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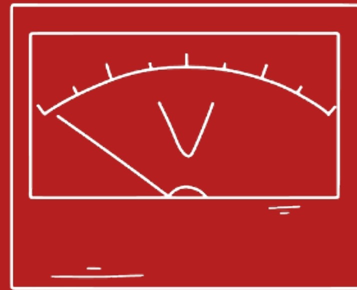
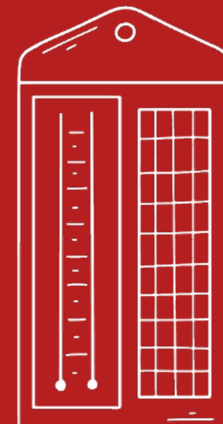
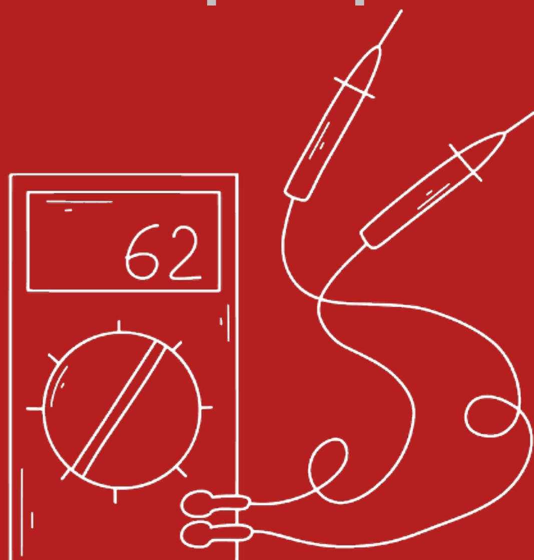
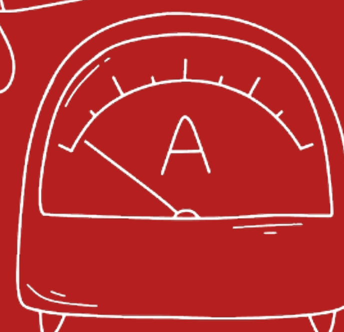




ME-301 MEASUREMENT TECHNIQUES

General measurement principles





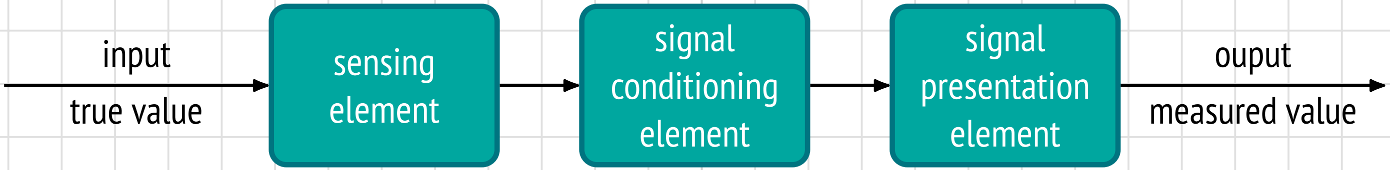
last compiled by K. Mulleners - 2024

Overview

- Measurement systems
  - General structure of a measurement system
  - Measurement system characteristics
- Measurement accuracy, precision, and errors
  - Measurement accuracy and precision
  - Measurement errors
- Examples

General structure of a measurement system

A measurement is the act of assigning a value to a physical variable. The physical variable is the *measurand*. A typical measurement system has three main components:



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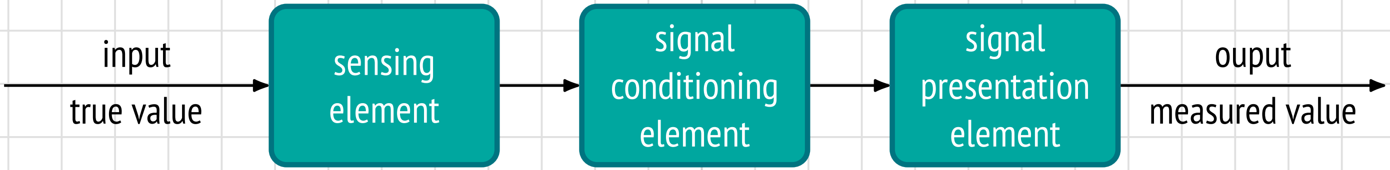

- The **sensing element** has a physical characteristic that responds to changes in the measurand

  Example of sensing elements are:

  - Thermocouple: millivolt electromotive force depends on temperature
  - Strain gauge: resistance depends on mechanical strain
  - Orifice plate: pressure drop depends on flow rate.

