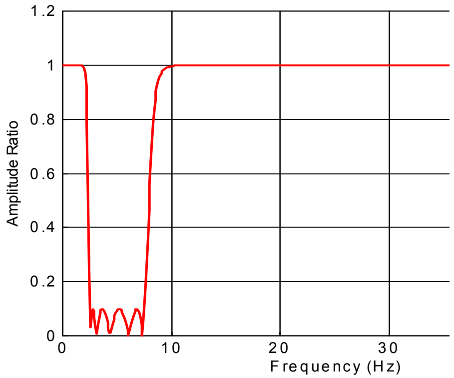
Removes High Frequency Noise

High Pass Filter

Removes DC and Low Frequency Noise

(Such as 60, 120 Hz)

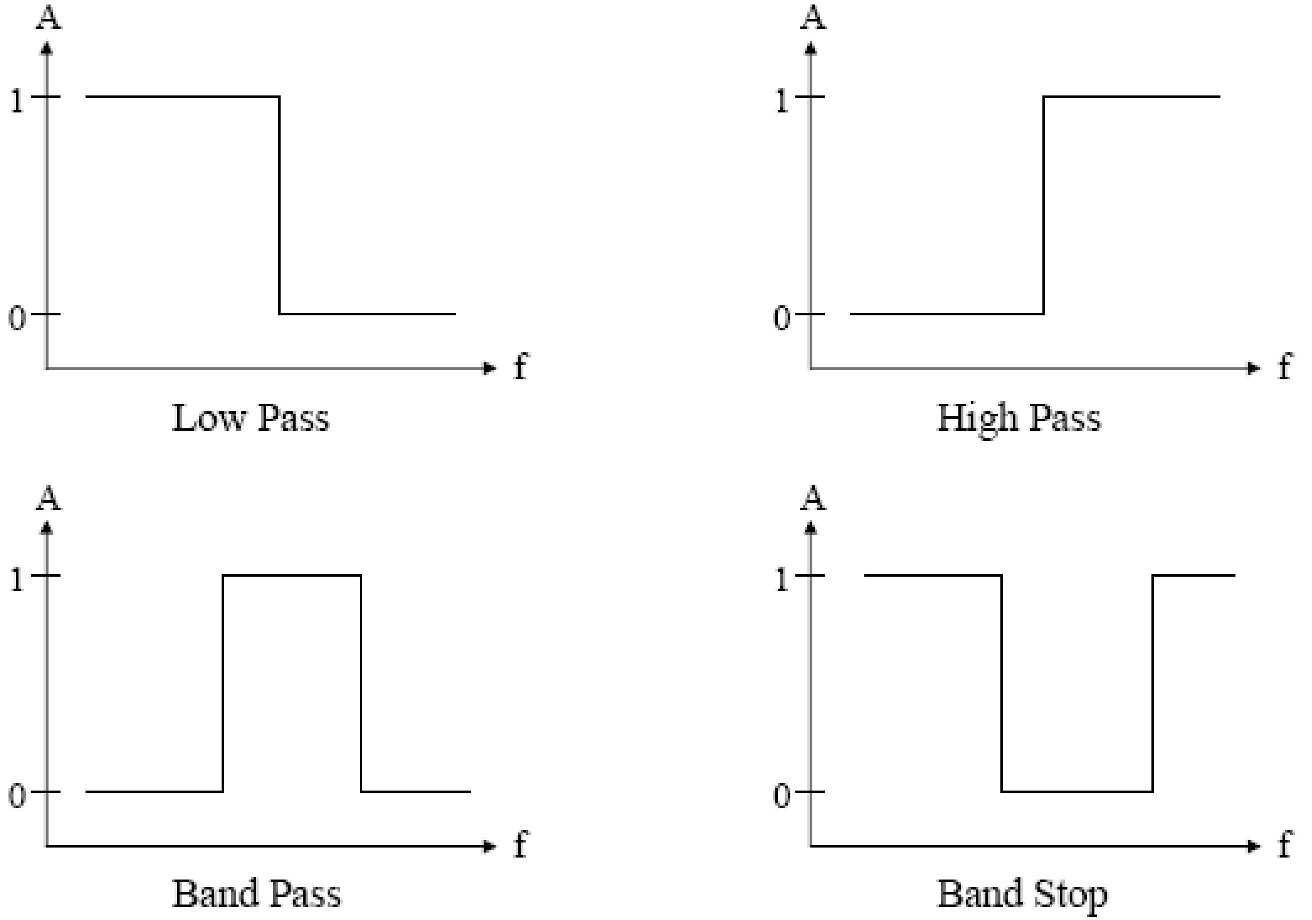




Band Pass

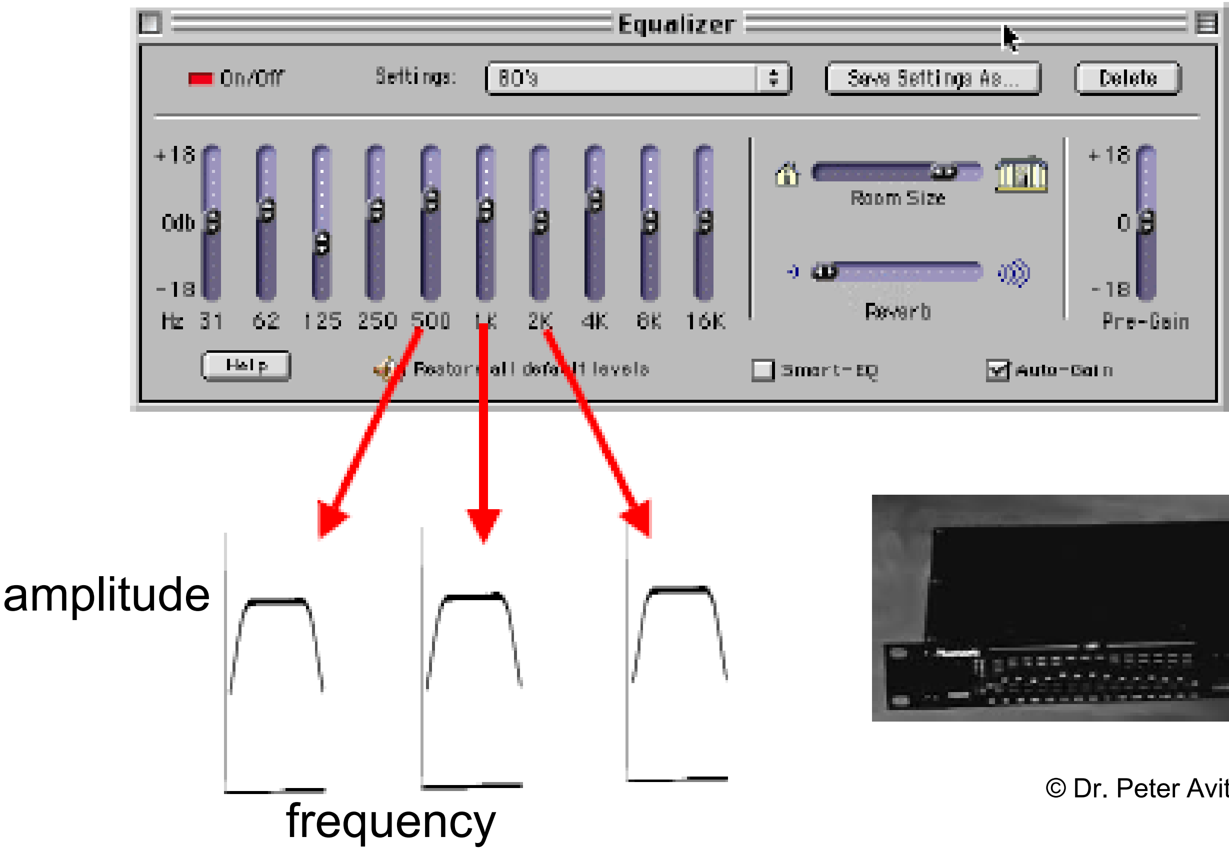
Band Stop

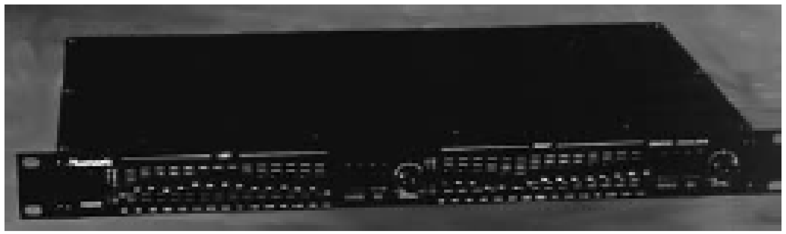
Ideal Filters



Example: MUSIC

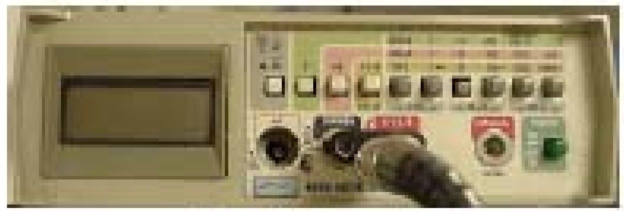
Basically, the equalizer in your stereo is nothing more than a set of band pass filters in parallel. Each filter has a different frequency band that it controls. The equalizer is used to balance the signal over different frequencies to “shape” the noise (music)



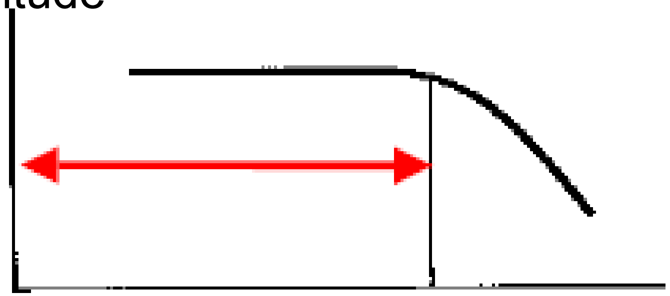


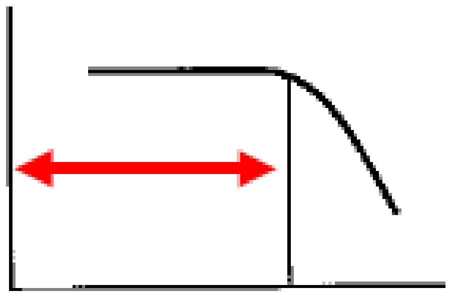
The instrument that is used to make measurements will have some very definite frequency characteristics. This defines the "usable" frequency range of the instrument. As part of the lab and measurements taken, there was a different usable frequency range for the oscilloscope and the digital multimeter

