Data Acquisition System

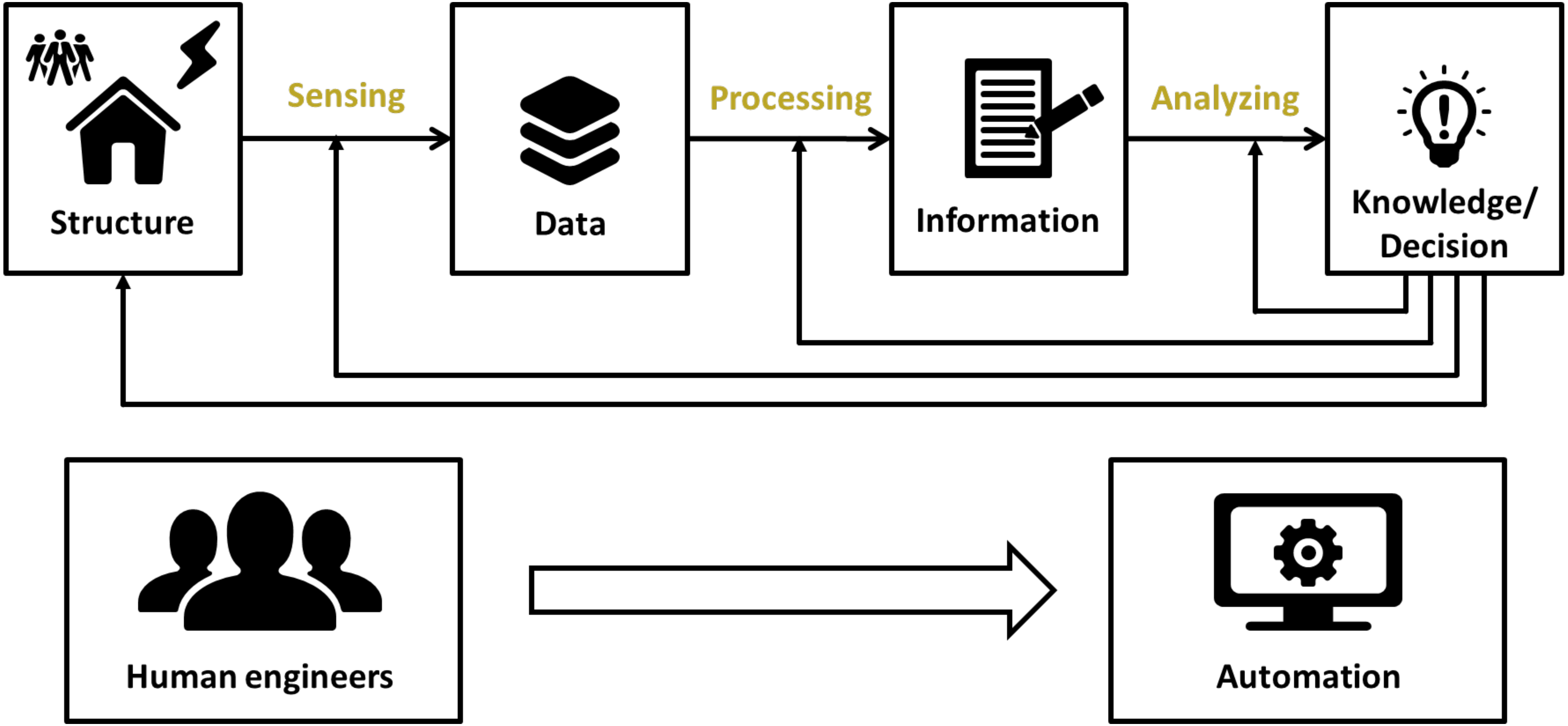
Chul Min Yeum
Assistant Professor
Civil and Environmental Engineering
University of Waterloo, Canada

CIVE 497 – CIVE 700: Smart Structure Technology

Last updated: 2024-01-01

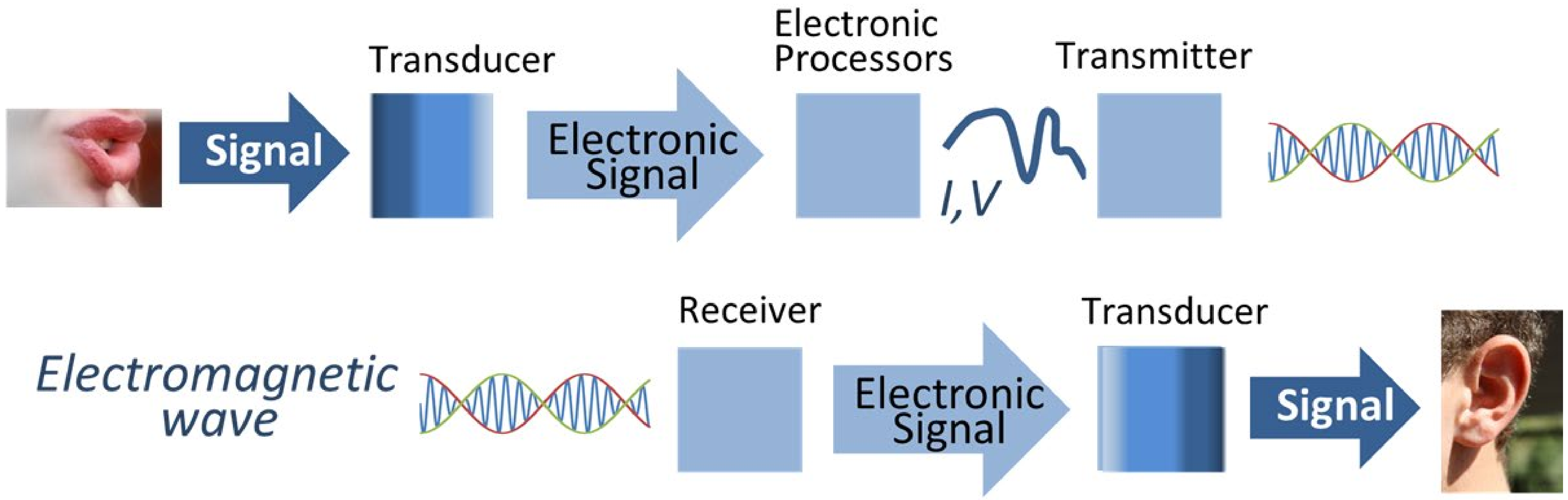
UNIVERSITY OF WATERLOO
FACULTY OF ENGINEERING

Smart Infrastructure



What is Signal Processing?

- Signal processing is procedures to reveal the information about the behavior or attributes of some phenomenon contained in the measurements, such as sound, image, or acceleration.
- These procedures rely on various transformation that are mathematically based and implemented using digital techniques.

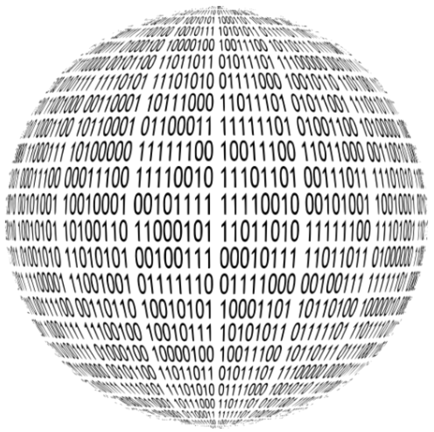


https://en.wikipedia.org/wiki/Signal_processing

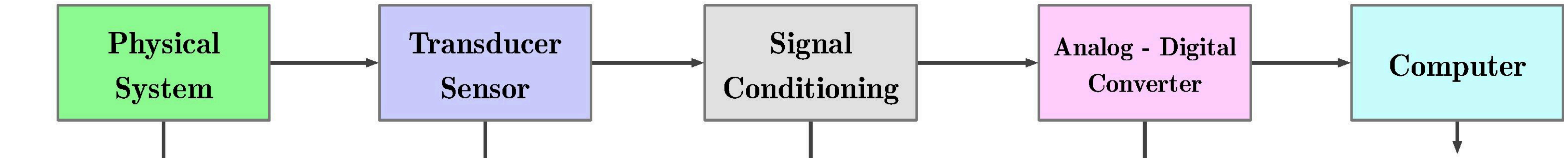
Data Acquisition

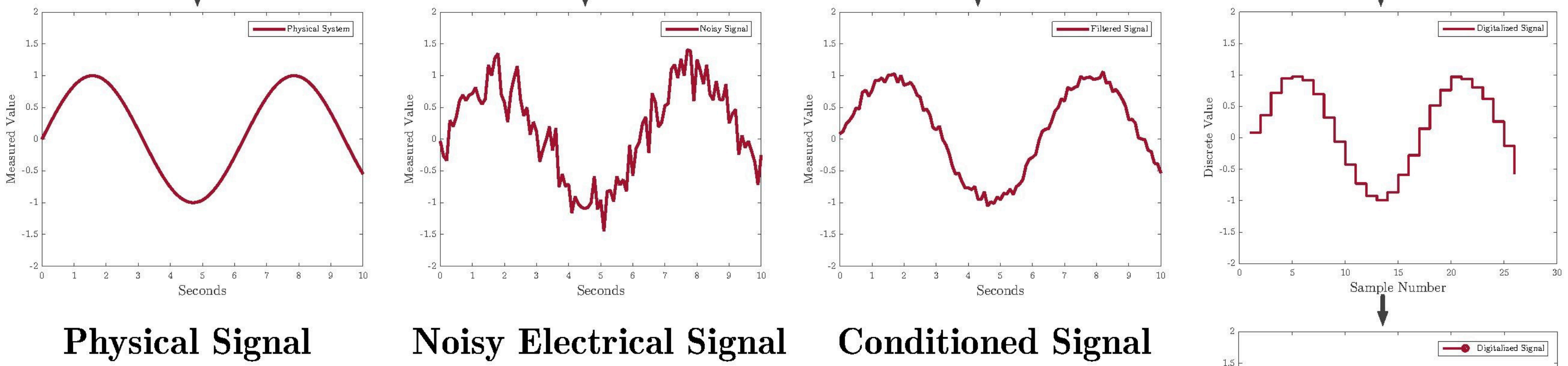
- Data acquisition is the process of sampling signals that measure real world physical conditions and converting the resulting samples into **finite digital numerical values** that can be manipulated by a computer.
- Data acquisition systems are used by most engineers and scientists for laboratory research, industrial control, test, and measurement to input and output data to and from a computer.

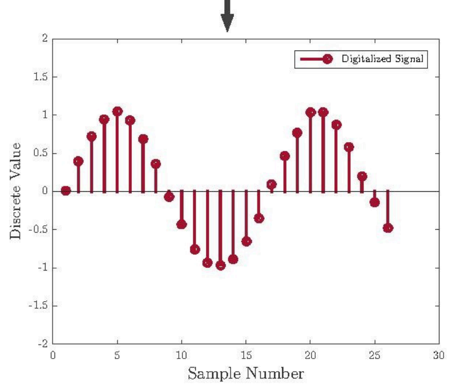
Welcome to Digital World !!!!