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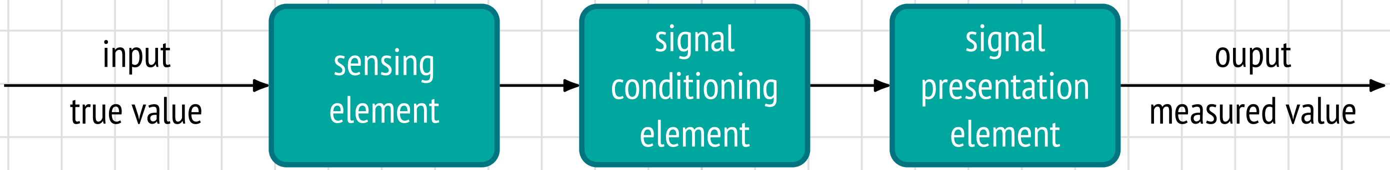

- The **sensing element** has a physical characteristic that responds to changes in the measurand
- The **signal conditioning element** converts the signal from the sensing element to a more suitable form for presentation or recording.

  Examples of signal conditioning elements are:

  - Deflection bridge which converts an impedance change into a voltage change
  - Amplifier which amplifies millivolts to volts
  - Oscillator which converts an impedance change to a variable frequency voltage
  - Analogue-to-digital converter (ADC) converting a voltage into a digital form
  - Computing element that calculates the measured value from the incoming digital data, e.g.
    - computation of total mass of product gas from flow rate and density data
    - integration of chromatograph peaks to give the composition of a gas stream
    - correction for sensing element non-linearity

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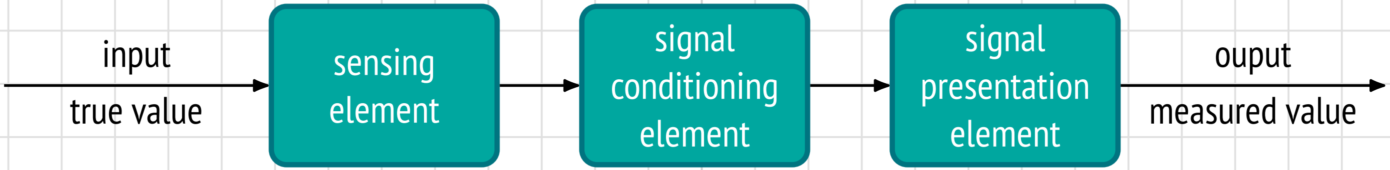
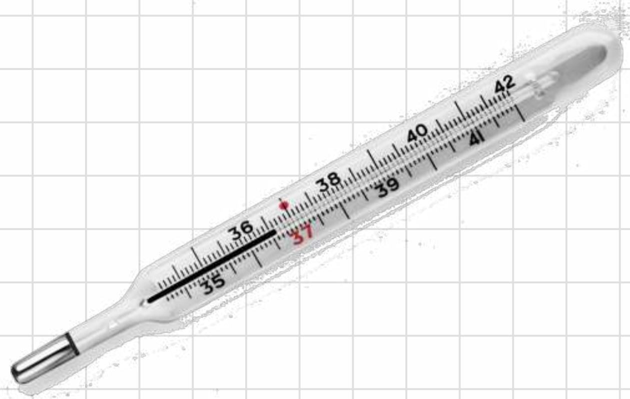