Oscilloscope

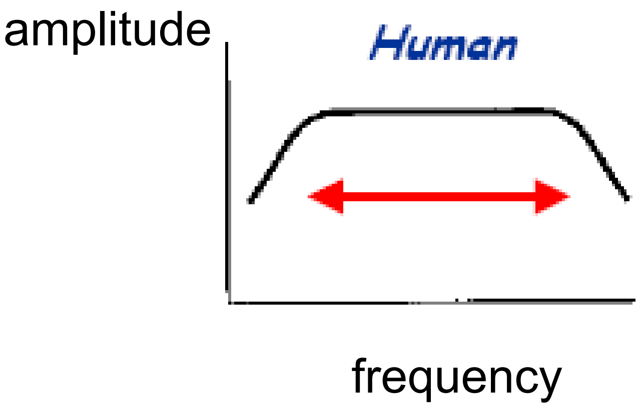


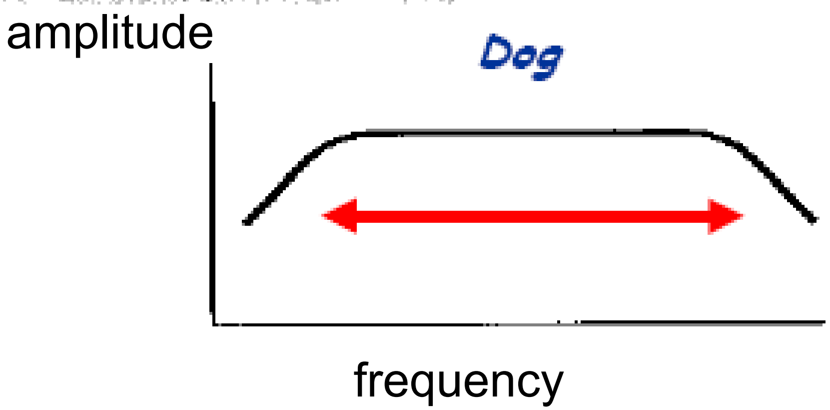
Multimeter



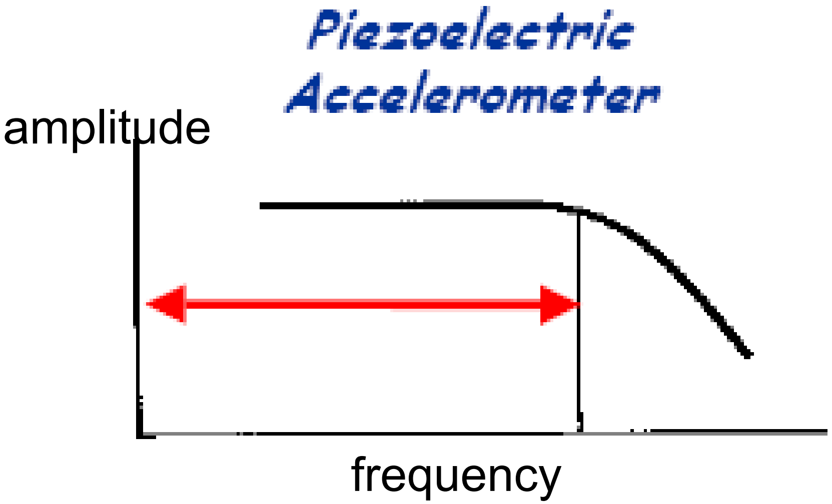


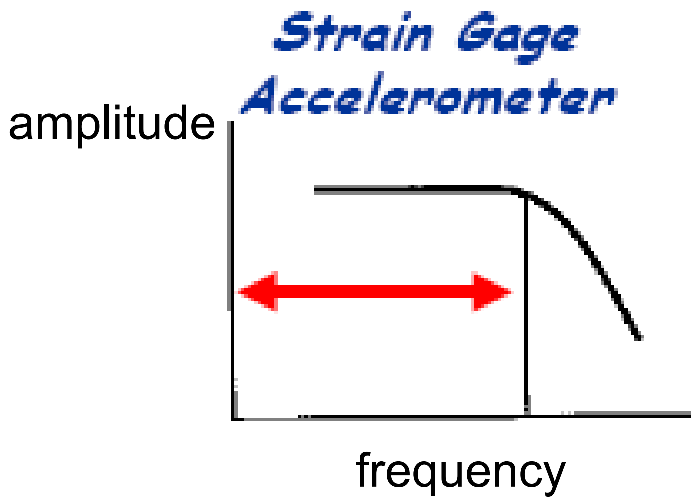
If we consider the hearing ability of a human and a dog, then we also see that there is some usable (or hearable) frequency range. Basically, a dog can hear much higher frequencies than a human.



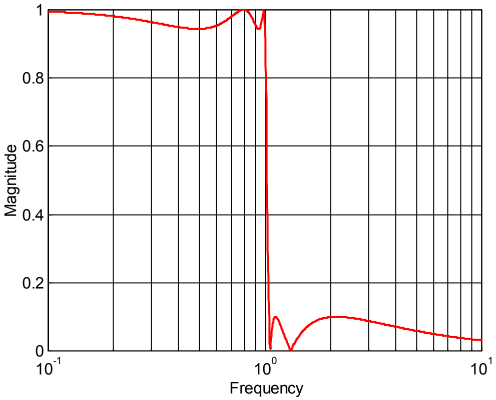


In addition to instruments, the actual transducers used to make measurements also have useful frequency ranges. For instance, a strain gage accelerometer and a peizoelectric accelerometer have different useful frequency ranges

