Measuring

SFERA school 2013

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PROCESSES,MATERIALS
and SOLAR ENERGY
LABORATORY

Emmanuel Guillot
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Odeillo, France

SEVENTH FRAMEWORK PROGRAMME


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Plan

- Measuring?
- Part I: Instrumentation
- Part II: Uncertainties
- [Part III: Quality]
- Measurement techniques

Special slide

Some tools should be shortly defined and usable here

Introduction

- What is measuring?
  - Determine a numeric value of a physical parameter in a given set of conditions
    - => instrumentation
  - With an evaluated trust of the numeric value
    - => uncertainties
  - With an evaluated trust of the procedure
    - => quality

It is a science!

- Instrumentation + Uncertainties = **Metrology**

__Metrology__ is defined by the International Bureau of Weights and Measures (BIPM) as
"the __science of measurement__,
embracing both __experimental and theoretical__ determinations
at any level of uncertainty
in any field of science and technology."

Part I
Instrumentation

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Instrumentation

MEASURING
IS
COMPARING

Instrumentation

- Measuring: determine a numeric evaluation of a physical parameter of a process
  - *Primary characteristics: time, length, mass…*
  - *Derived characteristics: speed, surface, mass flow, viscosity, specific heat, hardness…*

…

Instrumentation

- Measuring: determine a numeric evaluation of a physical quantity of a process…

- …With comparison to a reference quantity

  => **Number** + **Unit**

What is the length of the car? 4,3 m

What is the temperature of the oil? 235 °C

How strong is the DNI of the sun? 954 W/m2

Instrumentation

MEASURING

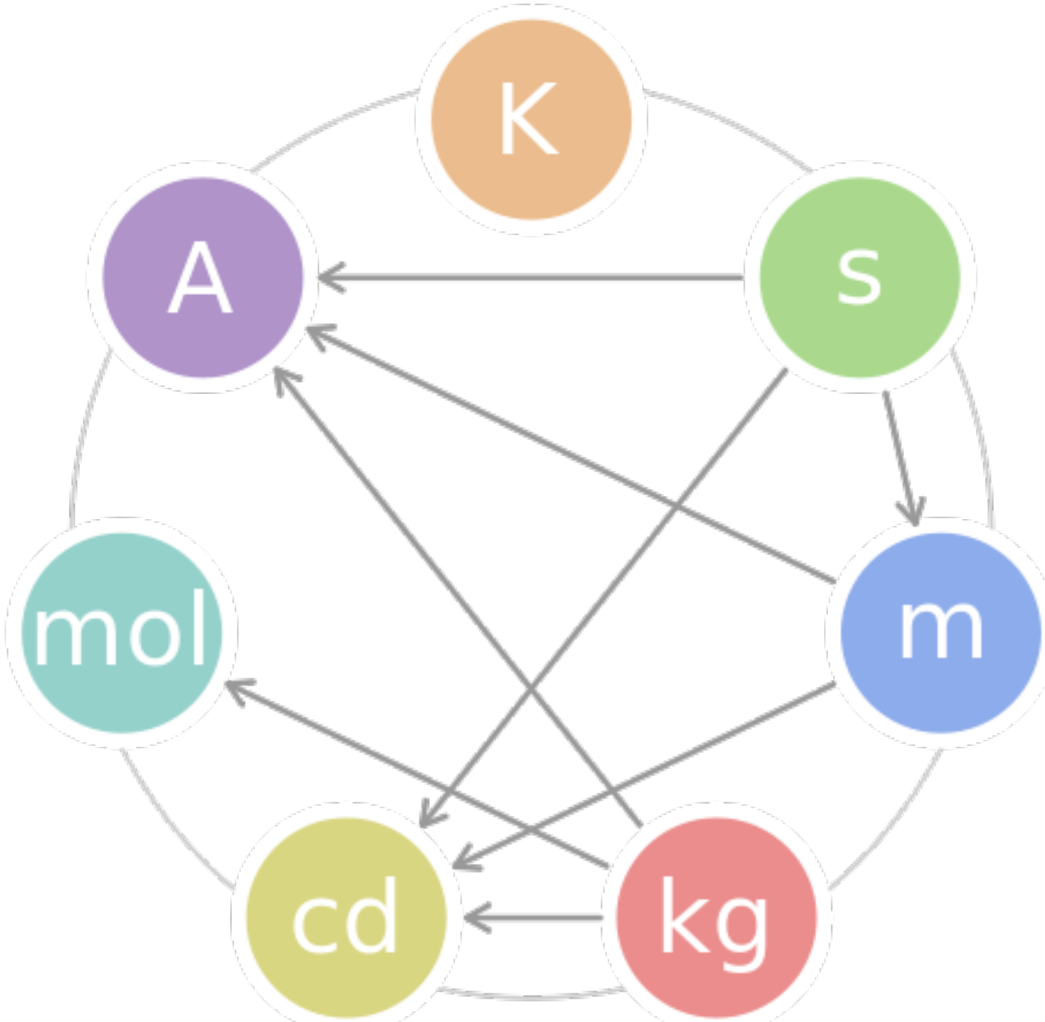
IS

COMPARING

The SI system of units

- 7 units to define it all:
  - *Temperature* => kelvin
  - *Time* => second
  - *Length* => meter
  - *Mass* => kilogram
  - *Luminous intensity* => candela
  - *Quantity of matter* => mole
  - *Electric current* => ampere

The SI system of units



The SI system of units

- Definitions of the units? Universal!
  - It should be stable in time
  - With a repeatable procedure