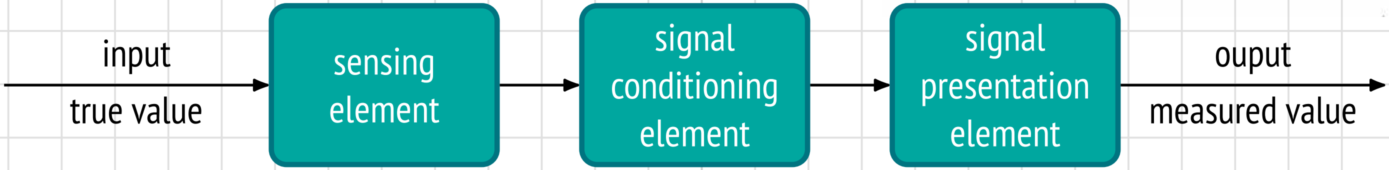
- The **sensing element** has a physical characteristic that responds to changes in the measurand
- The **signal conditioning element** converts the signal from the sensing element to a more suitable form for presentation or recording.
- The **signal presentation element** presents the measured value in a form which can be easily recognised by the observer

  Examples of signal presentation elements are:
  - Simple pointer-scale indicator
  - Chart recorder
  - Alphanumeric display

Examples of measurement systems

Mercury-in-glass thermometer



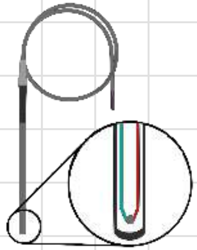


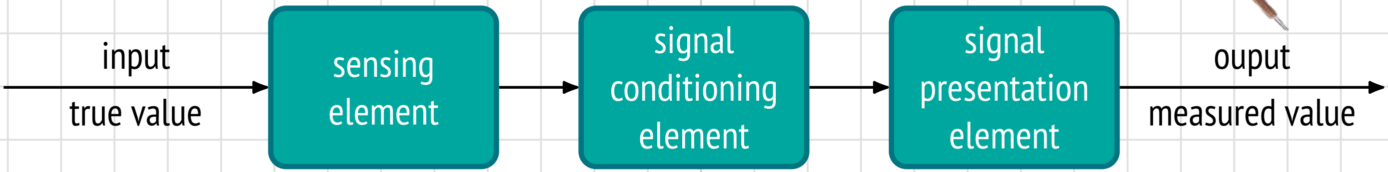
- **Sensing element**: the volume of mercury will change with temperature $V \propto T$
- **Signal conditioning element**: to emphasize the change in volume, a thin stem is used above the sphere (makes the device more *sensitive*)
- **Signal presentation element**: an indicator to side to convert the change in height to temperature. This conversion relies on a *calibration* procedure.[a]

[a] A calibration procedure is the comparison of measurement values delivered by a measurement device with those of a calibration standard of known accuracy.

Examples of measurement systems

Thermocouple





- **Sensing element**: two wires of different metals that are in contact with each other at the measuring point. The different metals react differently to a change in temperature that will give rise to a temperature dependent voltage.[a]
- **Signal conditioning element**: the sensing element typically gives a millivolt output. Signal conditioning consists of a circuit to compensate for changes in reference junction temperature, and an amplifier. The voltage signal is converted into digital form using an analogue-to-digital converter, the computer corrects for sensor non-linearity.
- **Signal presentation element**: the measured value can be displayed on the screen of a multimeter or saved in a text file.

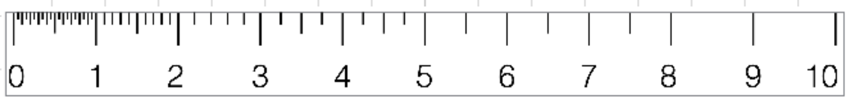
[a] see lecture on *Temperature and thermal property measurements* for more details

Measurement range, span, resolution, dynamic range

- **Range**: the input range of a sensing element is specified by the minimum and maximum values of its input. The output range is specified by the minimum and maximum values of its output.

  A pressure transducer may have an input range of 0 Pa *to* 104 Pa *and an output range of* 4 mA *to* 20 mA*; a thermocouple may have an input range of* 100 °C *to* 250 °C *and an output range of* 4 mV *to* 10 mV*.*
- **Span**: the span is the maximum variation in input or output.