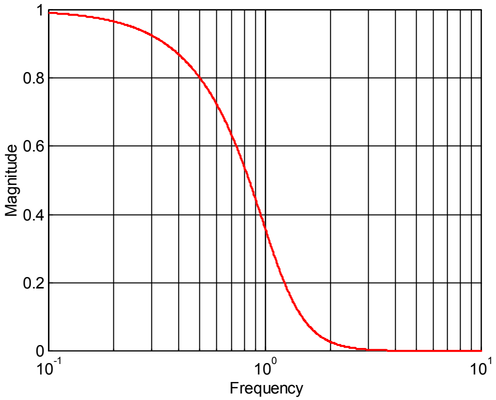




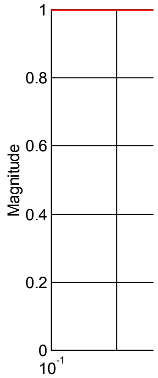
Low Pass Filter Examples



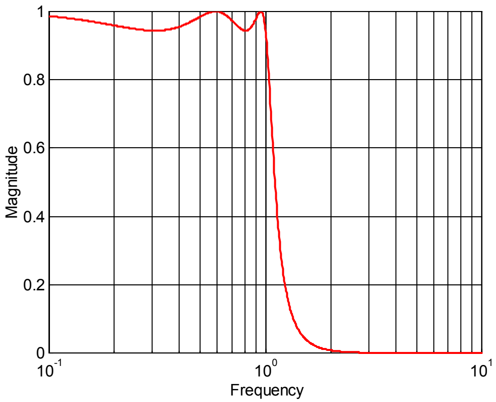
Elliptic Filter



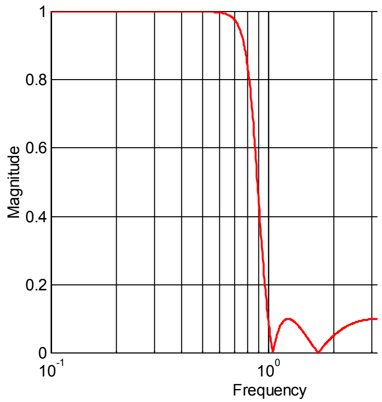
Bessel Filter



Butterworth



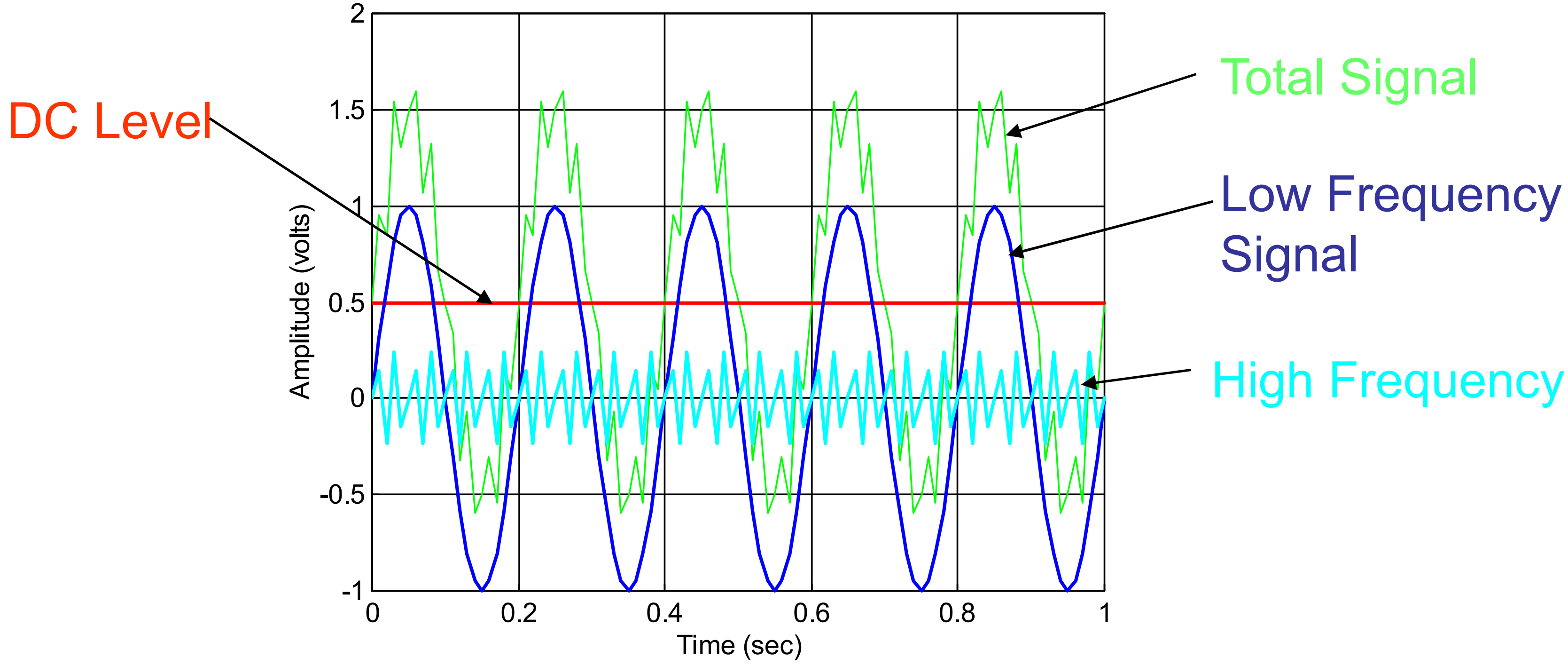
Chebyshev I Filter



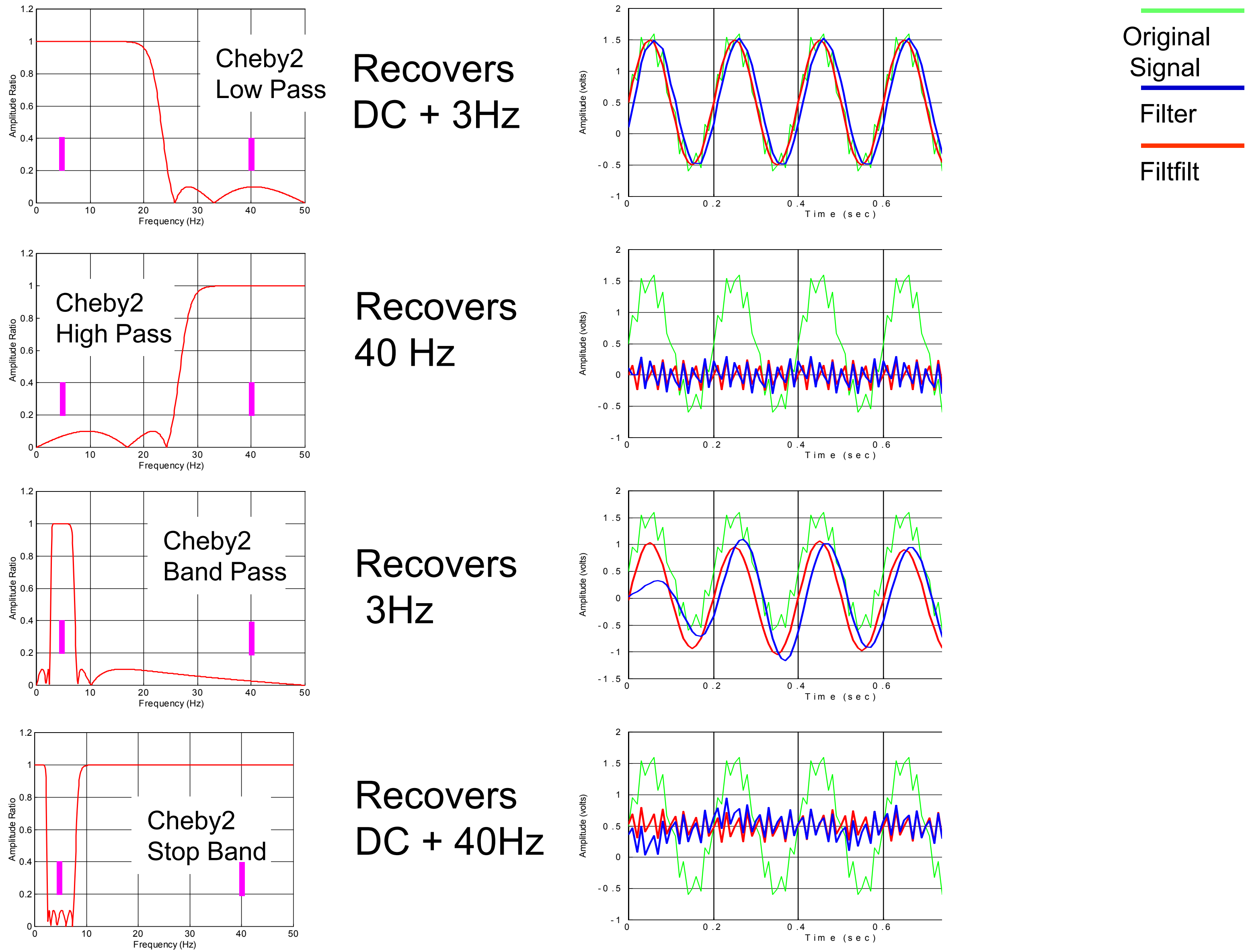
Chebyshev II

Example Signal

```
Fs = 100;
t = 0:1/Fs:1;
x =.5+ sin(2*pi*t*5)+.25*sin(2*pi*t*40);
%  DC plus 5 Hz signal and 40 Hz signal sampled at 100 Hz for 1 sec