⇒ Second = number of pulsations of transition state of Cesium

⇒ Meter = distance travelled by light in vacuum in 1 *second*

⇒ Mole = as many as many atoms in 12 mg of Carbon 12

⇒ …

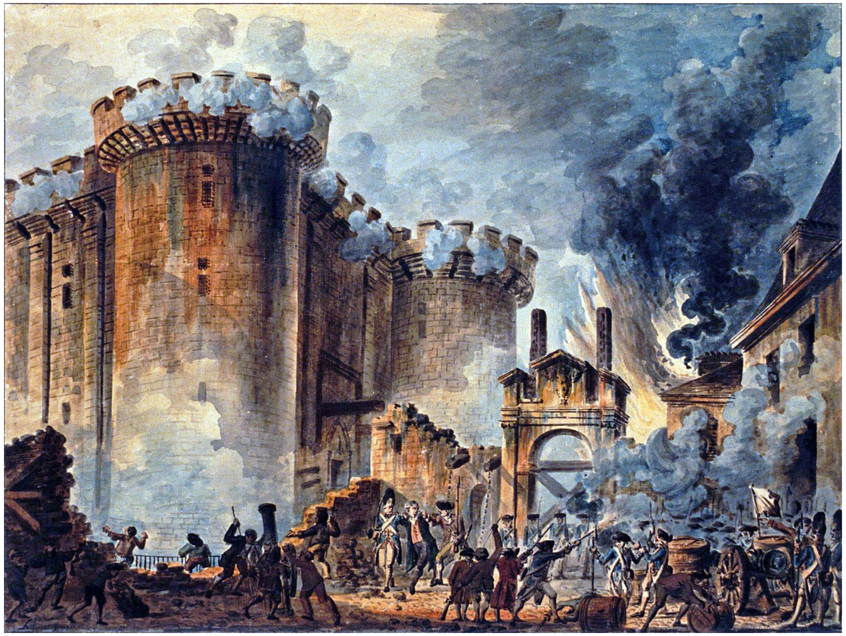
⇒ Kilogram = mass of the International Prototype Kilogram

The SI system of units

- SI = Système International d'unités
- French Revolution: Universal for Mankind

  => including the measurement system

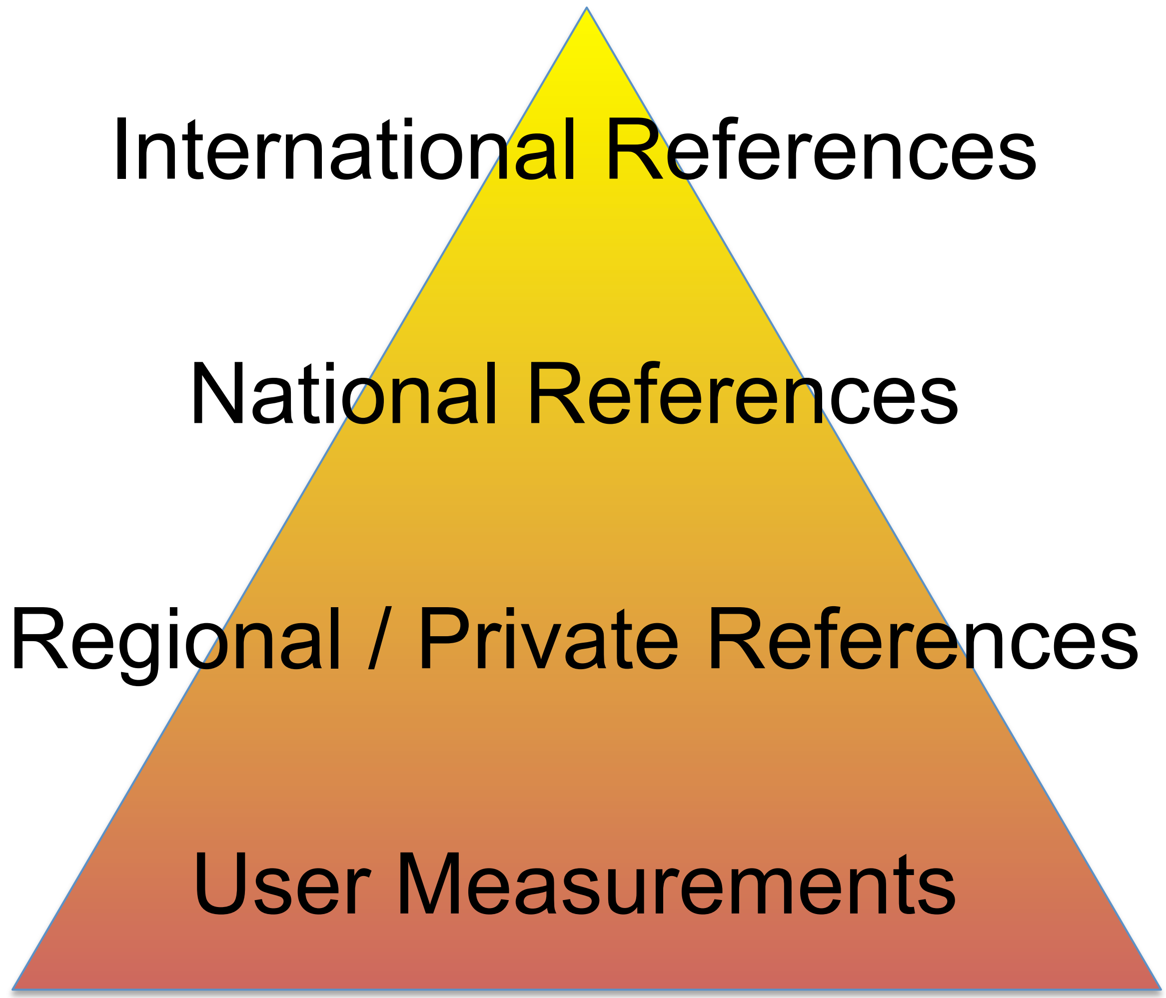
  => still many things in French by French organisations