Data Acquisition Diagram







Digitalized Signal

8 Bit Code

0	1	1	1
0	0	0	1
0	1	1	1
1	0	1	1
1	1	0	0
1	1	1	1
0	1	1	0
1	0	1	0
1	1	1	0
1	1	1	1
0	1	1	1
1	1	1	0
1	1	1	1
0	0	1	1
1	1	0	0
0	1	1	1
0	1	1	1
0	1	1	0
0	1	1	0
1	0	1	1
1	1	1	0
0	0	0	1
1	1	1	1
1	0	1	1
0	0	1	0
0	0	1	1
1	1	1	1
1	0	0	1
1	1	0	1
1	1	1	0

- Sensors, to convert physical parameters to **electrical signals**.
- Signal conditioning circuitry, to convert sensor signals into a form that can be converted to digital values.
- Analog-to-digital converters, to convert conditioned sensor **signals to digital values.**

https://en.wikipedia.org/wiki/Data_acquisition

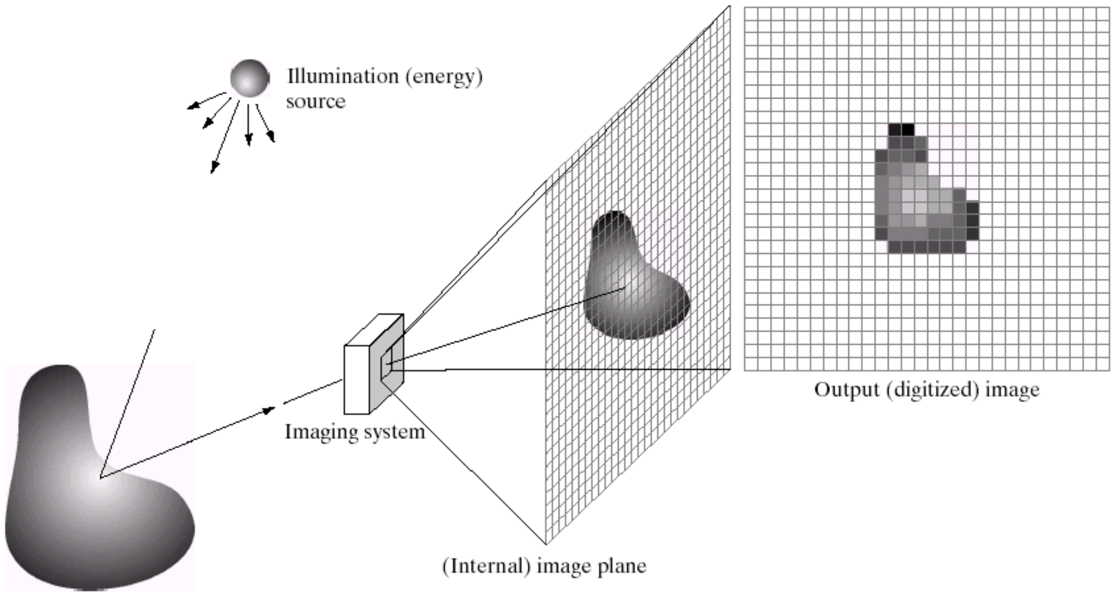
Analog vs Digital Signal

A digital signal refers to an electrical signal that is converted into a pattern of bits. Unlike an analog signal, which is a continuous signal that contains time-varying quantities, a digital signal has a discrete value at each sampling point. Several issues need to be solved to minimize distortion of the original signal (sampling, quantization, aliasing, and leakage).

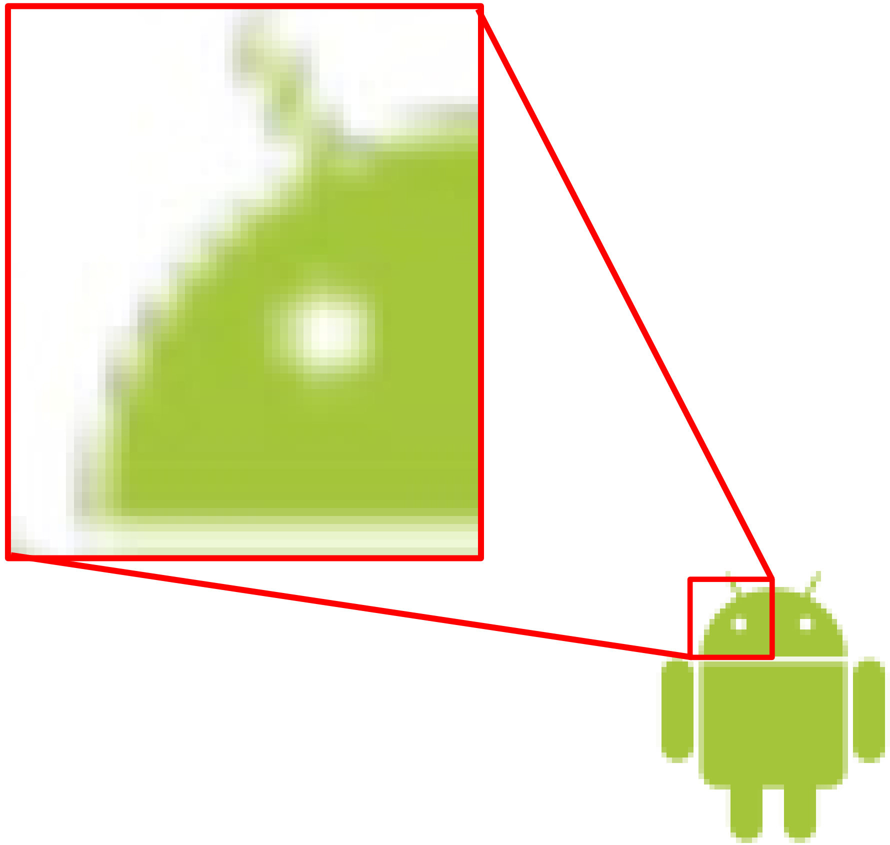
- Continuous-time vs Discrete-time signal
- Continuous-valued vs Discrete-valued signal
- Output range

Note that in certain physical situations, 'time' may not be a sole variable, for example, a plot of road roughness as a function of spatial position. Similarly, the images are considered as signals (functions) with respect to x and y pixels values.

Example: Imaging System



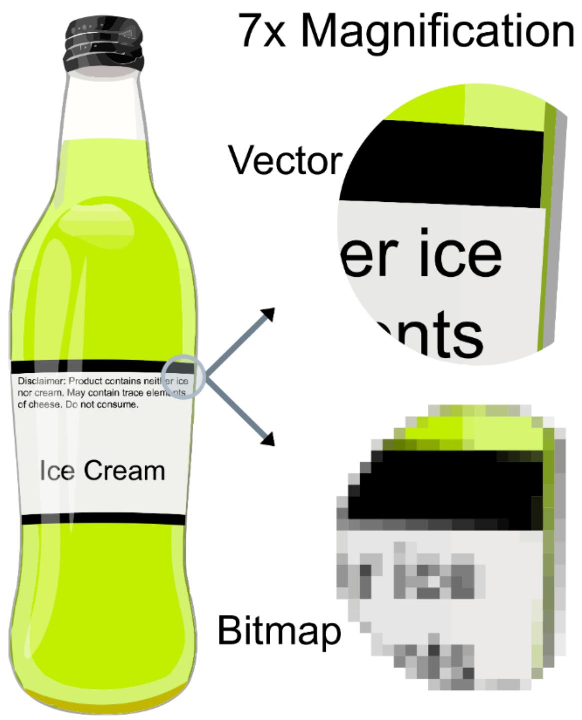
Digital Image Acquisition

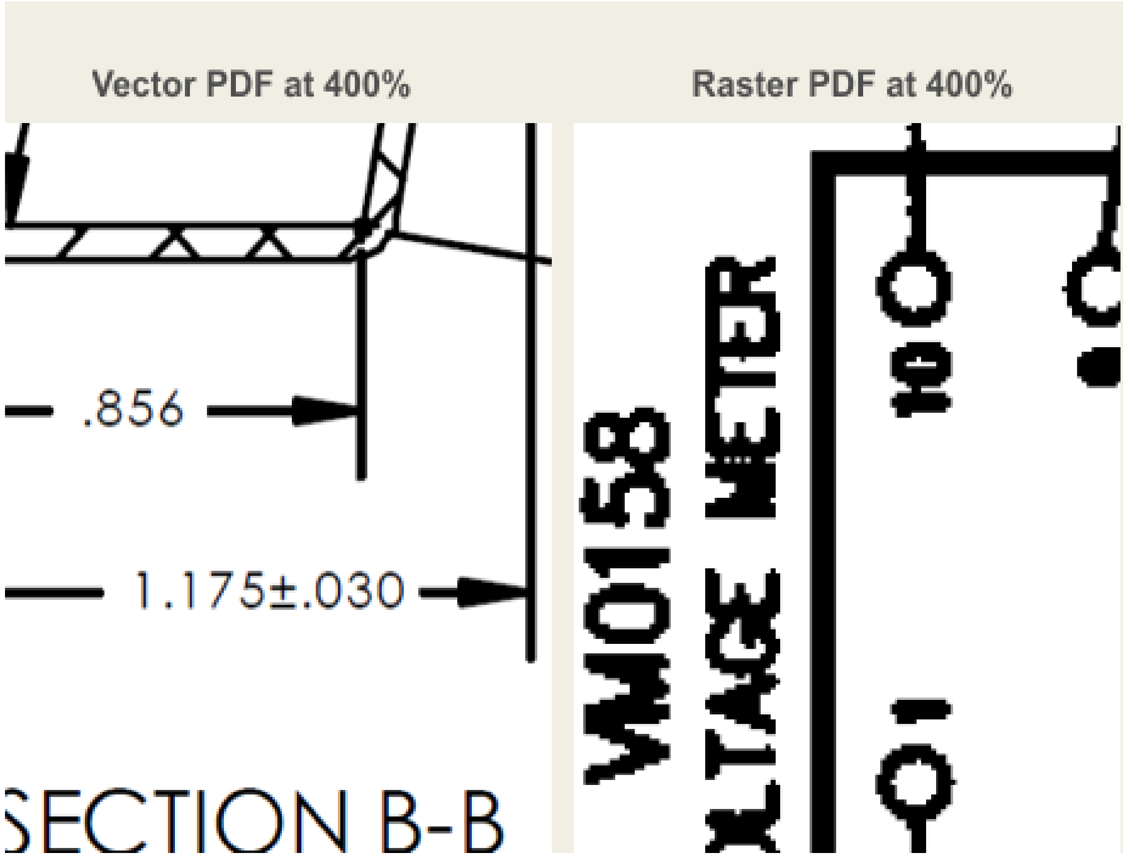


Pixel

Example: Vector Graphics

Supplement





Vector graphics is the creation of digital images through <u>a sequence of commands or mathematical statements that place lines and shapes</u> in a given two-dimensional or three-dimensional space. In physics, a vector is a representation of both a quantity and a direction at the same time.