  In the previous examples the pressure transducer has an input span of 104 Pa *and an output span of* 16 mA*; the thermocouple has an input span of* 150 °C *and an output span of* 6 mV*.*
- **Resolution**: the resolution of a measurement system is the smallest value that can be measured.
- **Dynamic range**: the dynamic range of a measurement system is the ratio of its measurement span to its resolution.



range	span	resolution	dynamic range
0 cm to 1 cm			
1 cm to 2 cm			
2 cm to 3 cm			
3 cm to 5 cm			
5 cm to 8 cm			
8 cm to 10 cm			

Measurement range, span, resolution, dynamic range

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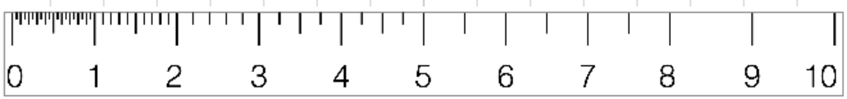
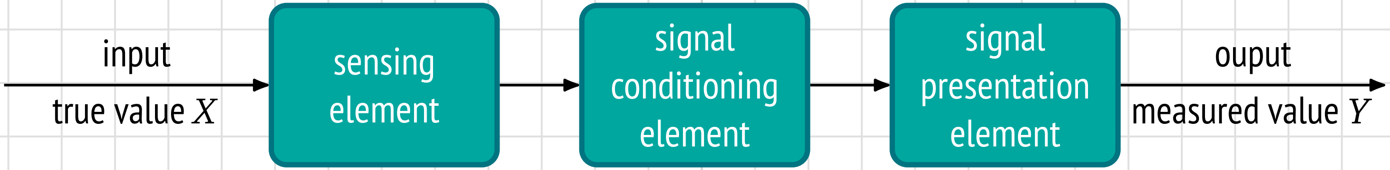


range	span	resolution	dynamic range
0 cm to 1 cm	1 cm	0.5 mm	20
1 cm to 2 cm	1 cm	1 mm	10
2 cm to 3 cm	1 cm	2 mm	5
3 cm to 5 cm	2 cm	2.5 mm	8
5 cm to 8 cm	3 cm	5 mm	6
8 cm to 10 cm	2 cm	1 cm	2

Measurement accuracy or uncertainty



Error (ϵ) = measured value (Y) - true value (X)

- a measurement error does not (have to) imply we made a mistake
- a measurement error indicates that our measurement system is imperfect
- a measurement system is *never* perfect, but we should *always* want to know how imperfect it is

The **uncertainty** or **accuracy** is a numerical estimate of the possible range of the error in a measurement. In any measurement, the error is not known exactly since the true value is rarely known exactly. When using a measurement system, we should know the error bounds or uncertainty (the plus or minus range around the measured value where the true value would lie). Uncertainty is brought about by all the errors that are present in the measurement system.

Accuracy and sensitivity

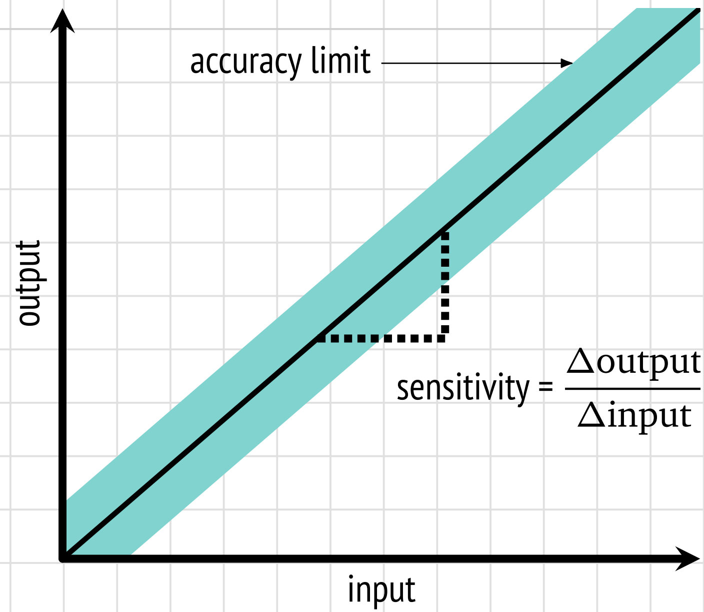
Accuracy is either expressed as a percentage of full span (FS) or percentage of the reading (rgd) + some integer-multiple of the least significant digit (dgt) on the scale.