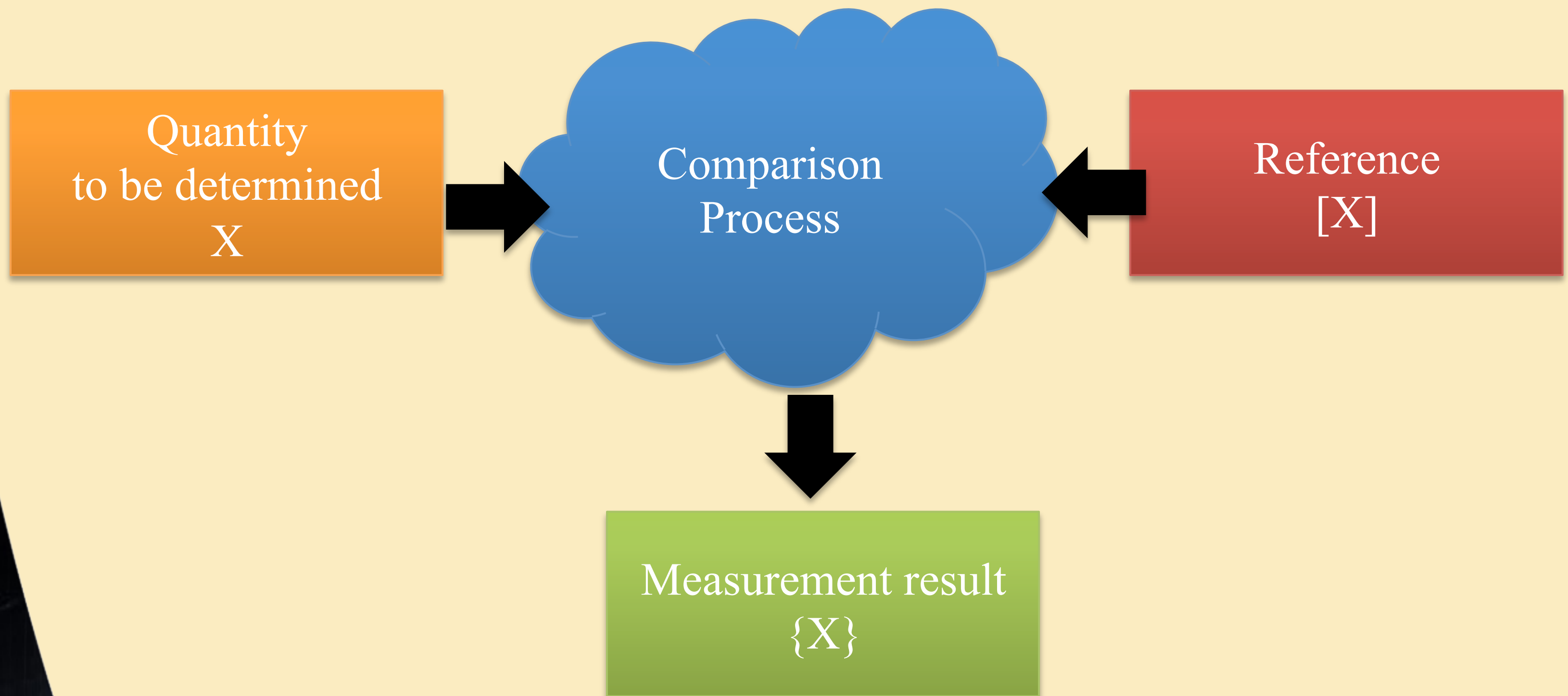
Traceability

MEASURING
IS
COMPARING

Traceability



Comparison: Process of Measurement

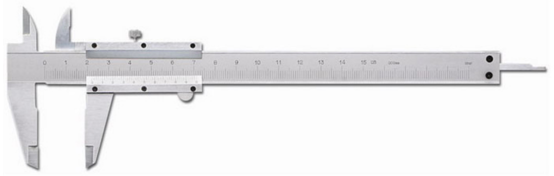


Process of measurement

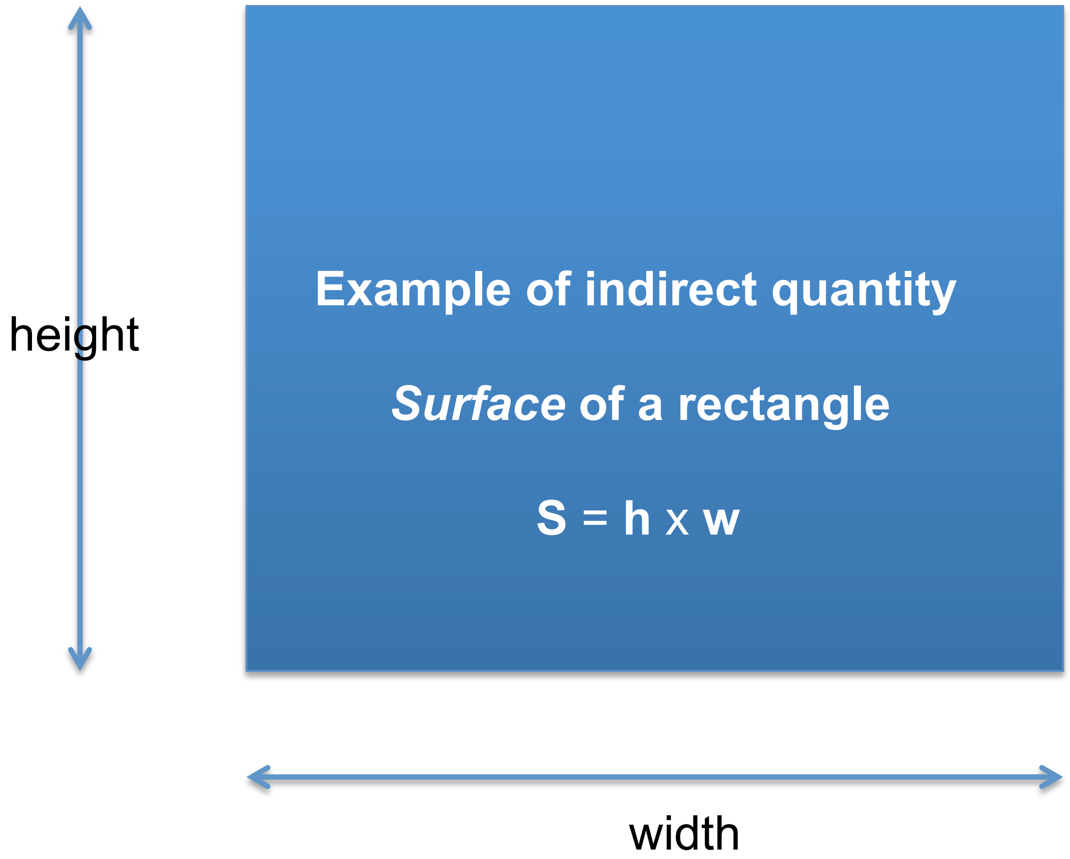
Direct quantity

***Width* of a rectangle**

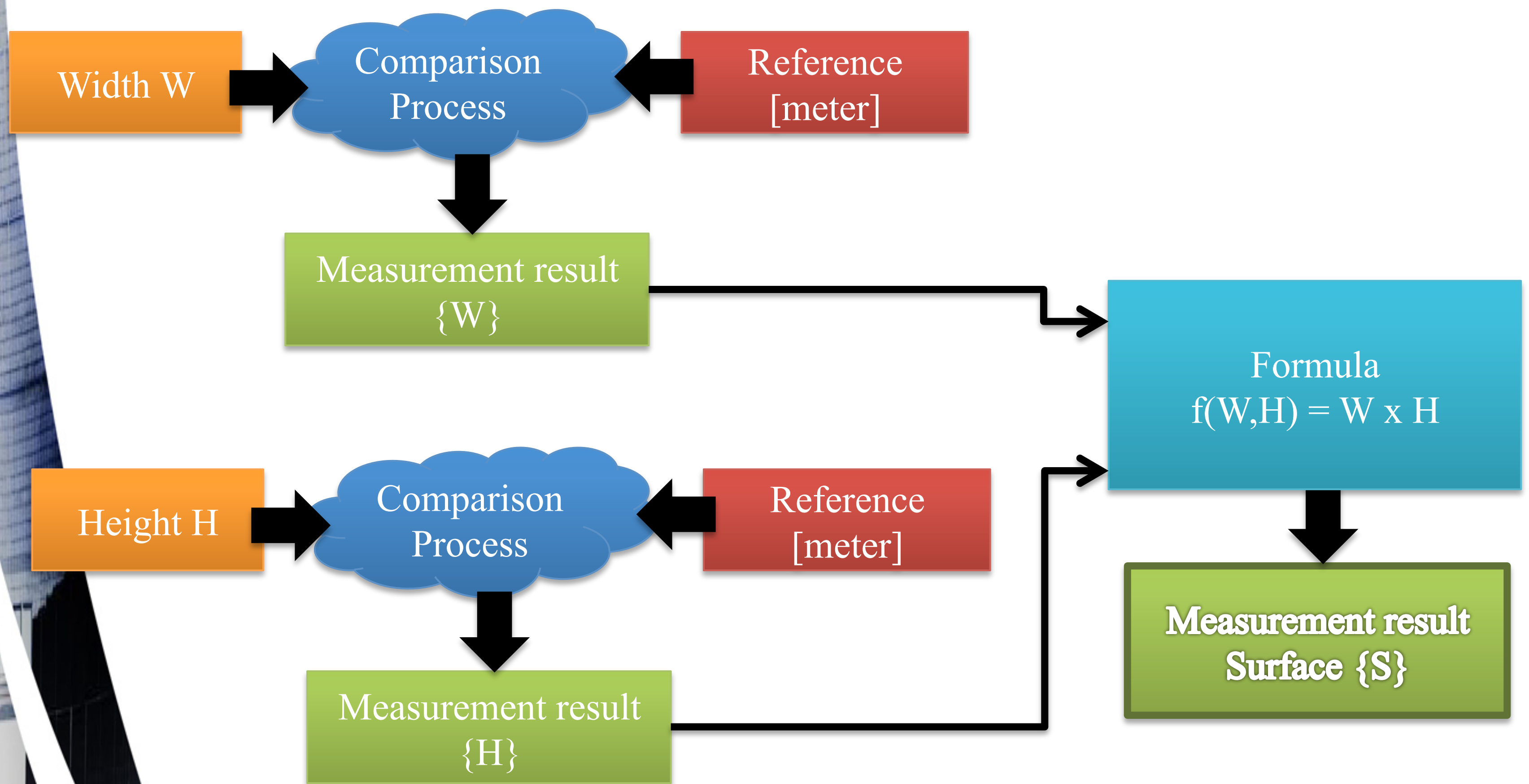
width



Process of measurement