Digitization of Analog Signals

Sampling: How often the data is sampled in the time axis.

$$y = \sin(2\pi f t)$$

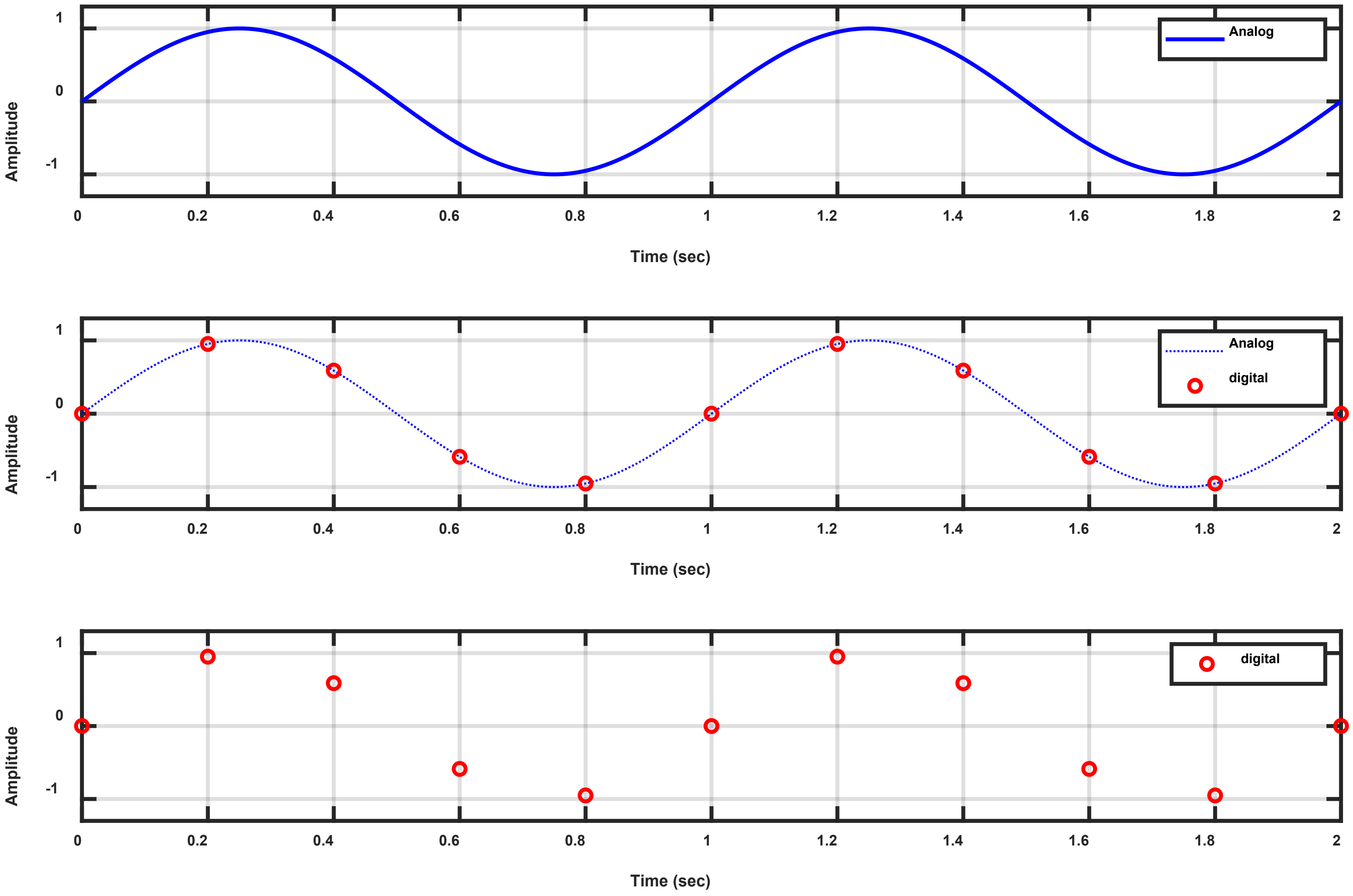
Frequency (f): 1Hz

Sampling frequency

$$f_s = 5 \text{ Hz}$$

Sampling interval

$$\Delta t = 0.2 \text{ sec}$$



Tutorial

Determination of a Sampling Frequency (Rate)

- Sampling frequency (Hz) is the inverse of the sampling interval

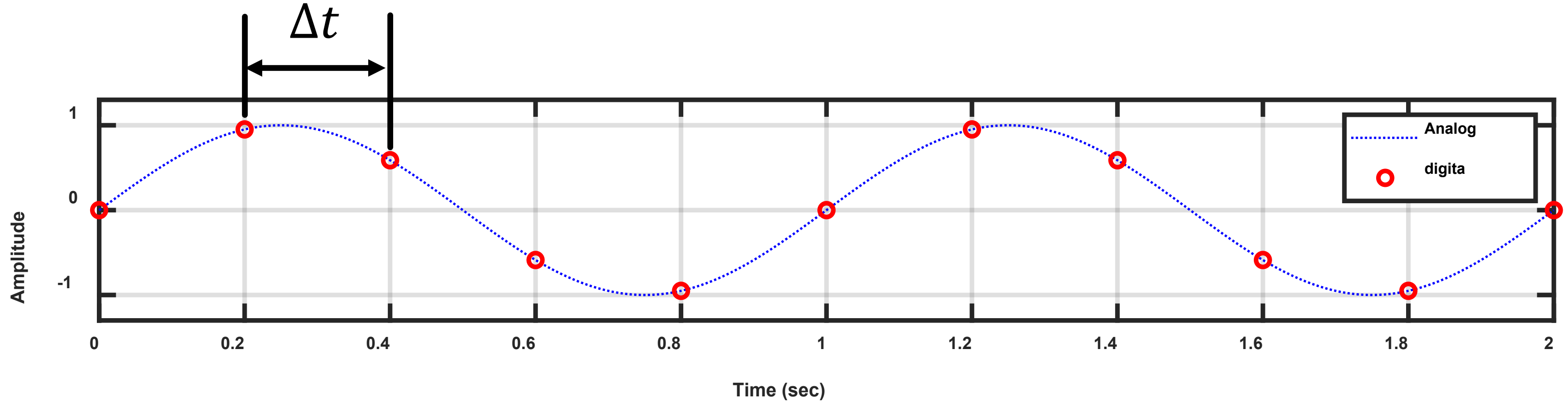
$$f_s = 1/\Delta t \text{ (Hz)}$$

- **<u>Make sure the sampling frequency is at least twice the desired frequency to be measured.</u>** (When the signal is analyzed in the frequency domain)

$$f_h < \frac{f_s}{2} = 1/(2\Delta t)$$

$$\boxed{f_N = \frac{f_s}{2}\text{: Nyquist frequency}}$$

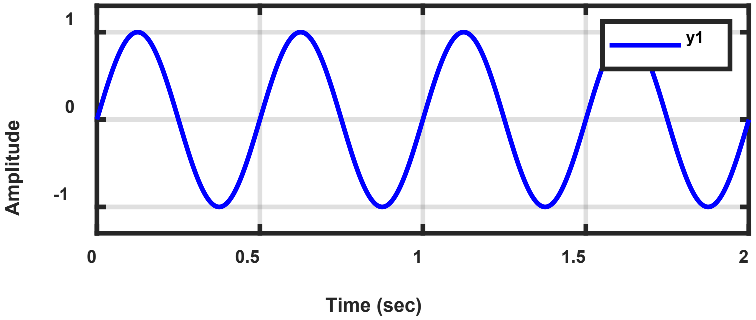
- As a rule of thumb, 10 samples or more digital points during the signal period of interest (when the signal is analyzed in the time domain.

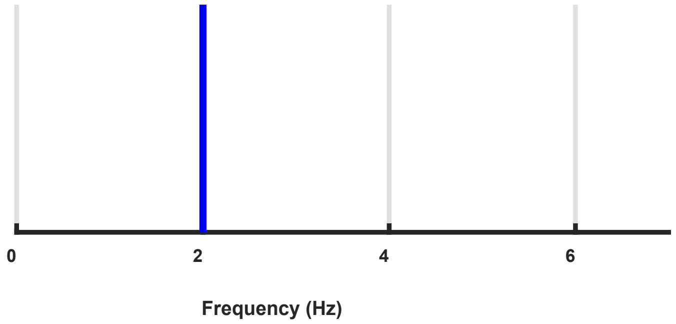


Continuous Time Signals in a Frequency Domain

$$y_1 = \sin(2\pi f_1 t)$$

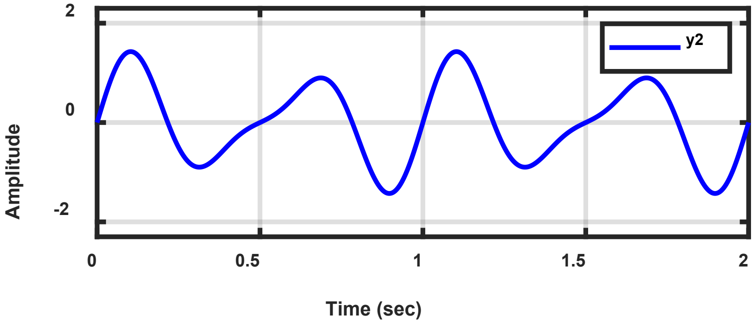
f_1: 2Hz

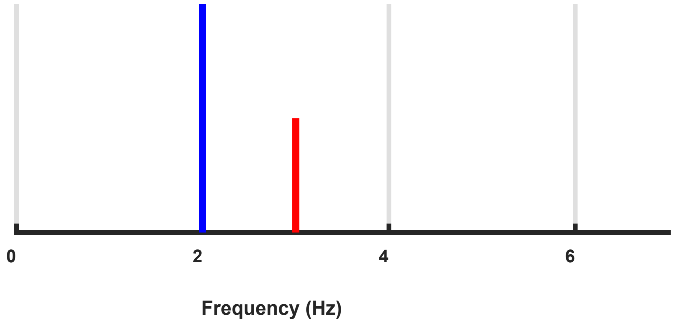




$$y_2 = \sin(2\pi f_1 t) + 0.5\sin(2\pi f_2 t)$$

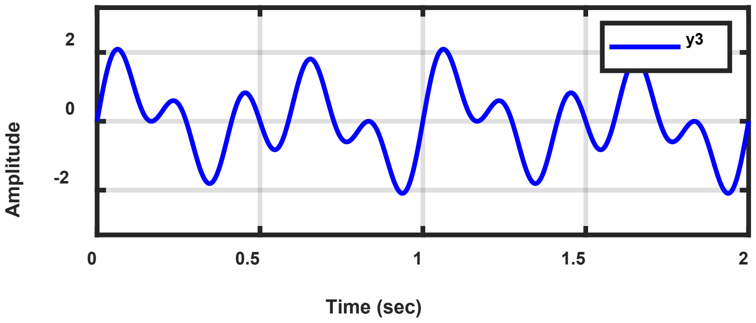
f_1: 2Hz, f_2: 3Hz

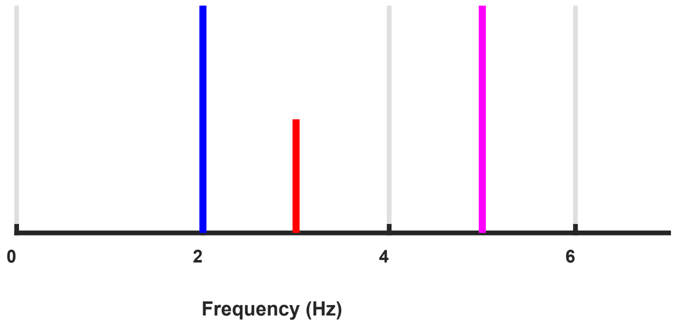




$$y_3 = \sin(2\pi f_1 t) + 0.5\sin(2\pi f_2 t)$$
$$+\sin(2\pi f_3 t)$$

f_1: 2Hz, f_2: 3Hz , f_3: 5Hz

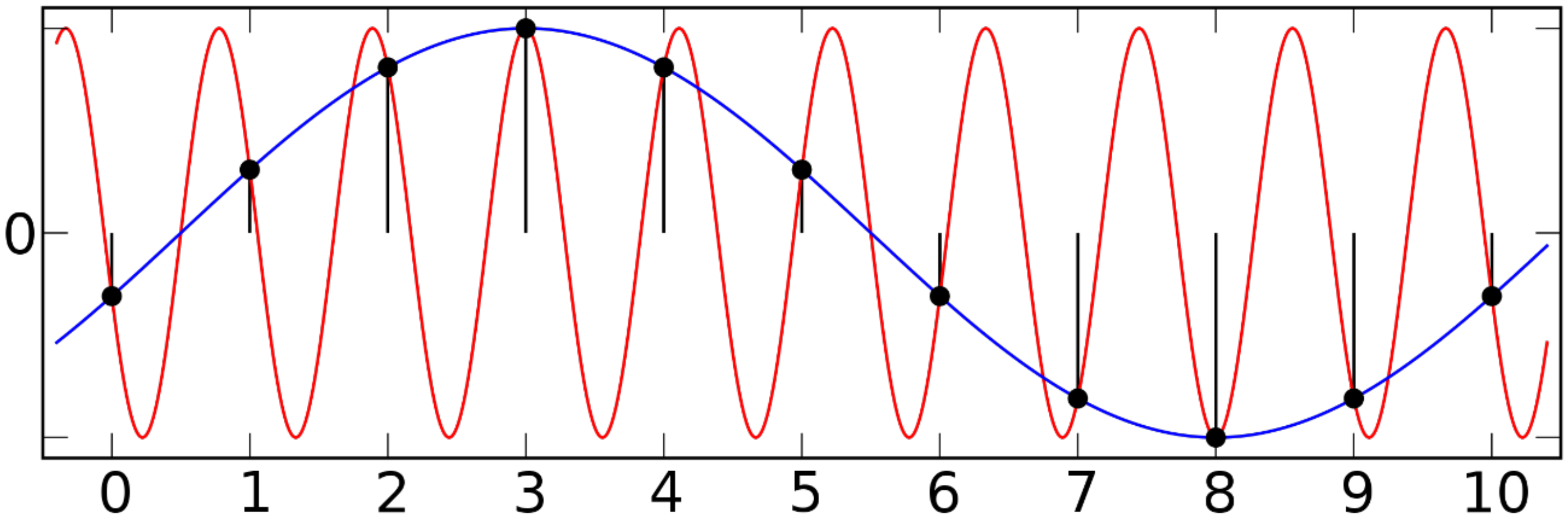




Tutorial

Aliasing

- Aliasing refers to <u>the distortion or **artifact**</u> that results when the signal reconstructed from samples is **<u>different</u>** from the original continuous signal.
- A higher frequency component is disguised as a lower frequency component because of inadequate sampling.