```

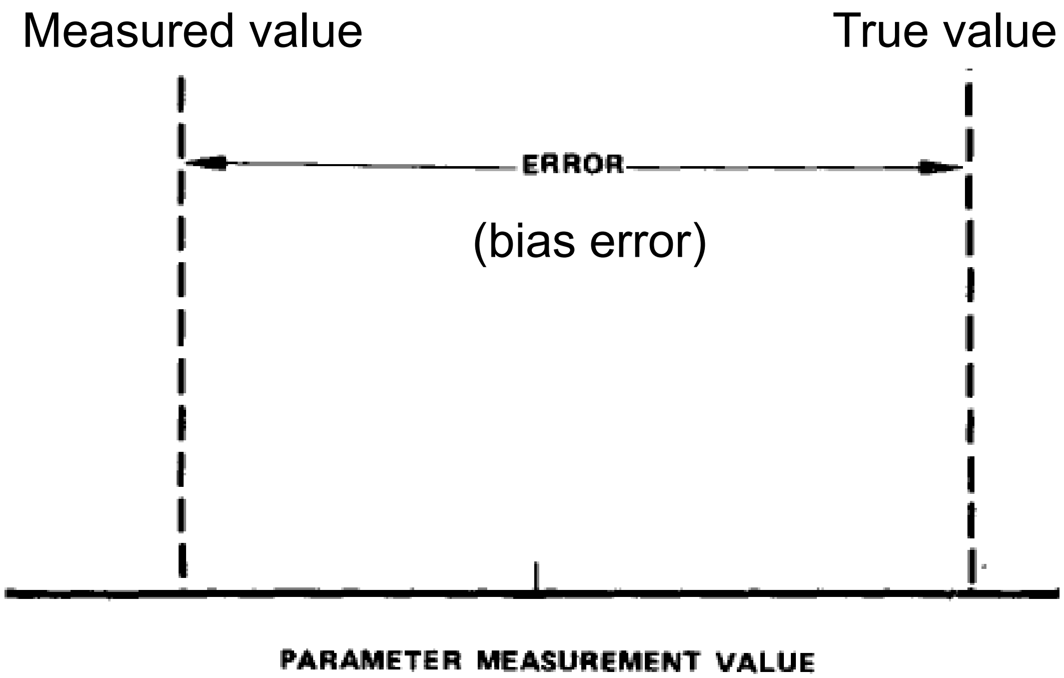


http://cobweb.ecn.purdue.edu/~aae520/


Original Signal
Filter
Filtfilt
Cheby2 Low Pass
Recovers DC + 3Hz
Cheby2 High Pass
Recovers 40 Hz
Cheby2 Band Pass
Recovers 3Hz
Cheby2 Stop Band
Recovers DC + 40Hz
Amplitude Ratio
Frequency (Hz)
Amplitude (volts)
Time (sec)

Measurement Error

The basis for the uncertainty model lies in the nature of measurement error. We view error as the difference between what we see and what is truth.