Process of measurement



One observation of a measurement

- At the end, a numeric evaluation with a unit

The width of the rectangle is

13,45 cm

The surface of the rectangle is

127 cm²

Part II
Uncertainties

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Reference

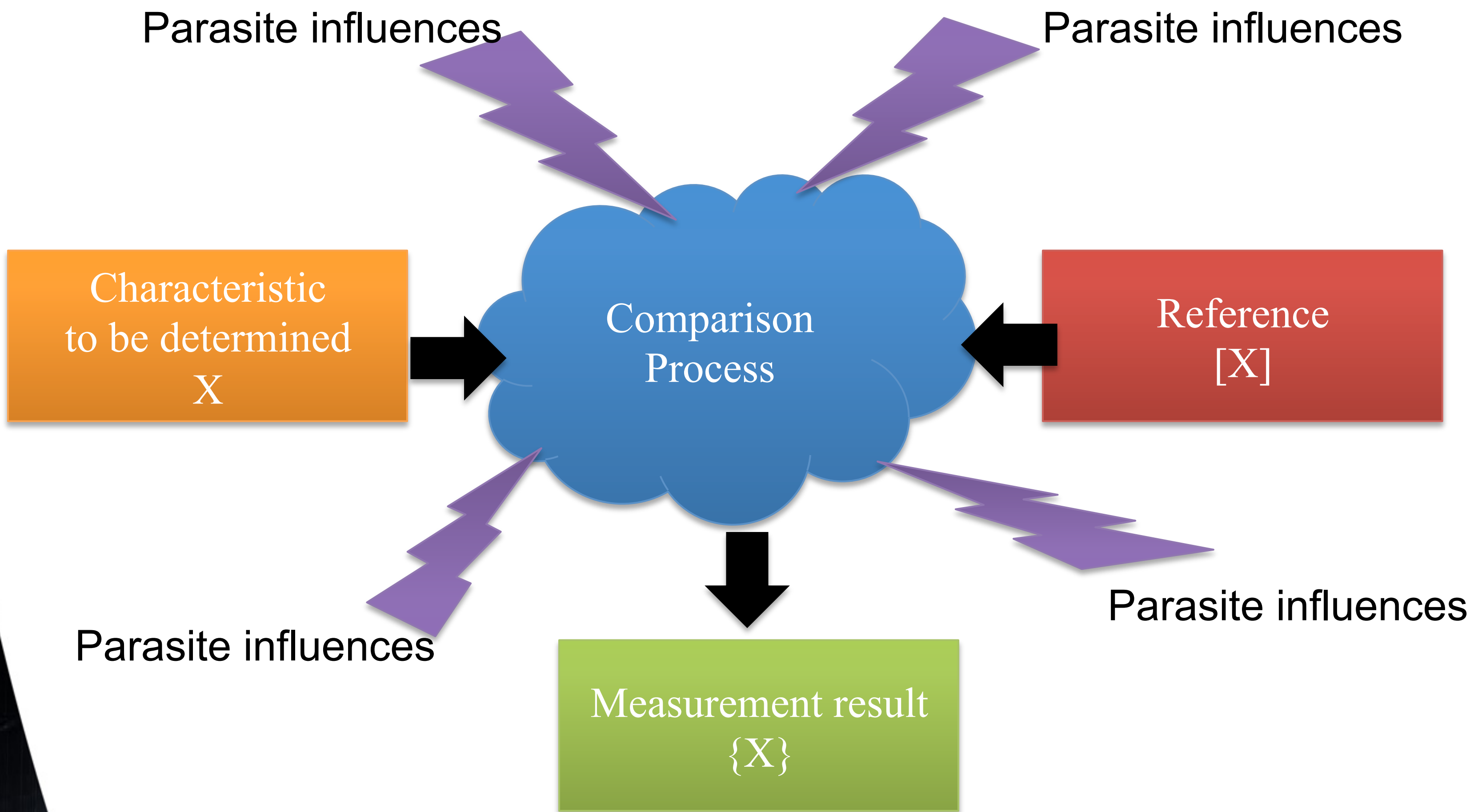
Guide to the expression of
Uncertainty in
Measurement