Example: consider a voltmeter with a stated uncertainty of $\pm(0.5\,\% + 1\,\mathrm{dgt})$ on a $4\,\mathrm{V}$ span. The least significant digit shown on the display is $0.01\,\mathrm{V}$.
This voltmeter has an absolute uncertainty of:

$$0.005 \times 4\,\mathrm{V} + 0.01\,\mathrm{V} = 0.03\,\mathrm{V}$$

Sensitivity is defined as the change in output signal per unit change of input signal. It is essentially the gradient of the input-output curve. High sensitivity means that small variations in the input signal give large changes in the output signal.

Always aim for maximum sensitivity when selecting a measurement system.



Measurement errors

Errors in measurements can arise from many causes; there are remedies for some types of errors, but others haunt us as intrinsic properties of the measurement system under use, and can only be mitigated by system redesign.

We can classify errors in these categories:

- **Gross errors** are errors made by the human by mistake or carelessness.
  Examples:
  - typos and misreadings
  - conversion errors
  - connecting wires the wrong way around

  By definition, gross errors are the avoidable errors and should be eliminated.

- System errors
  - **Systematic errors** or **bias errors**: $B := \epsilon_s = \overline{Y} - X$
    refer to repeatable errors or biases in the system

  - **Random errors** or **precision errors**: $P := \epsilon_r = Y - \overline{Y}$
    refer to errors that can not be predicted and have a direct effect on the precision of the reading

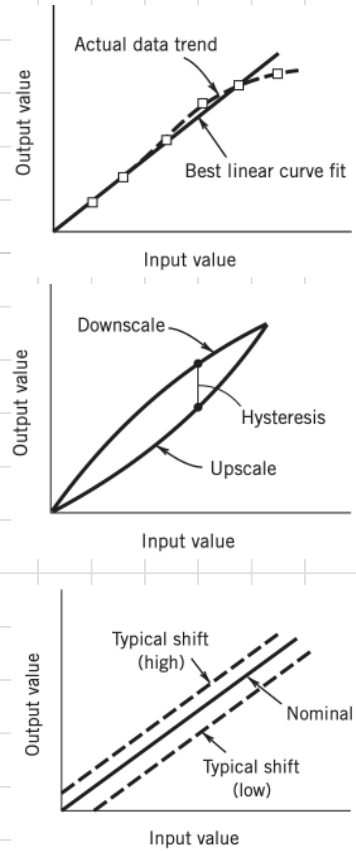
Systematic errors or bias errors

$$B := \epsilon_s = \overline{Y} - X$$

Systematic errors or bias errors refer to repeatable errors or biases in the system

They cover:

- **Loading errors**: disturbances from the measurement process itself, particularly where the measurements are intrusive and the sensing element interferes with the measurand.
- **Calibration errors**: errors that arise due to incorrect estimates of the calibration curve.[a] For example, if we assume a linear calibration function, say $T = aV$ a calibration error arises by having an incorrect value of a.
- **Hysteresis errors**: error due to differences between an upscale sequential test and a downscale sequential test.
- **Fixed offsets**: constant values that are added to all the measurements, independent of the measurement. For example, a voltmeter that gives 10.1 V when reading a 10 V battery, and reads 0.1 V when shorted.