Sample from a sine wave

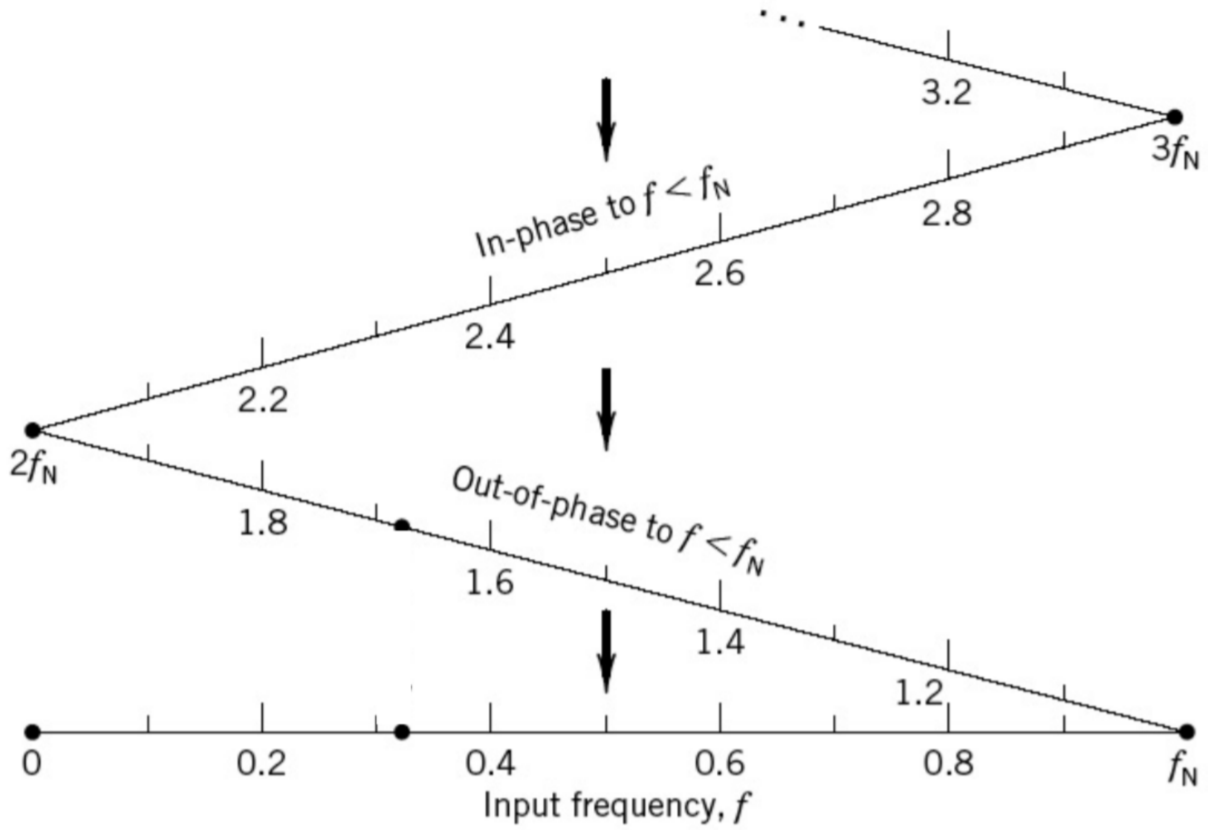
Original signal

Sampled points

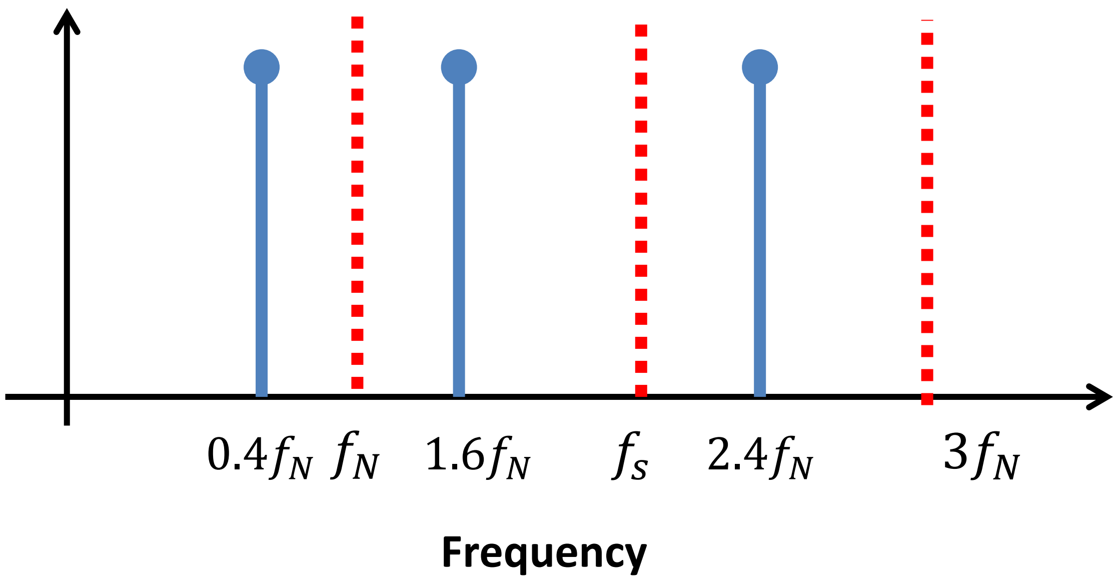
Q: What do you learn from this graph?

Aliasing (Continue)

Folding Diagram

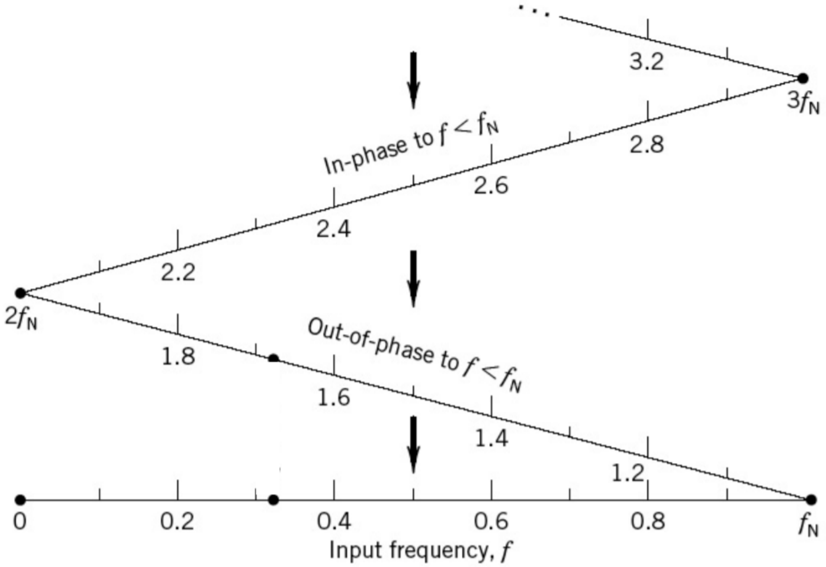


f_N: Nyquist frequency



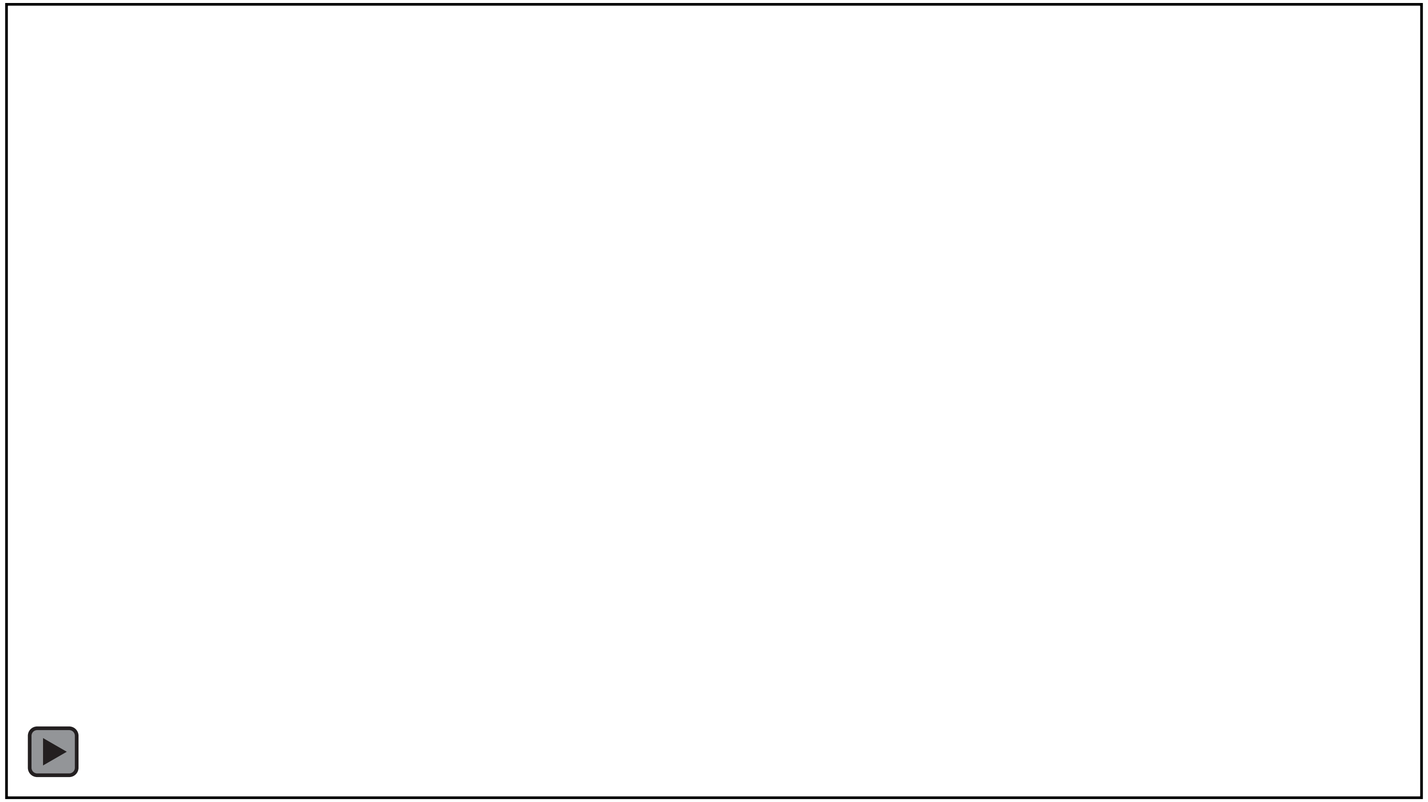
- Signal frequency: 160 Hz (or 240 Hz)
- Sample rate: 200 Hz
- Nyquist frequency: 100 Hz
- Alias frequency: 40 Hz