MEASURING IS COMPARING

But how good is the comparison?

How trustworthy is it?

Process of measurement



Uncertainties

Provide a **reasonable** *evaluation*

of how much **doubt** we have

about the numeric *evaluation* of the measurement

The Truth Is Out There

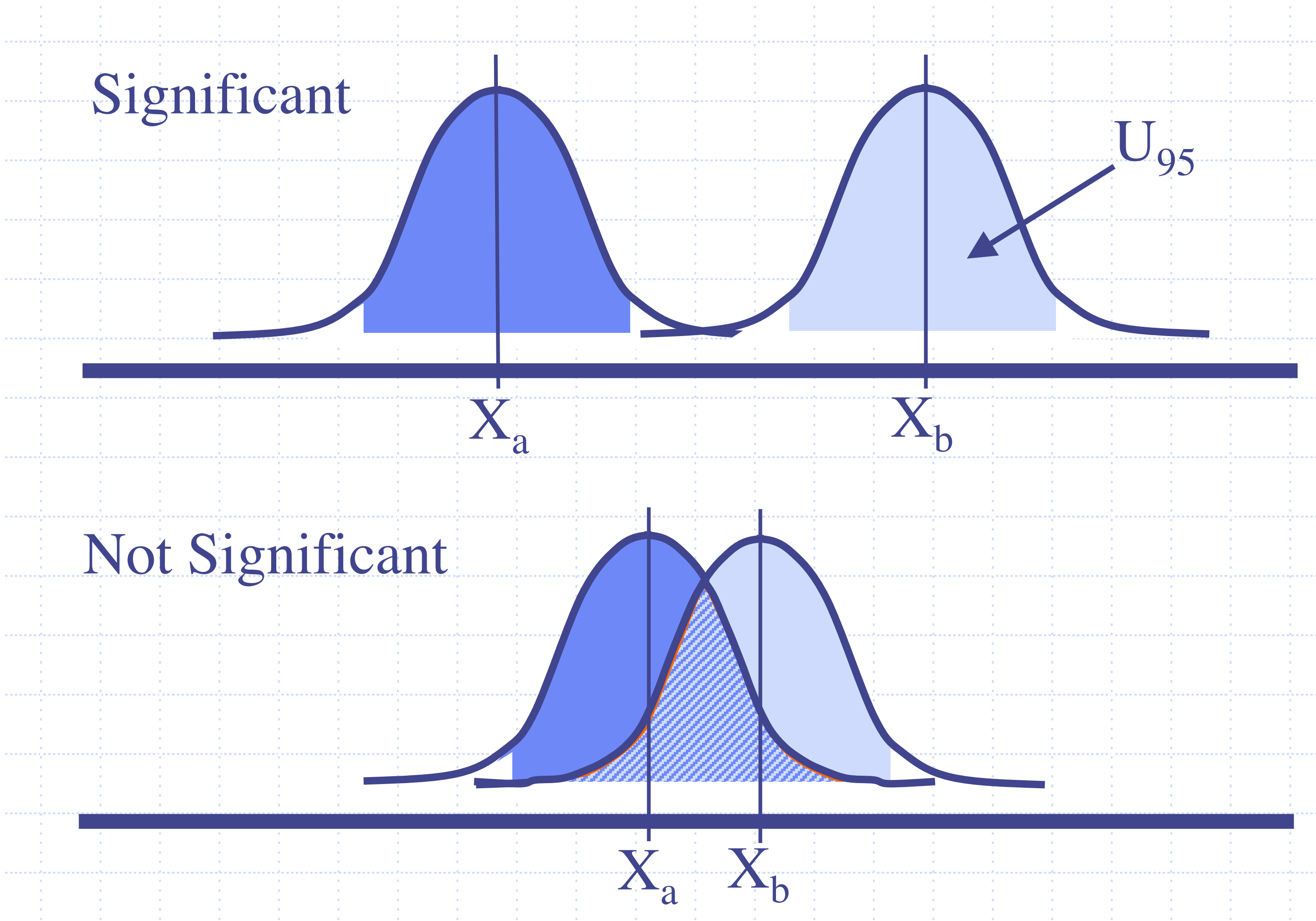
Uncertainty

Measurement = number + unit + uncertainty