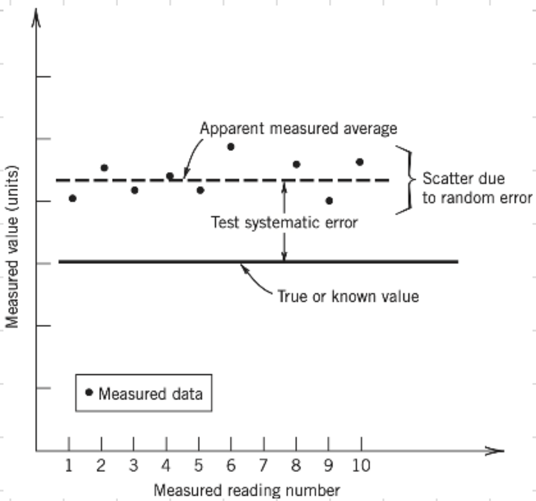
[a]A calibration applies a known input value to a measurement system for the purpose of observing the system output value. It establishes the relationship between the input and output values referred to as the calibration curve. The known value used for the calibration is called the standard.

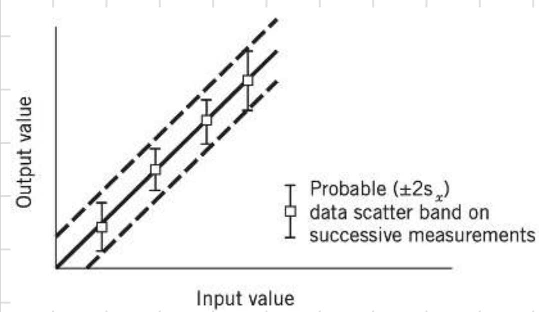
Random errors or precision errors

$$P := \epsilon_r = Y - \overline{Y}$$

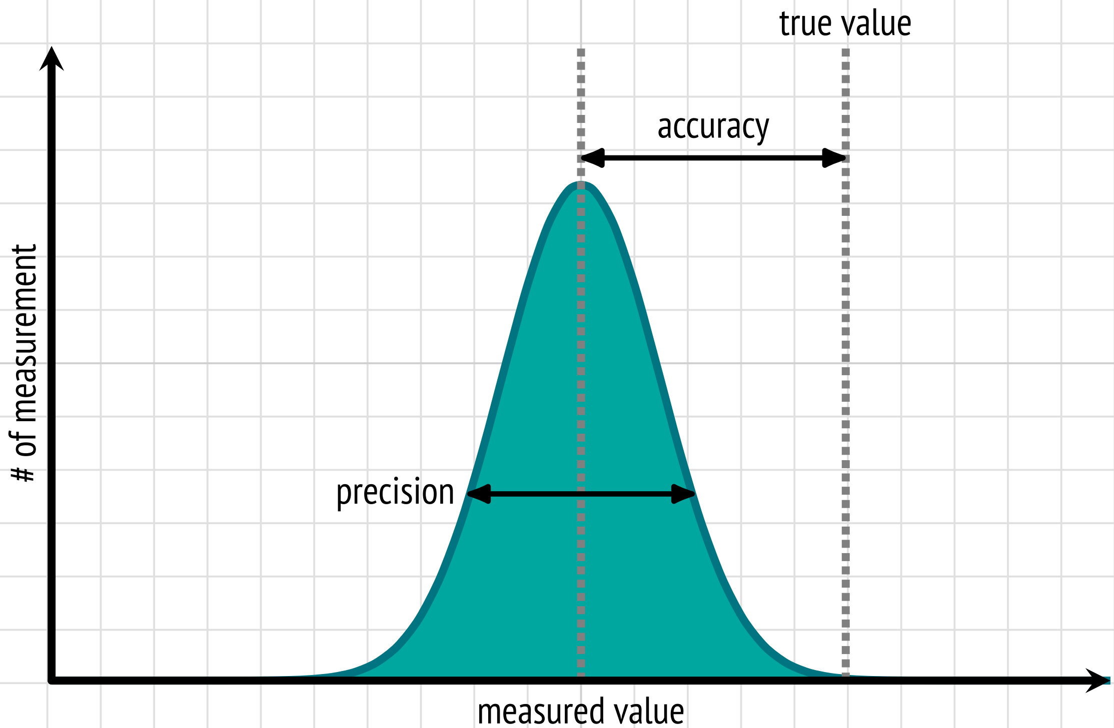
Random errors or precision errors refer to errors that can not be predicted and have a direct effect on the **precision** of the reading.