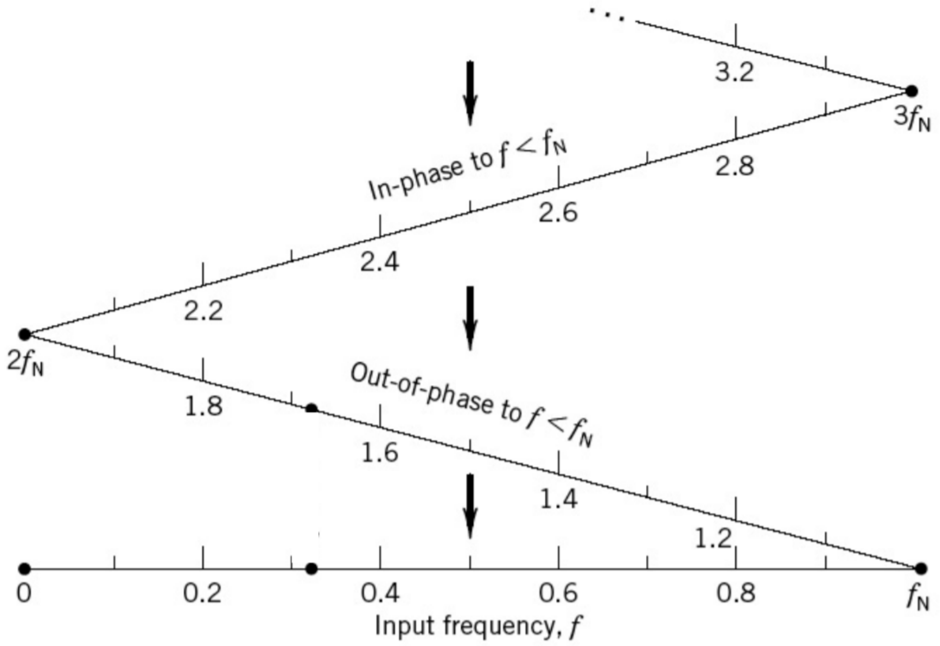
Example: Spinner



https://www.youtube.com/watch?v=cMZJZGtWFCA

Example: Helicopter Like Spaceship 1



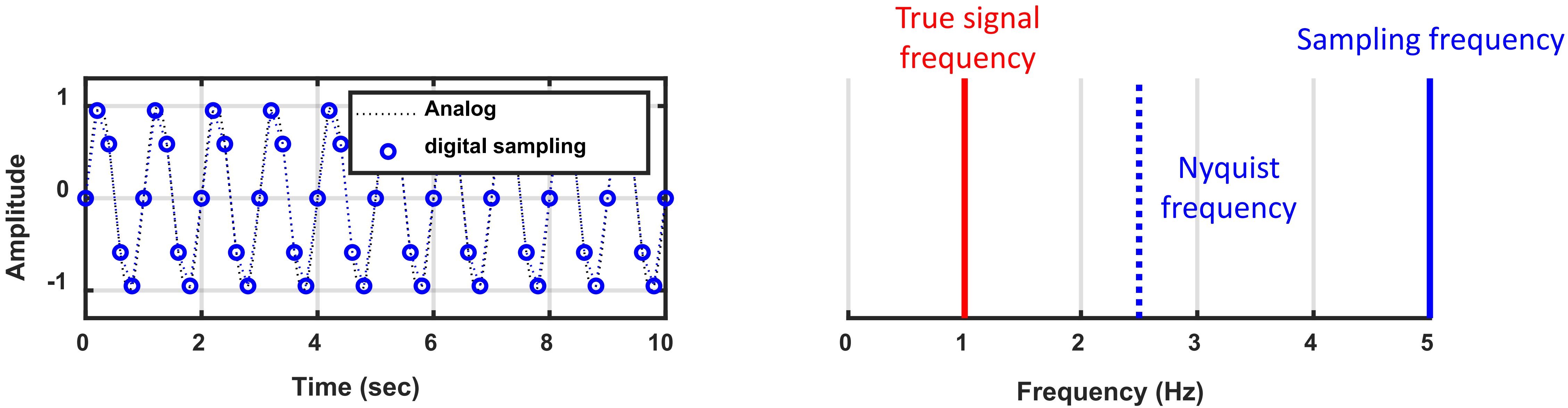


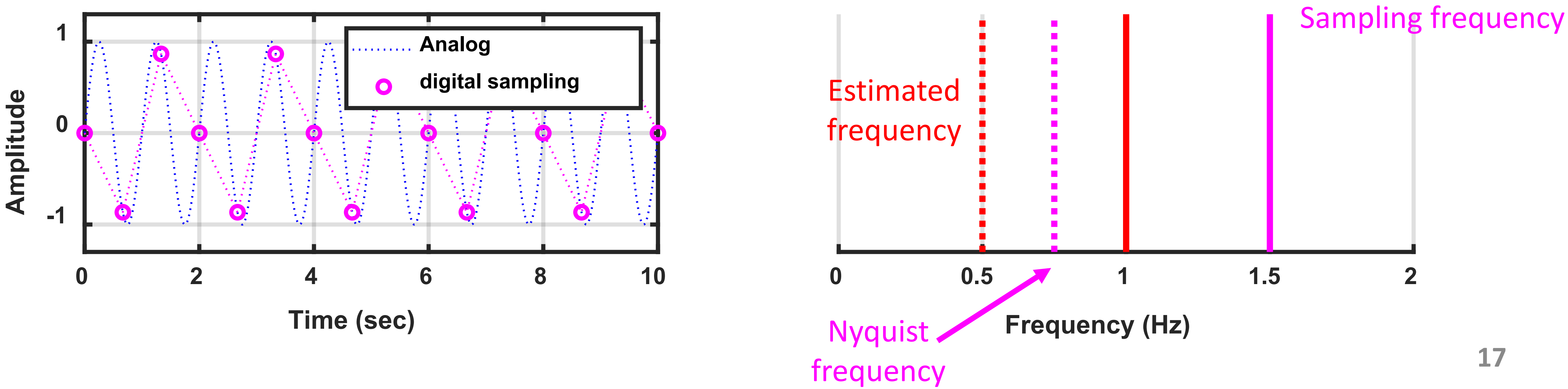
https://www.youtube.com/watch?v=yr3ngmRuGUc

Example: Helicopter Like Spaceship 2

https://www.youtube.com/watch?v=_xTjyV8F6XU&ab_channel=Tomatsoldat

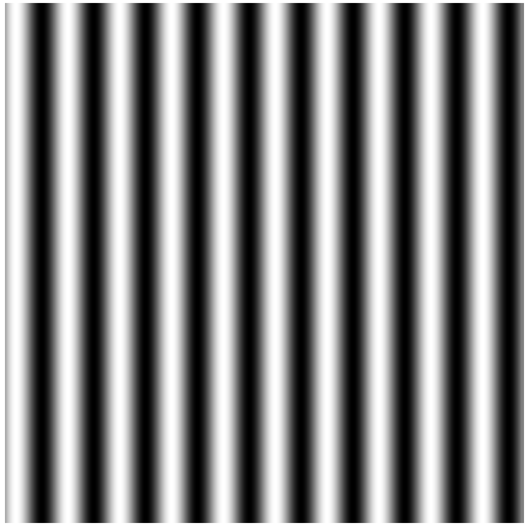
Example: Effect of Aliasing



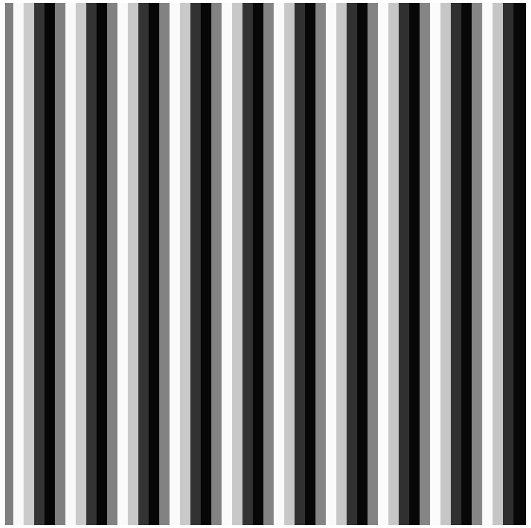


Tutorial

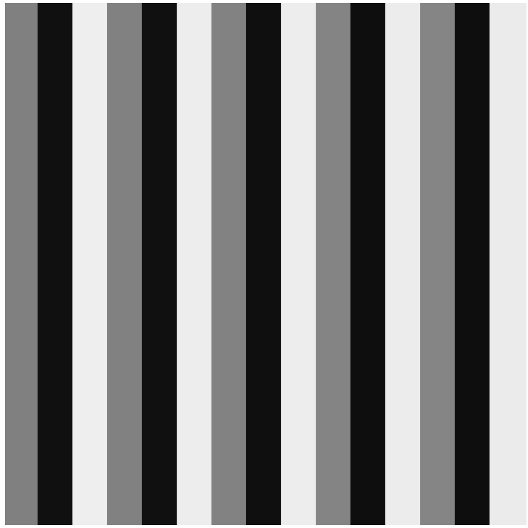
Example: Spatial Aliasing



Original image (1200 x 1200)