Measurement error

Measurement Error

- **Accuracy**
  - Measure of how close the result of the experiment comes to the “true” value
- **Precision**
  - Measure of how exactly the result is determined without reference to the “true” value

Measurement Error

- **Bias Error**

To determine the magnitude of bias in a given measurement situation, we must define the true value of the quantity being measured. Sometimes this error is correctable by calibration.

To determine the magnitude of bias in a given measurement situation, we must define the true value of the quantity being measured. This true value is usually unknown.

- **Random Error**

Random error is seen in repeated measurements. The measurements do not agree exactly; we do not expect them to. There are always numerous small effects which cause disagreements. This random error between repeated measurements is called precision error.
We use the standard deviation as a measure of precision error.

Measurement Error

Bias Error

Systematic Error

Remains Constant During Test

Estimated Based On Calibration

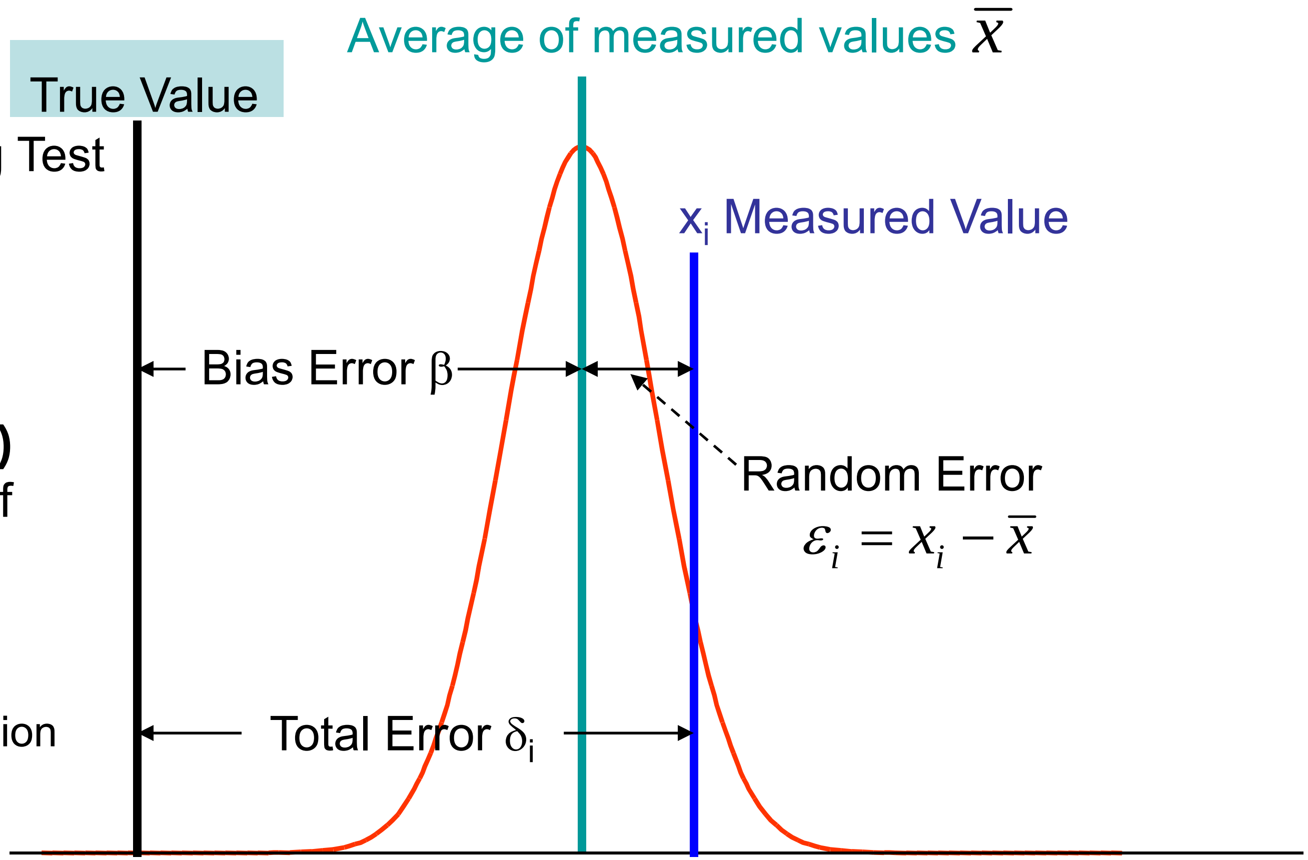
or judgement

Precision (Random Error)

Precision Index - Estimate of Standard Deviation

A statistic, s, is calculated from data to estimate the precision error and is called the precision index

$$s = \sqrt{\frac{\sum_{1}^{N} (x_i - \bar{x})^2}{N - 1}}$$



$\delta_i = \beta + \varepsilon_i$

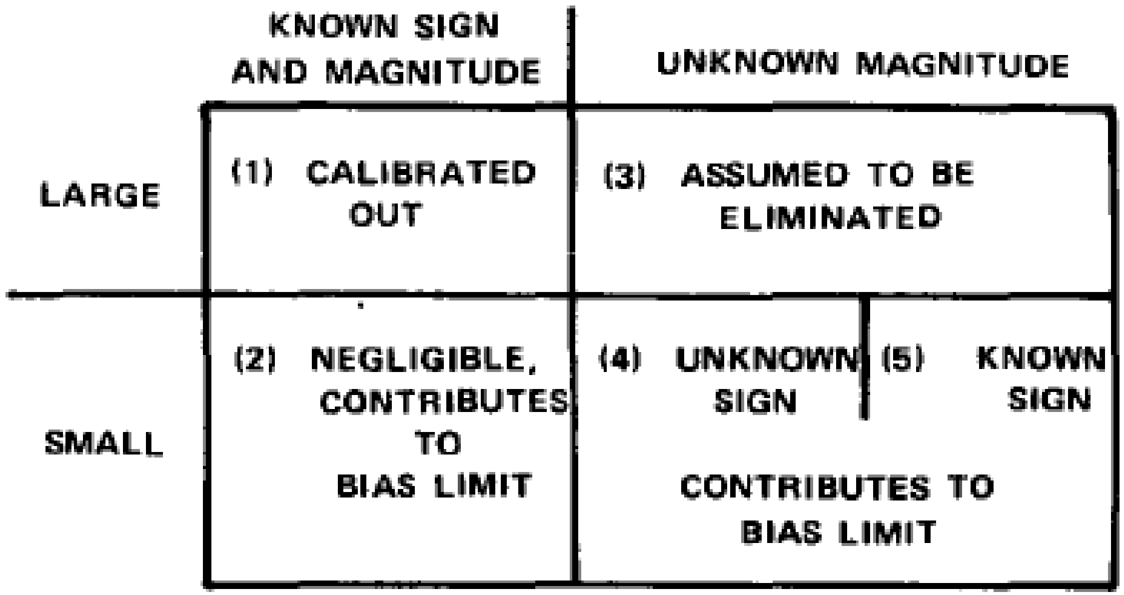
We may categorize bias into five classes :