Scatter in measurement data is as an indicator of random error and can be caused by a number of factors, including environmental conditions (temperature, humidity, mechanical vibrations, electrical noise, etc.). The random error bands can be estimated by statical analysis of the repeated measurements.





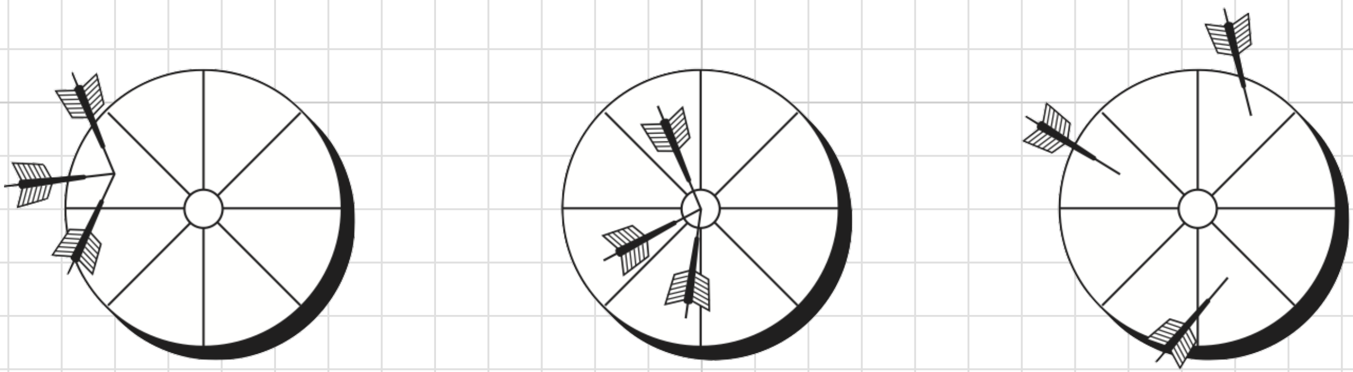
Precision vs Accuracy



Precision vs Accuracy

Beware!

A measurement system that has a low random error is considered precise.
Yet, a precise system in not necessarily accurate.



(a) High repeatability gives low random error but no direct indication of accuracy.

(b) High accuracy means low random and systematic errors.

(c) Systematic and random errors lead to poor accuracy.

Examples

Example 1

In a calibration test, 9 measurements, using a digital voltmeter, have been made of the voltage of a battery that is known to have a true voltage of $6.11\,\mathrm{V}$. The readings are: $5.98\,\mathrm{V}$, $6.05\,\mathrm{V}$, $6.10\,\mathrm{V}$, $6.06\,\mathrm{V}$, $5.99\,\mathrm{V}$, $5.96\,\mathrm{V}$, $6.02\,\mathrm{V}$, $6.03\,\mathrm{V}$ and $5.99\,\mathrm{V}$.
Estimate the systematic and maximum (largest) absolute random error caused by the voltmeter.

Examples

Example 2

A pressure sensing device has an electrical output and is approximately linear. When the input is 100 kPa, the output is 5 mV and when the output is 1000 kPa, the output is 125 mV.
What is the sensitivity of the device?

Examples

Example 3

Specifications Accuracies are indicated at 23 °C ± 5 °C; < 75 % R.H.

Function	Range	Accuracy
Voltage		
DC Voltage	2 V, 20 V, 200 V, 600 V ± (1.2 % rdg + 3 dgts)	
Resolution	1 mV in 2 V range	
Input Impedance	1 MΩ	
Display	3-1/2 digit LCD, 1999 counts	

We wish to measure the voltage of a rated 4.8 VDC battery.
Which range of the voltmeter should we use for this measurement and why?

span	2 V	20 V	200 V	600 V
resolution				
perfect reading				
1.2 % rdg 3 dgts				
uncertainty				

Examples

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Resolution	1 mV in 2 V range	
Input Impedance	1 MΩ	
Display	3-1/2 digit LCD, 1999 counts	

We wish to measure the voltage of a rated 4.8 VDC battery.
Which range of the voltmeter should we use for this measurement and why?

span	2 V	20 V	200 V	600 V
resolution	0.001	0.01	0.1	1
perfect reading	-	4.80	4.8	5
1.2 % rdg 3 dgts	- 0.003	0.06 0.03	0.1 0.3	0 3
uncertainty	-	0.09	0.4	3

Examples

Example 3

Specifications Accuracies are indicated at 23 °C ± 5 °C; < 75 % R.H.