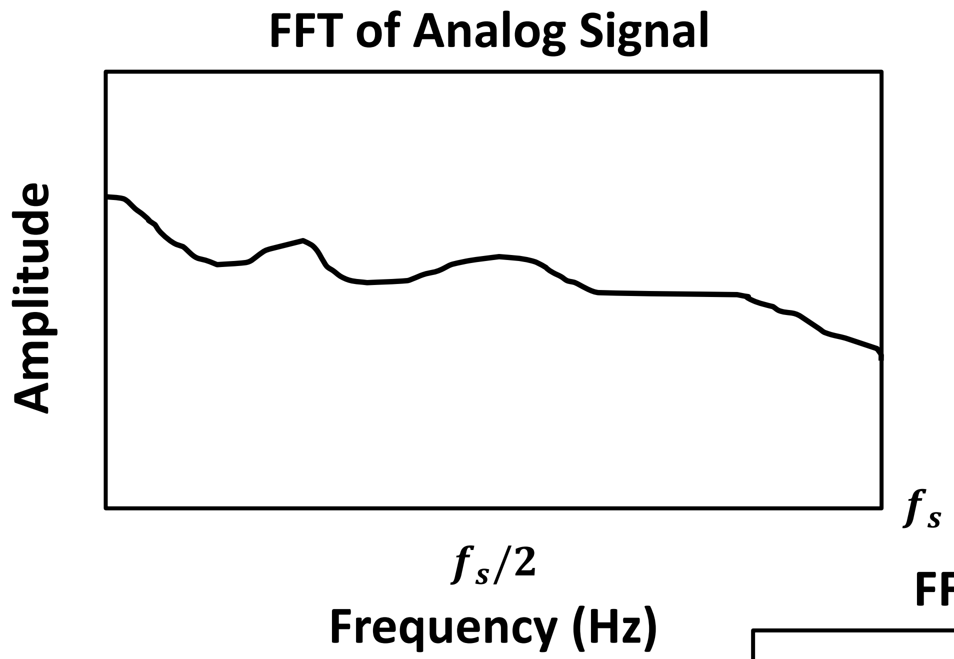


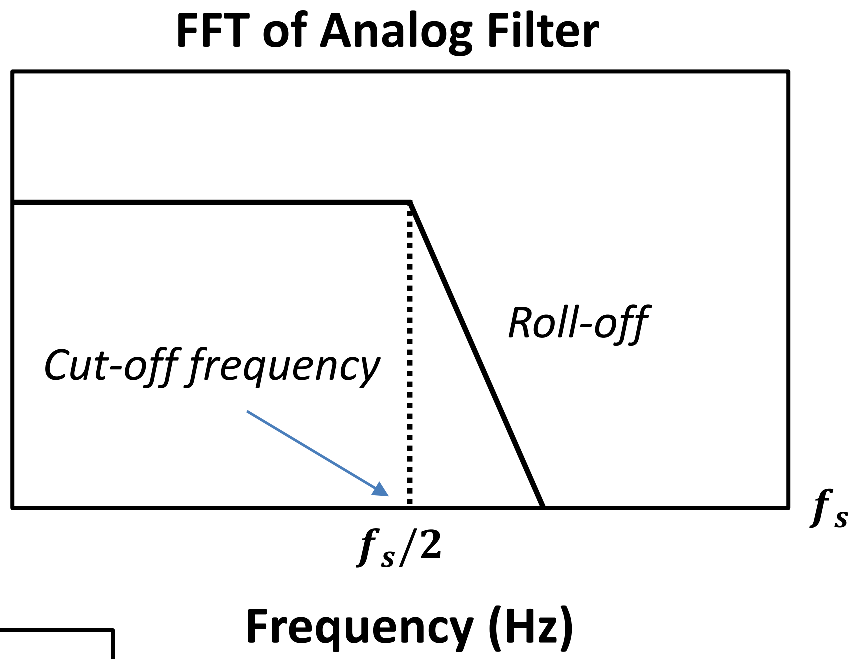
Resampling (50 X 50)

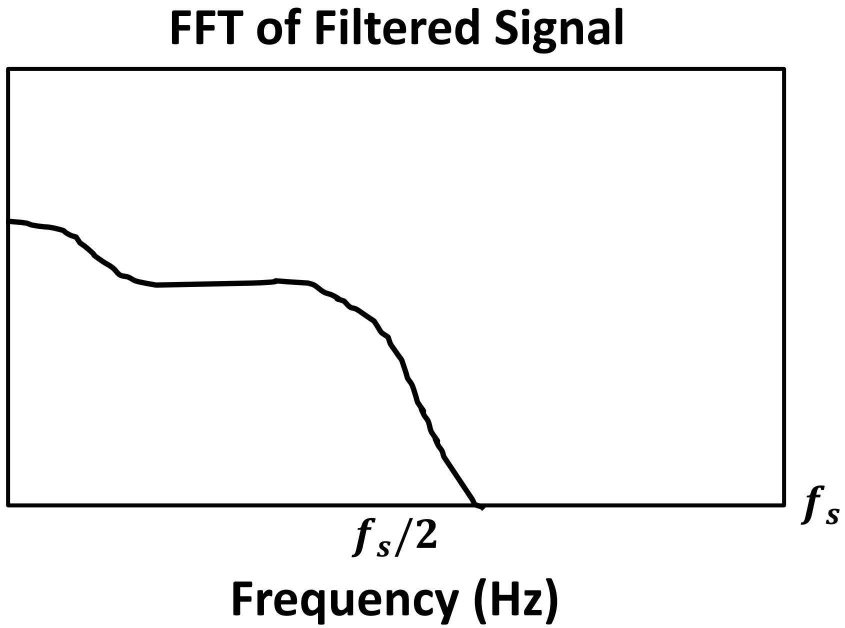


Resampling (15 X 15)

Anti-Aliasing Analog Filter





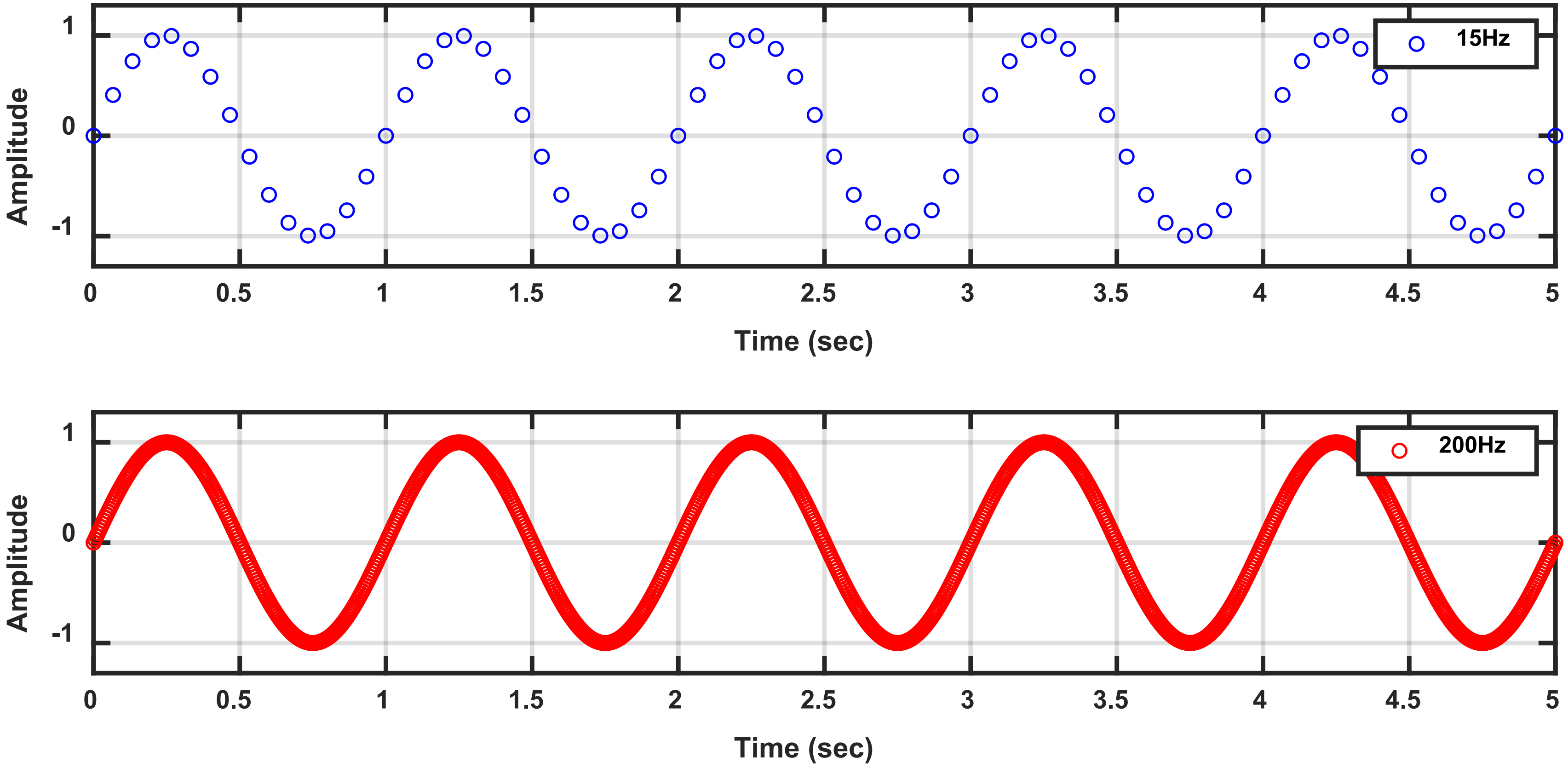


Anti-Aliasing is done before sampling.

Oversampling

Oversampling will provide a true picture of the time course of the event being studied but too much oversampling will result in very large data files.

Example: Drawing a graph



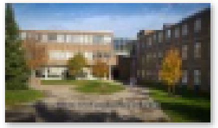
Do we really need 200Hz?

Tutorial

Example: Image Oversampling

maxresdefault.jpg

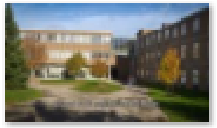
JPG File



Date taken:	Specify date taken
Tags:	Add a tag
Rating:	☆☆☆☆☆
Dimensions:	150 x 84
Size:	5.77 KB
Title:	Add a title
Authors:	Add an author
Comments:	Add comments
Camera maker:	Add text
Camera model:	Add a name
Subject:	Specify the subject
Date created:	12/26/2018 1:56 PM
Date modified:	12/26/2018 1:58 PM

maxresdefault_high.jpg

JPG File



Date taken:	Specify date taken
Tags:	Add a tag
Rating:	☆☆☆☆☆
Dimensions:	1500 x 840
Size:	104 KB
Title:	Add a title
Authors:	Add an author
Comments:	Add comments
Camera maker:	Add text
Camera model:	Add a name
Subject:	Specify the subject
Date created:	12/26/2018 2:01 PM
Date modified:	12/26/2018 2:01 PM

Quantization of Analog Signals

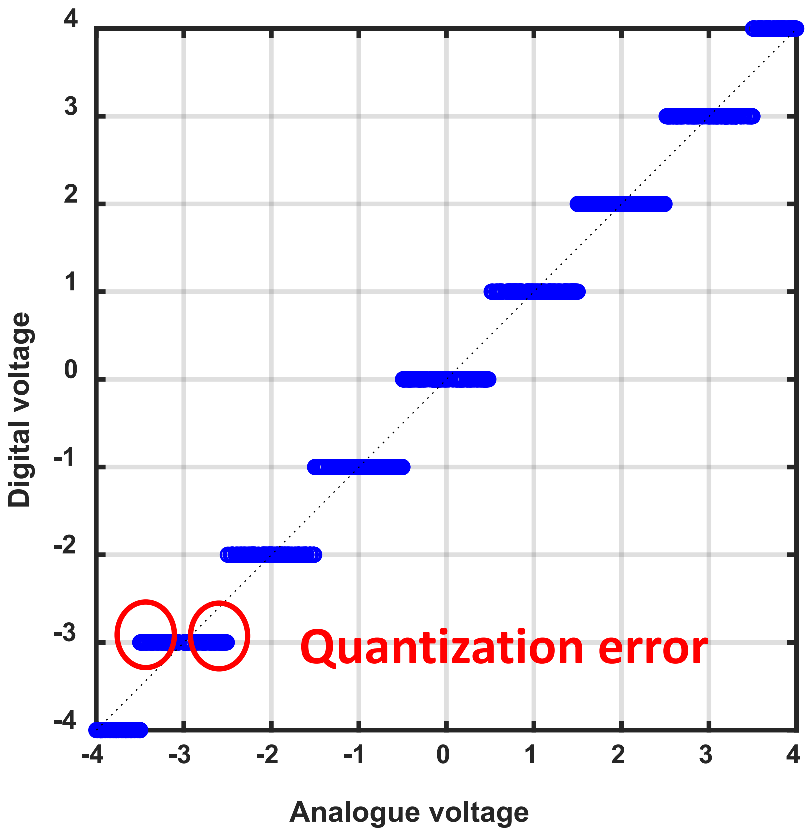
- **Quantization** is the process of constraining an input from a continuous or otherwise large set of values (such as the real numbers) to a discrete set (such as the integers).
- An analog signal from a sensor is sampled in time (sampling frequency) and in amplitude (Quantization).

Example)

3 bit Analog-digital converter produces

2^3= 8 bins for a voltage range of $-4 \sim 4$ v.