the length of the truck is

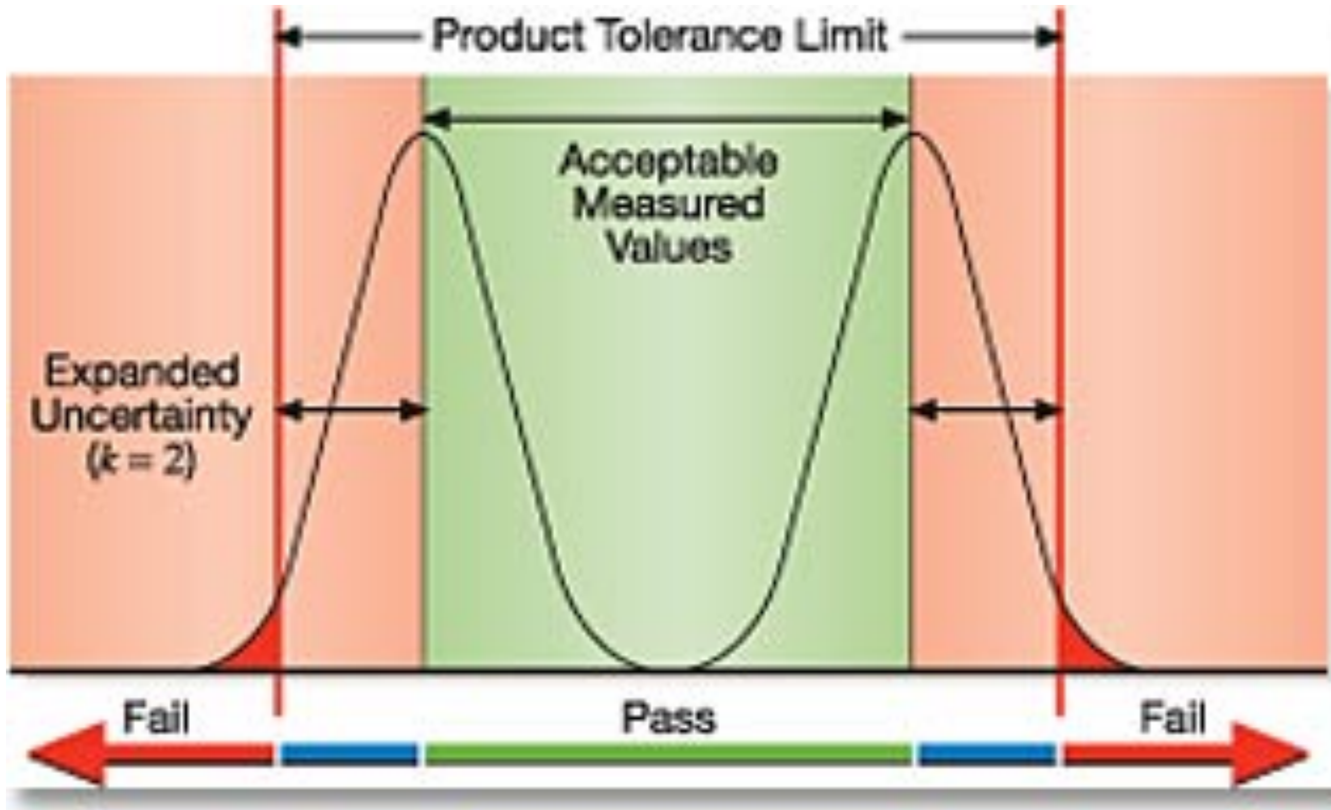
12,5 m ± 0,1 m with 95 % confidence

Significance of differences



From WMO — Instruments And Observing Methods Report No. 86

Conformity tests



Modelisation of a measurement

{One observed value}

=

(True value)

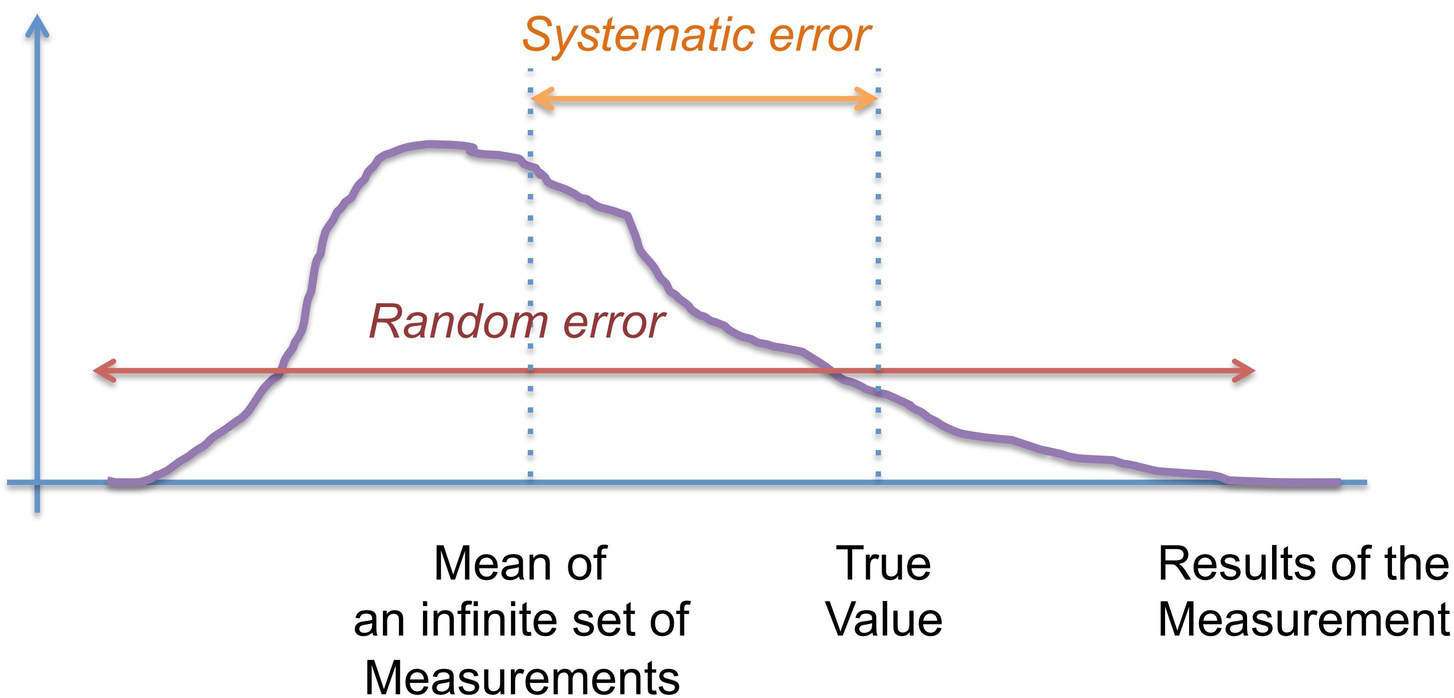
+

(systematic error)