o large known biases,
o small known biases,
o large unknown biases and
o small unknown biases that may have unknown sign (±) or known sign.

The large known biases are eliminated by comparing the instrument to a standard instrument and obtaining a correction. This process is called calibration.

Small known biases may or may not be corrected depending on the difficulty of the correction and the magnitude of the bias.

The unknown biases, are not correctable. That is, we know that they may exist but we do not know the sign or magnitude of the bias.



Five types of bias errors

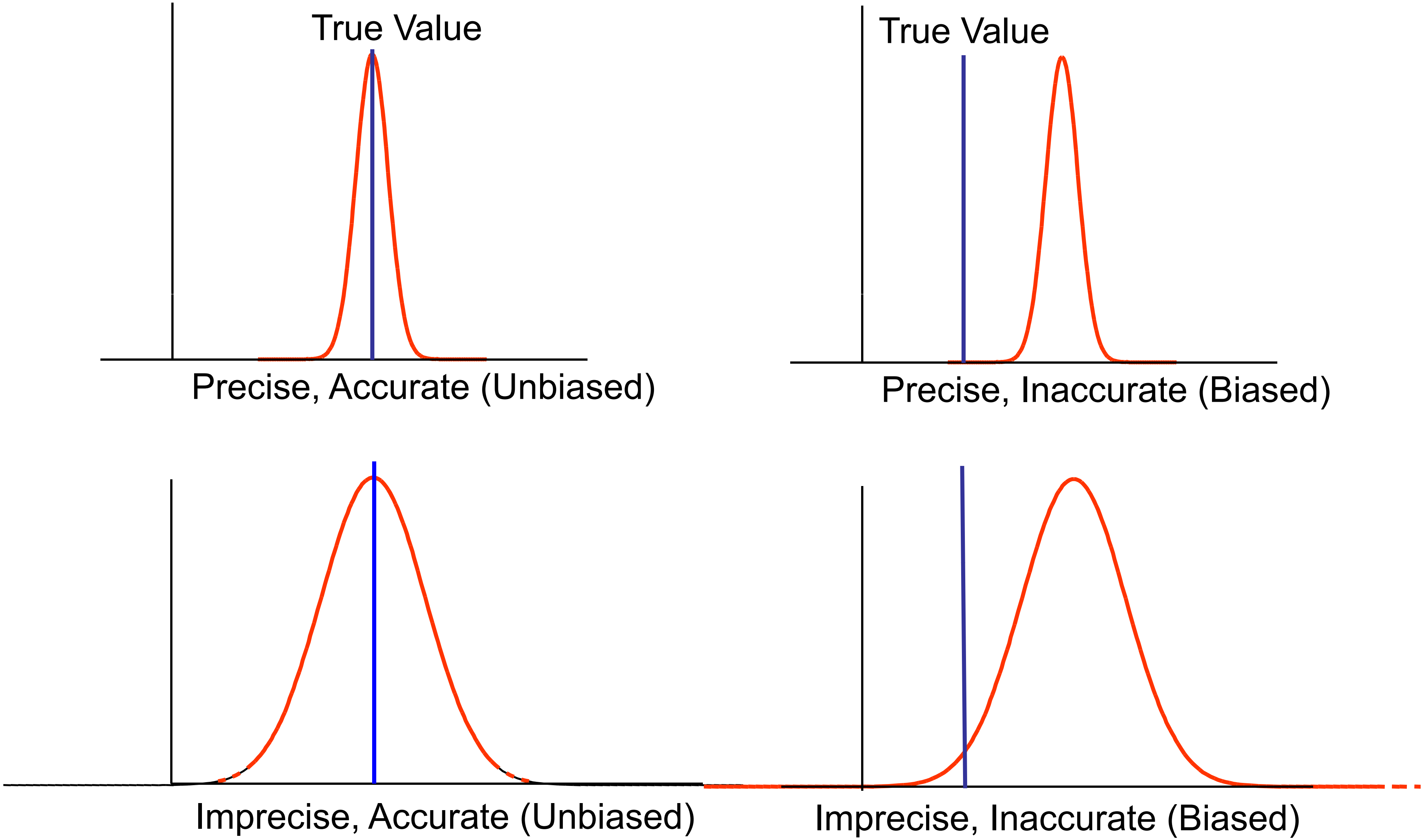
Every effort must be made to eliminate all large unknown biases.

The introduction of such errors converts the controlled measurement process into an uncontrolled worthless effort.