Q: example graph



Tutorial

Example for Resolution Calculation

- **Given parameters**
  - Sensor sensitivity: 100mV/g
  - Voltage output range: -2V to +2V
  - # of ADC bits: 16 bits
- **Calculation**
  - 16 bit ADC divides the full scale voltage into 2^{16} = 65536 bins
  - Resolution in terms of voltage: 4V/65536 = 6.1035e-005V
  - Resolution in terms of acceleration:

$$6.1035 \times 10^{-5}\,\mathrm{V} \times \frac{1}{100\mathrm{mV/g}} = 6.1035 \times 10^{-4}\mathrm{g}$$

$$Resolution\ (g) = \frac{Output\ voltage\ range\ (V)}{2^{\#\ of\ ADC\ bits}} \times \frac{1}{Sensor\ Sensitivitiy\ (V/g)}$$

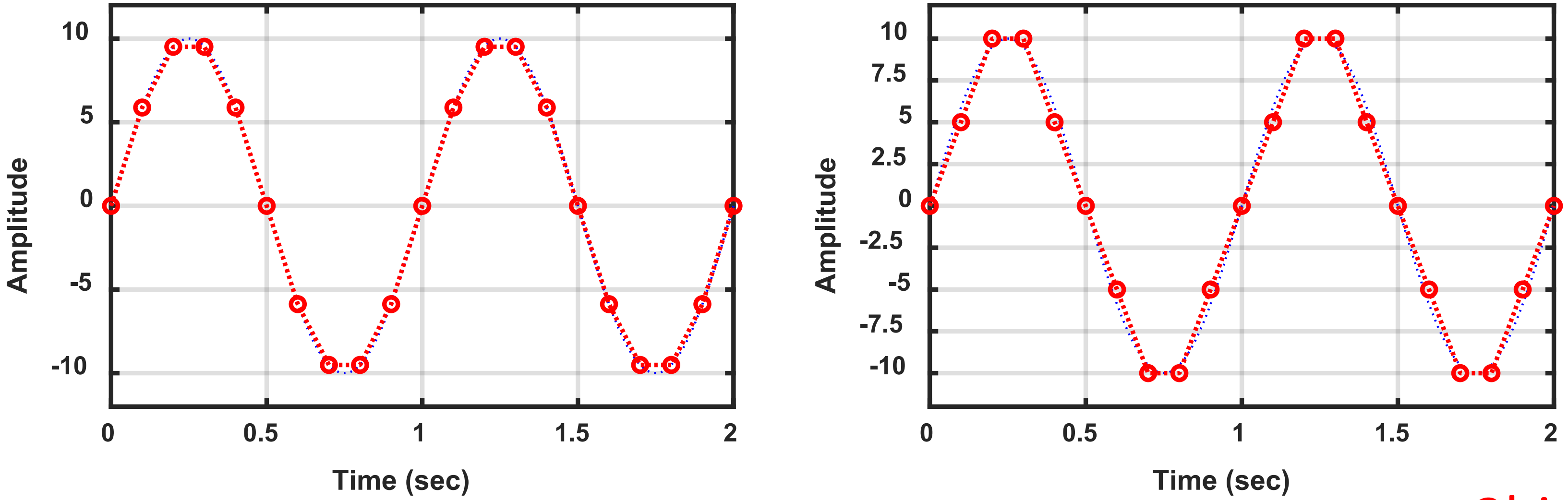
Other Considerations for Resolution

$y = 10 * \sin(2\pi f t)$

Frequency (f): 1

Sampling frequency

$f_s = 1/10$ Hz



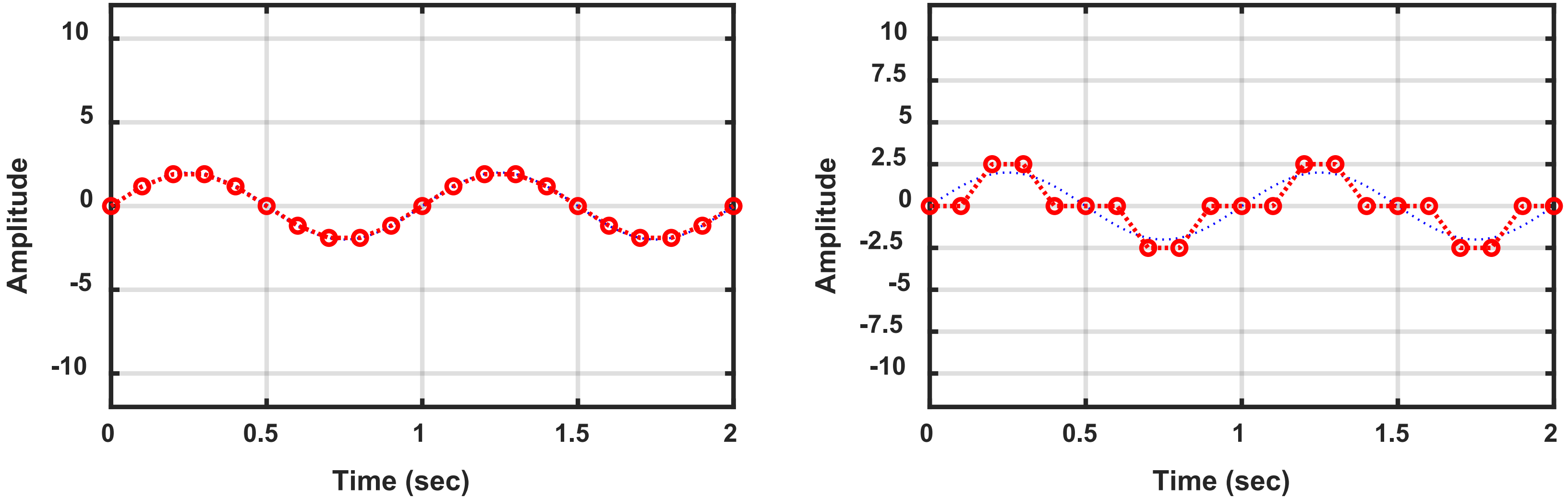
3bit ADC

$y = 2 * \sin(2\pi f t)$

Frequency (f): 1

Sampling frequency

$f_s = 1/10$ Hz



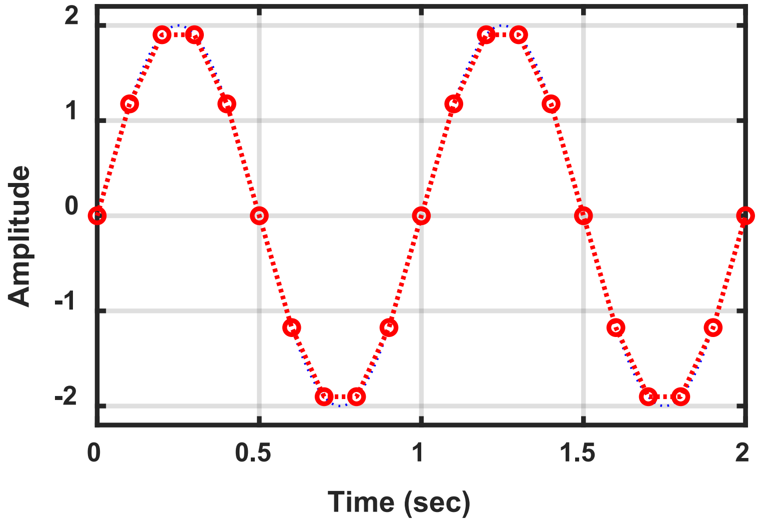
Clipping

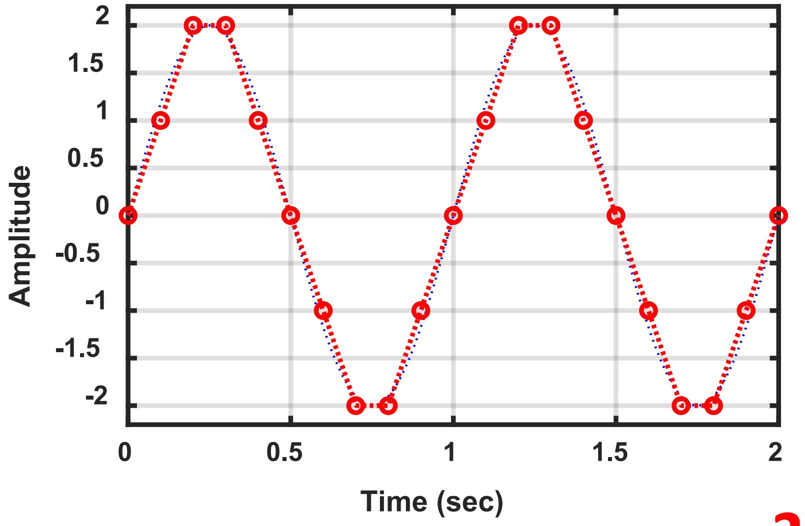
$$y = 2 * \sin(2\pi f t)$$

Frequency (f): 1

Sampling frequency

$$f_s = 1/10 \text{ Hz}$$





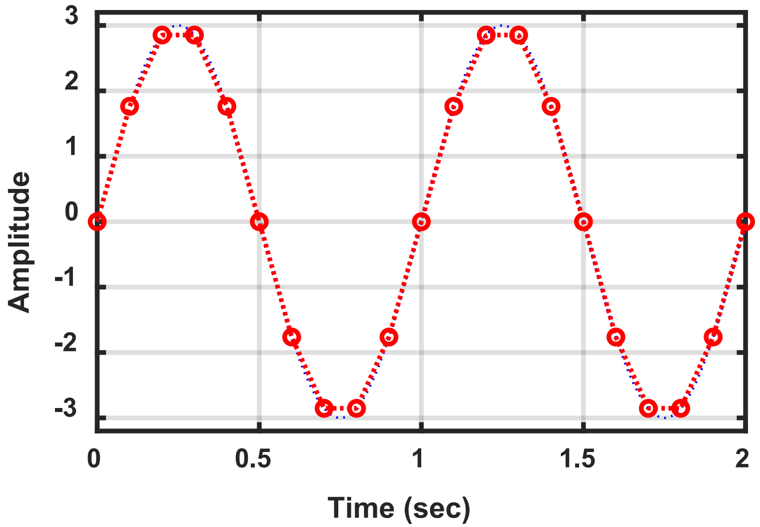
-2V - 2V

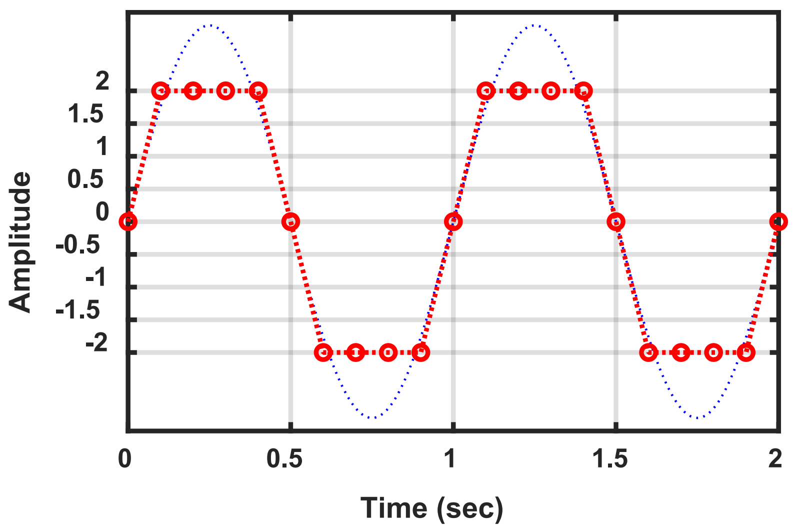
$$y = 3 * \sin(2\pi f t)$$

Frequency (f): 1

Sampling frequency

$$f_s = 1/10 \text{ Hz}$$





Example: Accelerometer in IPhone X Accelerometer

BMI 160, Bosch Sensortec

Parameter	Technical data
Digital resolution	Accelerometer (A): 16 bit Gyroscope (G): 16bit
Measurement ranges (programmable)	(A): ± 2 g, ± 4 g, ± 8 g, ± 16 g (G): ± 125°/s, ± 250°/s, ± 500°/s, ± 1000°/s, ± 2000°/s
Sensitivity (calibrated)	(A): ±2g: 16384LSB/g ±4g: 8192LSB/g ±8g: 4096LSB/g ±16g: 2048LSB/g (G): ±125°/s: 262.4 LSB/°/s ±250°/s: 131.2 LSB/°/s ±500°/s: 65.6 LSB/°/s ±1000°/s: 32.8 LSB/°/s ±2000°/s: 16.4 LSB/°/s
Zero-g offset (typ., over life-time)	(A): ±40mg (G): ± 10°/s
Noise density (typ.)	(A): 180 µg/√Hz (G): 0.008 °/s/√Hz
Bandwidths (programmable)	1600 Hz … 25/32 Hz