+

(random error)

Modelisation of a measurement



Systematic error

If a **systematic error** arises from a **recognized** effect of an influence quantity on a measurement result,

the effect can be quantified and, if it is significant in size relative to the required accuracy of the measurement,

a **correction** or **a correction factor** can be applied to compensate for the effect.

It is assumed that, after correction, the expectation or expected value of the error arising from a systematic effect is zero.

Systematic error

- Examples:
  - *While measuring a resistance, the connection wires* => $R_{observerd} = R_{unknown} + R_{wires}$
  - *The thermal expansion of a ruler* => $L = L_0 + \alpha \bullet \Delta T$
  - *A systematic bias observed during calibration of the sensor*

Random error

Random error presumably arises from **unpredictable or stochastic temporal and spatial variations** of influence quantities.

The effects of such variations give rise to **variations in repeated observations of the measurand**.

Although it is not possible to compensate for the random error of a measurement result, **it can usually be reduced by increasing the number of observations**; its expectation or expected value is zero.

Uncertainty evaluation

- Systematic errors can be **reduced** with a **correction**

  => *but we only have an estimate of the correction*

- Random error can be **reduced** with a **large number** of observations

  => *effect of the size of the set on the estimate knowledge??*

Uncertainty evaluation

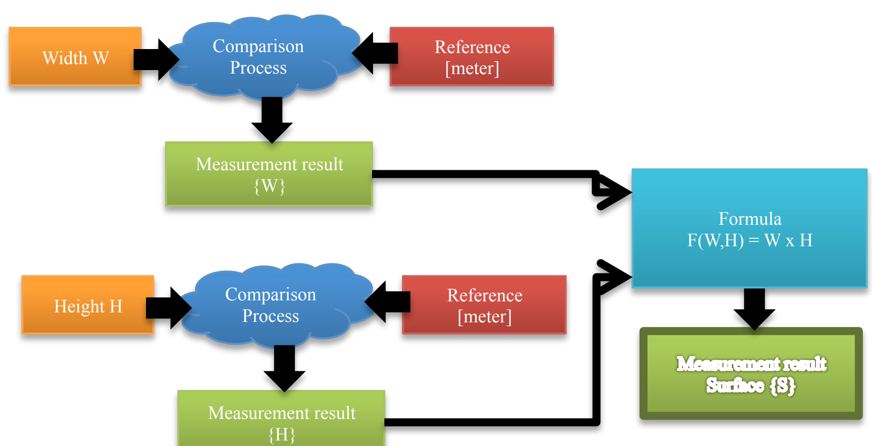
- Method:
  1. Describe the measurement: list all the influence quantities
  2. Determine each quantity
  3. Determine the uncertainty for each quantity
  4. Calculate the combined uncertainty
  5. Calculate the expanded uncertainty