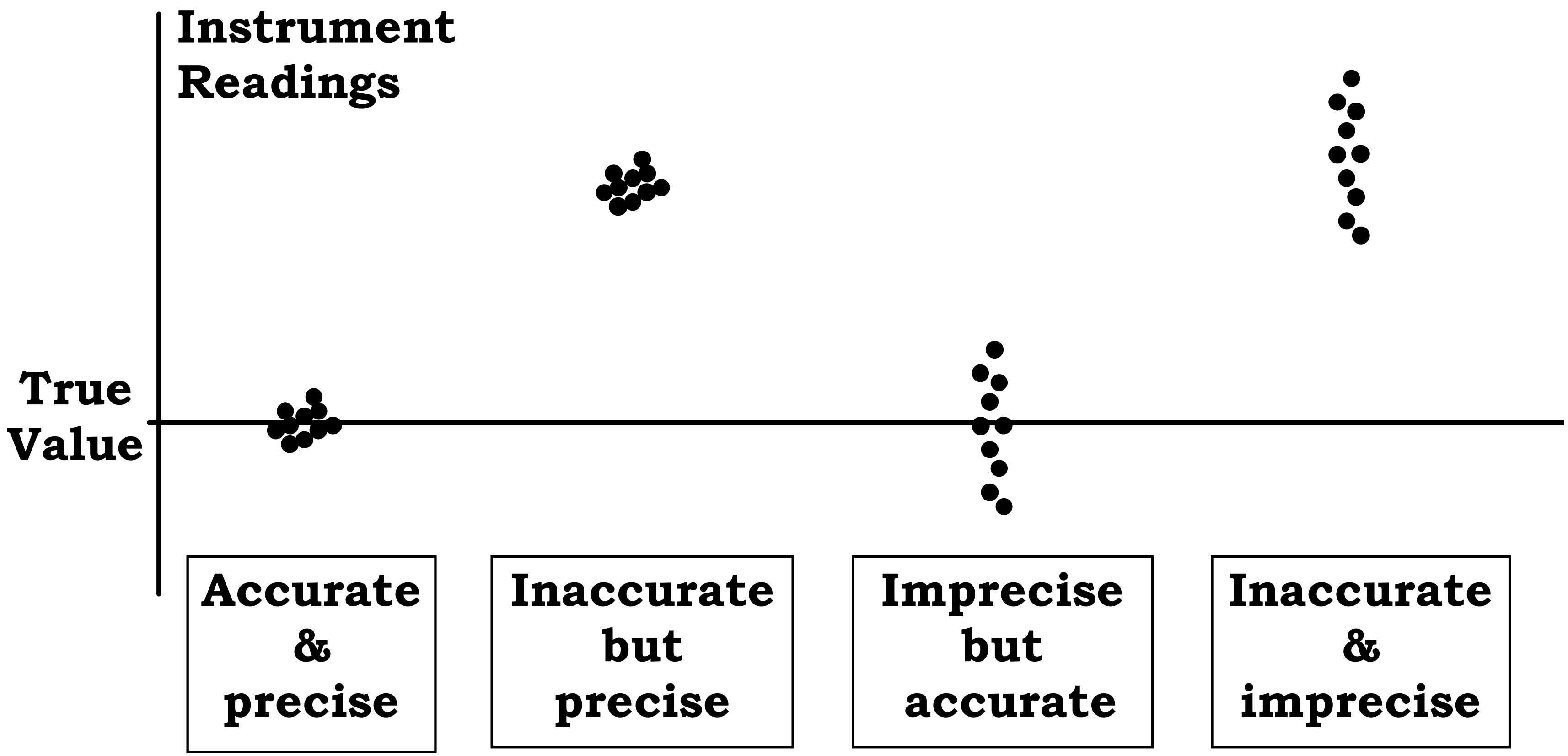
Large unknown biases usually come from **human errors in data processing, incorrect handling and installation of instrumentation, and unexpected environmental disturbances such as shock and bad flow profiles.** We must assume that in a well controlled measurement process there are no large unknown biases. To ensure that a controlled measurement process exists, all measurements should he monitored with statistical quality control charts.

	KNOWN SIGN AND MAGNITUDE	UNKNOWN MAGNITUDE
LARGE	(1) CALIBRATED OUT	(3) ASSUMED TO BE ELIMINATED
SMALL	(2) NEGLIGIBLE, CONTRIBUTES TO BIAS LIMIT	(4) UNKNOWN SIGN / (5) KNOWN SIGN CONTRIBUTES TO BIAS LIMIT

Measurement Error



ACCURACY AND PRECISION



Normal Distribution (Gaussian or Bell Curve)

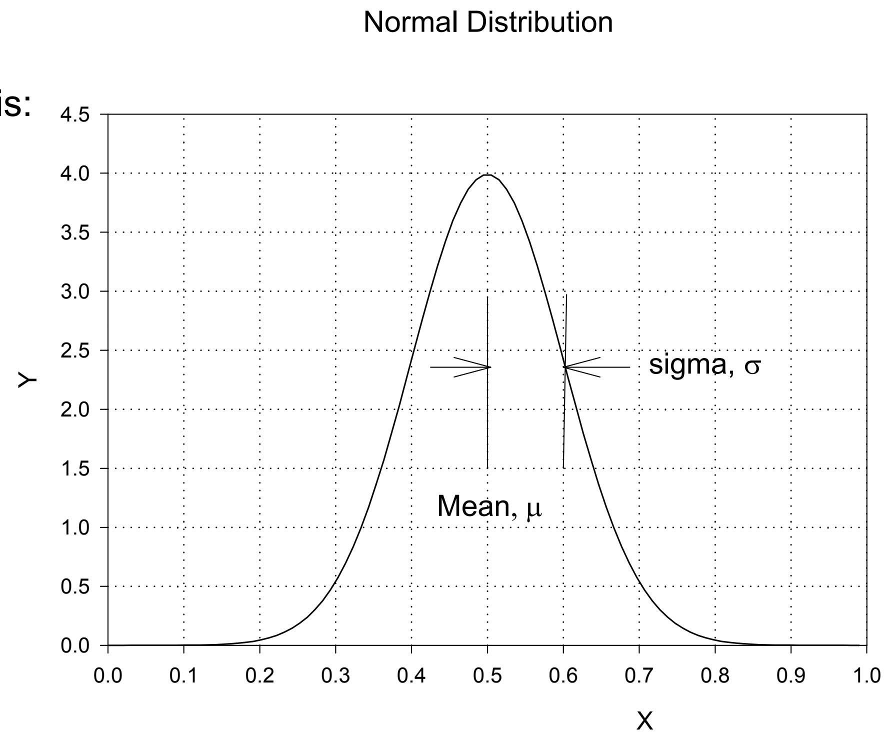
The normal distributions are a very important *class* of statistical distributions. All normal distributions are symmetric and have bell-shaped density curves with a single peak.

To speak specifically of any normal distribution, two quantities have to be specified: the mean μ, where the peak of the density occurs, and the standard deviation , σ which indicates the spread of the bell curve.

The normal pdf (probability density function) is:

$$y = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

normalized so that the area under the curve = 1.0



Parameter Estimation

A desirable criterion in a statistical estimator is unbiasedness. A statistic is unbiased if the expected value of the statistic is equal to the parameter being estimated.

Unbiased estimators of the parameters, μ, the mean, and σ, the standard deviation are:

$$\bar{x} = \frac{\sum_{1}^{N} x_i}{N}$$

Estimation of mean, μ

[**mean(data)**]