LSB: Least Square Bit

(resolution)

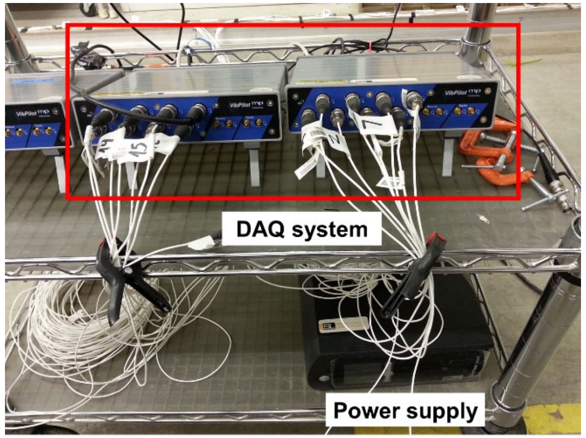
$$\mathrm{LSB} = \frac{\mathrm{Vref}(+) - \mathrm{Vref}(-)}{2^N}$$

Digital inputs/outputs	SPI, I²C, 4x digital interrupts
Supply voltage (VDD)	1.71 … 3.6 V
I/0 supply voltage (VDDIO)	1.2 … 3.6 V
Temperature range	-40 … +85°C
Current consumption - full operation - low-power mode	950 µA 3 µA
FIFO data buffer	1024 byte
LGA package	2.5 × 3.0 × 0.8 mm³
Shock resistance	10,000 g x 200 µs

2^{16} = 65536 bins

https://www.bosch-sensortec.com/bst/products/all_products/bmi160

Example: Modal Testing



Analog Input	
Number of channels	4 or 8; multiple unit daisy chain
Channel type	Voltage mode: single-ended or fully differential, selectable per channel IEPE mode: single-ended or pseudo-differential, selectable per channel
Analog-to-digital converter type	Sigma-delta
Resolution	24 bits
Sampling rate per channel	40 to 204.8 kHz
Input voltage range	± 1 V and ± 10 V peak full scale, selectable per channel
Overload protection	40 V
Input impedance	1 MΩ, capacitance: 45 pF
Coupling	AC/DC, switchable per channel
AC coupling	0.3 Hz 6 dB/oct. and 10 Hz 6 dB/oct., selectable per channel
Signal-to-noise ratio	At 102.4 kHz sampling: > 100 dB in 1 V range > 105 dB in 10 V range
Amplitude accuracy	± 0.06 dB (at 1 kHz)
Amplitude flatness	± 0.015 dB (DC to 80 kHz, relative to 1 kHz)

Click to zoom

Model: 333B30

Add to Cart for Quote

ADD TO CART

Product Summary | **Specifications** | Documents & Downloads

	English:	SI:	
PERFORMANCE			
Sensitivity (±10 %)	100 mV/g	10.2 mV/(m/s^2)	
Measurement Range	±50 g pk	±490 m/s^2 pk	
Frequency Range (±5 %)	0.5 to 3000 Hz	0.5 to 3000 Hz	
Resonant Frequency	≥40 kHz	≥40 kHz	
Phase Response (±5 °) (at 70°F [21°C])	2 to 3000 Hz	2 to 3000 Hz	
Broadband Resolution (1 to 10000 Hz)	0.00015 g rms	0.0015 m/s^2 rms	[2]
Non-Linearity	≤1 %	≤1 %	[1]
Transverse Sensitivity	≤5 %	≤5 %	[3]
ENVIRONMENTAL			
Overload Limit (Shock)	±5000 g pk	±49000 m/s^2 pk	
Temperature Range (Operating)	0 to +150 °F	-18 to +66 °C	
Temperature Response	See Graph %/°F	See Graph %/°F	
Base Strain Sensitivity	0.01 g/με	0.1 (m/s^2)/με	[2]
ELECTRICAL			
Excitation Voltage	18 to 30 VDC	18 to 30 VDC	
Constant Current Excitation	2 to 20 mA	2 to 20 mA	
Output Impedance	≤300 Ohm	≤300 Ohm	
Output Bias Voltage	7 to 12 VDC	7 to 12 VDC	
Discharge Time Constant	1.0 to 3.0 sec	1.0 to 3.0 sec	
Settling Time (within 10% of bias)	<12 sec	<12 sec	
Spectral Noise (1 Hz)	39 µg/√Hz	380 (µm/sec^2)/√Hz	[2]
Spectral Noise (10 Hz)	11 µg/√Hz	110 (µm/sec^2)/√Hz	[2]
Spectral Noise (100 Hz)	3.4 µg/√Hz	33 (µm/sec^2)/√Hz	[2]
Spectral Noise (1 kHz)	1.4 µg/√Hz	14 (µm/sec^2)/√Hz	[2]

↑ Accelerometer

← Data acquisition system

Demo: Acceleration Measurement using a Smart Phone – Arduino Science Journal

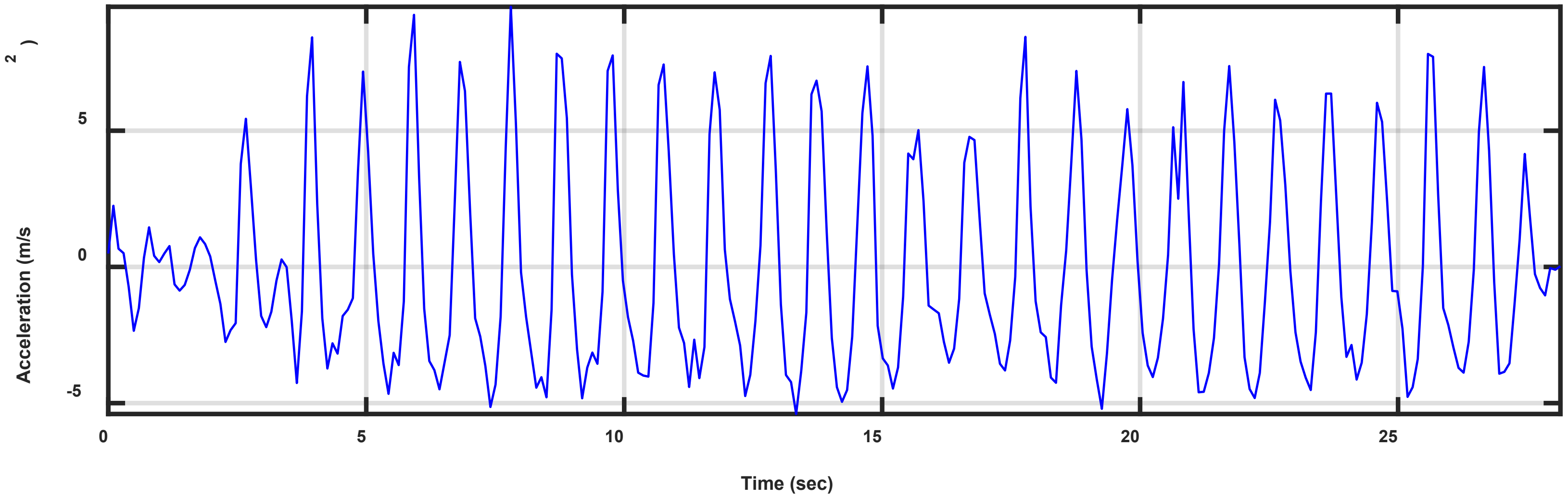
https://www.arduino.cc/education/science-journal

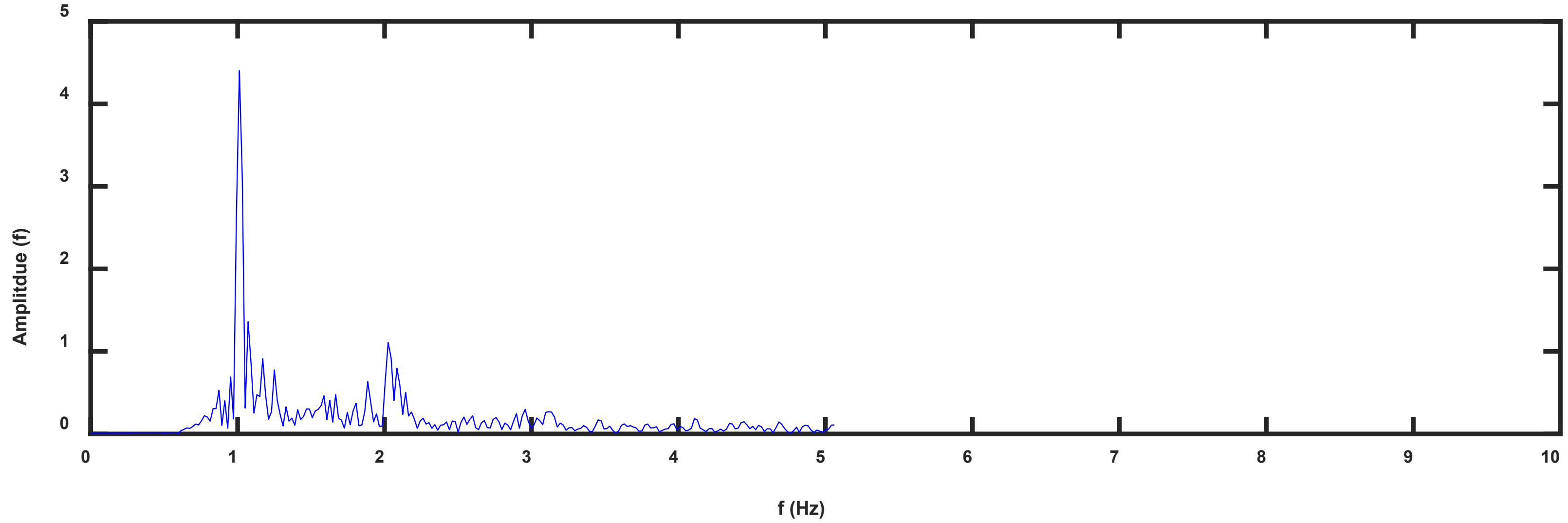
Demo: Acceleration Measurement using a Smart Phone – Vibration Analysis

Frequency (f): 1

Sampling frequency

$f_s = 10$ Hz





Slide Credits and References

- Shin, K., & Hammond, J. K. (2008). Fundamentals of Signal Processing: for Sound and Vibration Engineers, 418.
- http://www.now-instruments.com/get-help/5-vibsensor-user-guide
- http://courses.me.metu.edu.tr/courses/me410/notes/Week10/Week10.pdf
- Introduction to Smart Structure Technology (Spring 2009, KAIST)
- https://www.bosch-sensortec.com/bst/products/all_products/bmi160
- https://www.edaboard.com/showthread.php?250221-Accelerometer-Questions
- http://www2.hawaii.edu/~peterb/resources/equipment/analog_devices_accelermoter_specifications.pdf
- https://www.mpihome.com/files/mppdf/mppdf_product_guide/mp_ProductGuide_VibPilot.pdf
- http://www.lb-acoustics.at/wp-content/uploads/2018/05/data_mp_vibpilot_en.pdf
- http://www.pcb.com/products/model/333b30