Function	Range	Accuracy
Voltage		
DC Voltage	2 V, 20 V, 200 V, 600 V ± (1.2 % rdg + 3 dgts)	
Resolution	1 mV in 2 V range	
Input Impedance	1 MΩ	
Display	3-1/2 digit LCD, 1999 counts	

We wish to measure the voltage of a rated 4.8 VDC battery.
Which range of the voltmeter should we use for this measurement if the resolution was fixed for each range at 1 mV and the uncertainty is 1.2 % FS?

span	2 V	20 V	200 V	600 V
resolution	0.001	0.001	0.001	0.001
1.2 % FS				

Examples

Example 3

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Function	Range	Accuracy
Voltage		
DC Voltage	2 V, 20 V, 200 V, 600 V ± (1.2 % rdg + 3 dgts)	
Resolution	1 mV in 2 V range	
Input Impedance	1 MΩ	
Display	3-1/2 digit LCD, 1999 counts	

We wish to measure the voltage of a rated 4.8 VDC battery.
Which range of the voltmeter should we use for this measurement if the resolution was fixed for each range at 1 mV and the uncertainty is 1.2 % FS?

span	2 V	20 V	200 V	600 V
resolution	0.001	0.001	0.001	0.001
1.2 % FS	0.024	0.240	2.400	7.200

Examples

Example 4

In some optical measurement techniques, such as e.g. planar laser induced fluorescence (PLIF), the light intensity recorded by a digital camera is converted to a value of a measurand. Planar laser induced fluorescence is an optical measuring technique that can be used to measure instant whole-field concentrations in liquid and gaseous flows and the measurand is thus concentration.

Assume that the calibration curve for a given PLIF camera set-up is linear and the sensitivity of the system to measure a concentration of substance S in water is 1000 counts/(mg/L).

What is the input range, the output range, the resolution, and the dynamic range of the system when we use a grayscale camera with a bit depth of 8, 12 or 16bit?
(assume that the calibration curve passes through the origin)

bit depth	input range	output range	resolution	dynamic range
8 bit				
12 bit				
16 bit				

Examples

Example 4

In some optical measurement techniques, such as e.g. planar laser induced fluorescence (PLIF), the light intensity recorded by a digital camera is converted to a value of a measurand. Planar laser induced fluorescence is an optical measuring technique that can be used to measure instant whole-field concentrations in liquid and gaseous flows and the measurand is thus concentration.

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What is the input range, the output range, the resolution, and the dynamic range of the system when we use a grayscale camera with a bit depth of 8, 12 or 16bit?
(assume that the calibration curve passes through the origin)

bit depth	input range	output range	resolution	dynamic range
8 bit	0 to 255	0 mg/L to 0.255 mg/L	1 µg/L	255
12 bit	0 to 4095	0 mg/L to 4.096 mg/L	1 µg/L	4095
16 bit	0 to 65 535	0 mg/L to 65.535 mg/L	1 µg/L	65 535

Examples

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Assume that the calibration curve for a given PLIF camera set-up is linear and the sensitivity of the system to measure a concentration of substance S in water is 1000 counts/(mg/L).

What would be the measured value for the three cameras when the true concentration is 2.1482 mg/L? (ignore random errors)

true value	bit depth	measured value	error
2.1482 mg/L	8 bit		
2.1482 mg/L	12 bit		
2.1482 mg/L	16 bit		

Examples

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What would be the measured value for the three cameras when the true concentration is 2.1482 mg/L? (ignore random errors)

true value	bit depth	measured value	error
2.1482 mg/L	8 bit	0.255 mg/L	-1.8932 mg/L
2.1482 mg/L	12 bit	2.148 mg/L	-0.2 μg/L
2.1482 mg/L	16 bit	2.148 mg/L	-0.2 μg/L