$$s = \sqrt{\frac{\sum_{1}^{N} (x_i - \bar{x})^2}{N-1}}$$

Estimation of standard deviation, σ

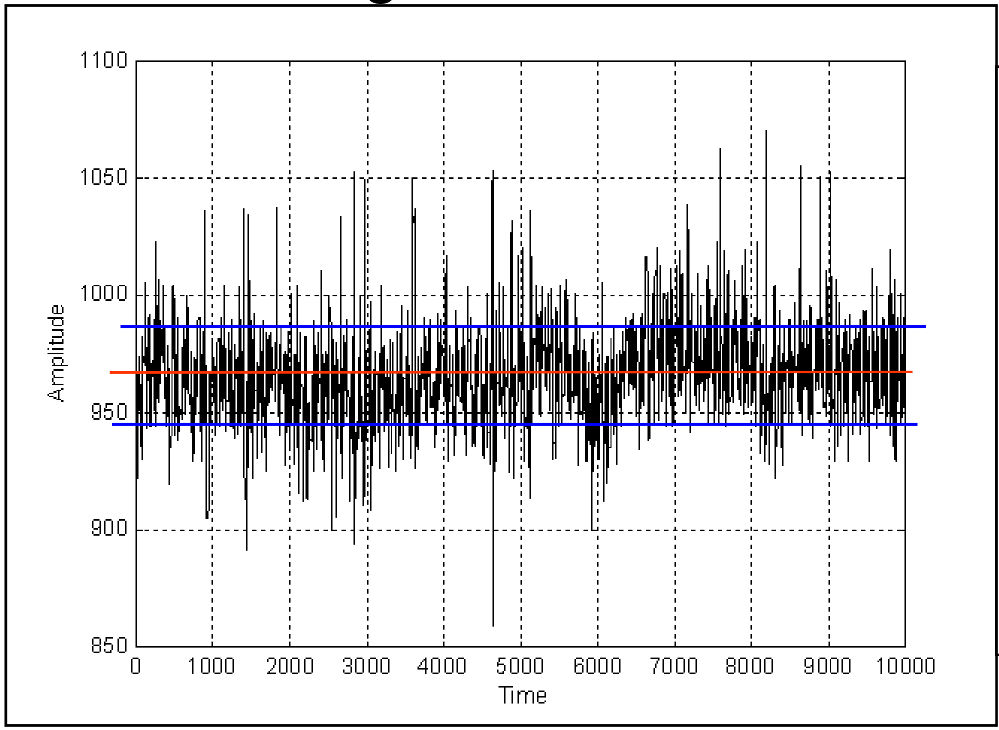
[**std(data)**]

N: number of data measured

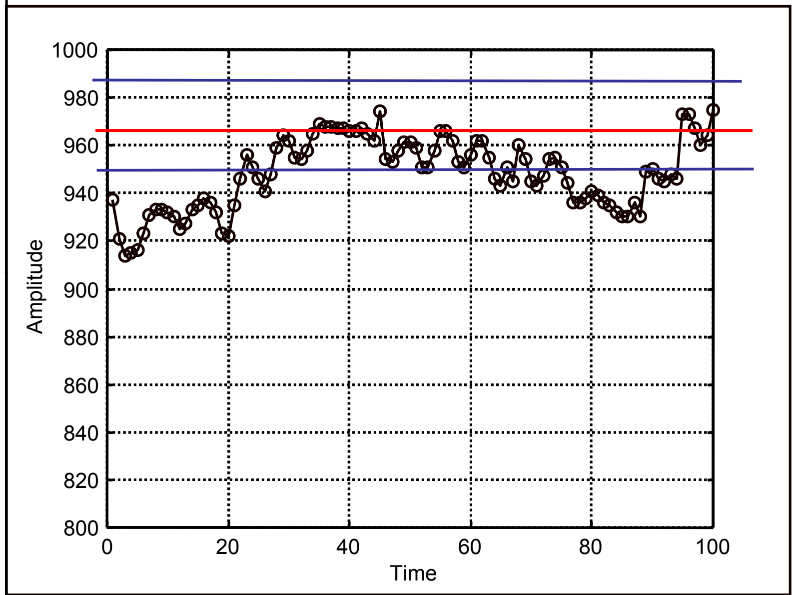
Data Sample

Signal from Hot Wire in a Turbulent Boundary Layer
Output from an A/D Converter (in counts) at Equal Time Intervals

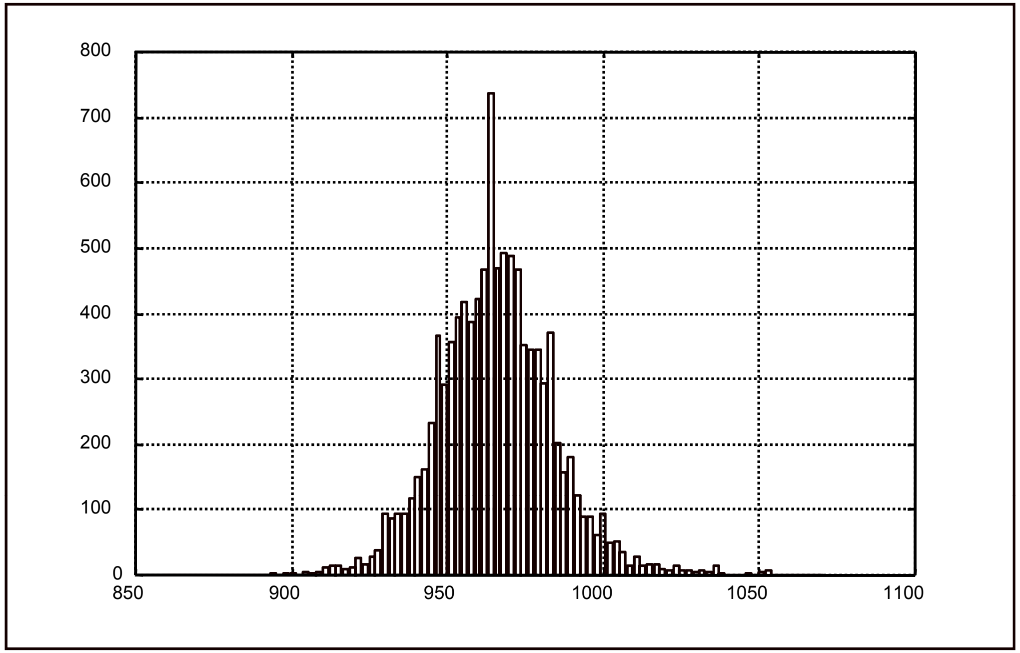
Long Time Record



Short Time Record



Estimate of the Probability Density Function
[**hist(data,# of bins)**]



Amplitude
(data measured)

Similar to a Gaussian curve

COMMON SENSE ERROR ANALYSIS

Examine the data for consistent. No matter how hard one tries, there will always be some data points that appear to be grossly in error. The data should follow common sense consistency, and points that do not appear "proper" should be eliminated. If very many data points fall in the category of "inconsistent" perhaps the entire experimental procedure should be investigated for gross mistakes or miscalculations.

Perform a statistical analysis of data where appropriate. A statistical analysis is only appropriate when measurements are repeated several times. If this is the case, make estimates of such parameters as standard deviation, etc.

Estimate the uncertainties in the results. These calculations must have been performed in advance so that the investigator will already know the influence of different variables by the time the final results are obtained.

Anticipate the results from theory. Before trying to obtain correlations of the experimental data, the investigator should carefully review the theory appropriate to the subject and try to think some information that will indicate the trends the results may take. Important dimensionless groups, pertinent functional relations, and other information may lead to a fruitful interpretation of the data.

Correlate the data. The experimental investigator should make sense of the data in terms of physical theories or on the basis of previous experimental work in the field. Certainly, the results of the experiments should be analyzed to show how they conform to or differ from previous investigations or standards that may be employed for such measurements.

(Ref. Holman, J. P., ”Experimental Methods for Engineers")