Uncertainty evaluation

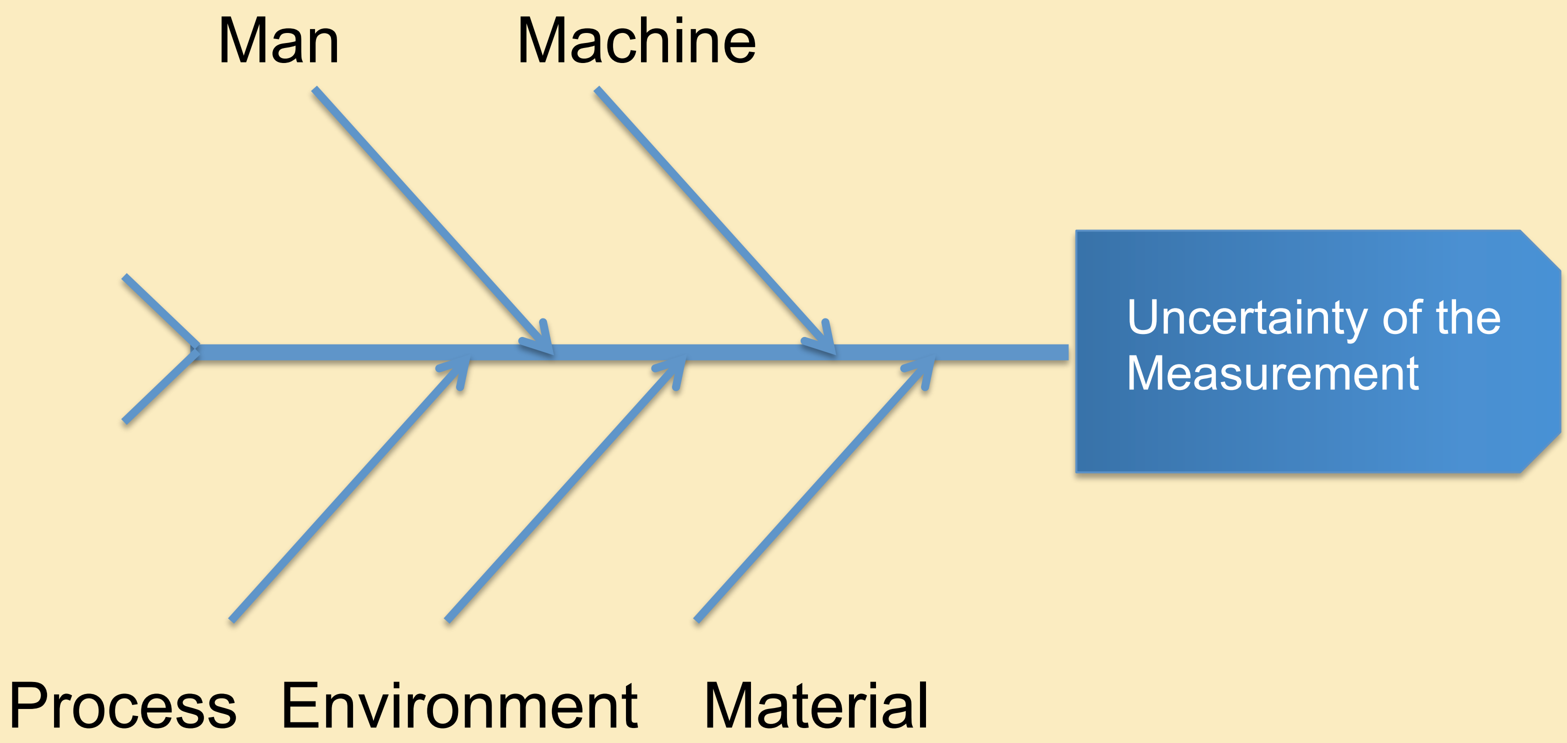
1. Describe the measurement

   Y is determined from N quantities Xi

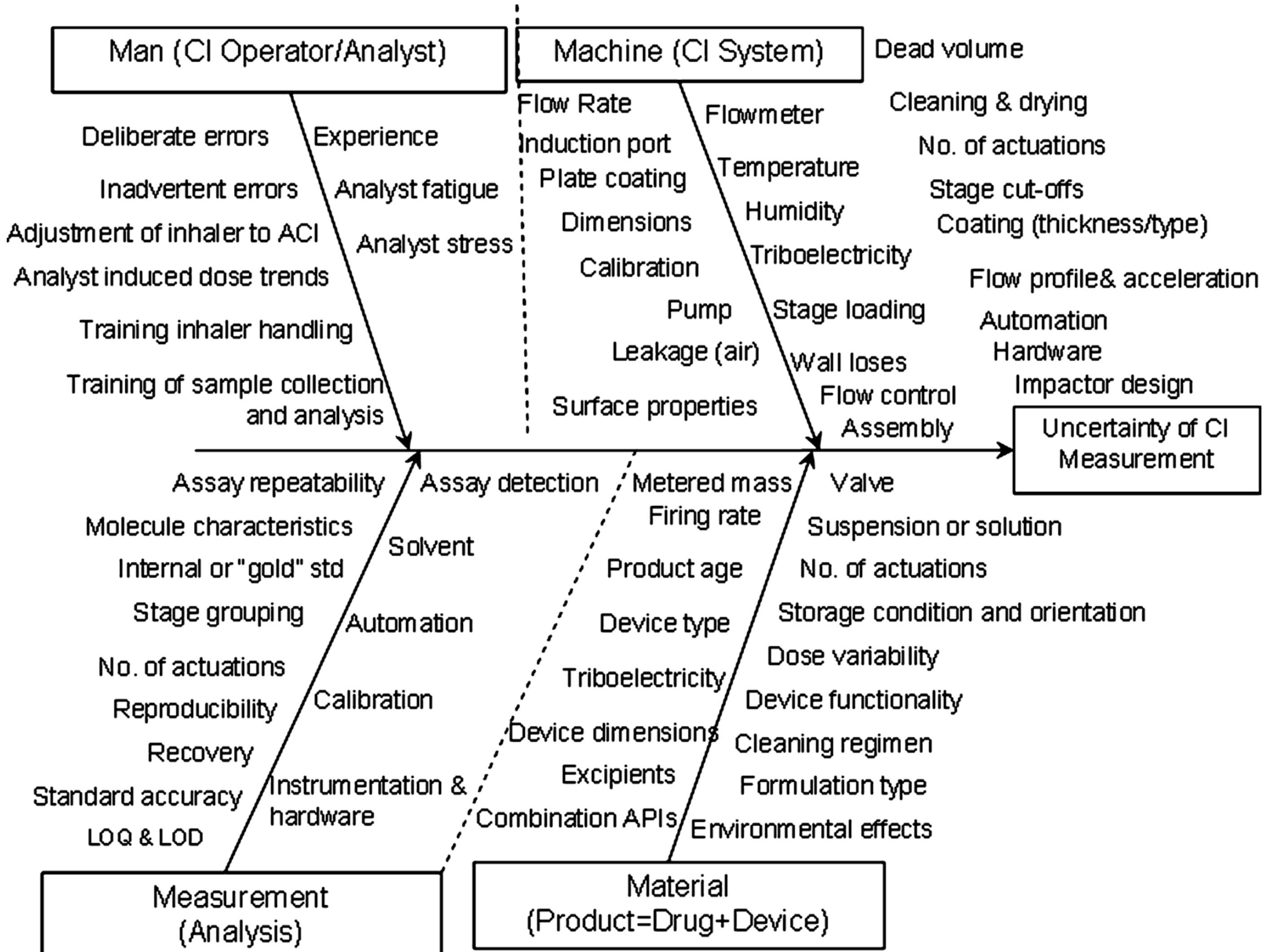
$$Y = f\left(X_1, X_2, \ldots, X_N\right)$$



5Ms — Ishikawa — Fishbone



5M — Ishikawa — Fishbone



Uncertainty evaluation

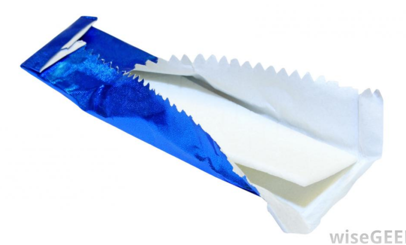
- Method:
  1. Describe the measurement: list all the influence quantities
  2. Determine each quantity
  3. Determine the uncertainty for each quantity
  4. Calculate the combined uncertainty
  5. Calculate the expanded uncertainty

Uncertainty evaluation

3. Determine the uncertainty for each quantity

=> 2 cases:

- Repeated observations => TYPE A
- Other evaluation => TYPE B



Uncertainty Type A

If we have *n* repeated observations:

⇒ The best *estimate* of the quantity is the **mean**

$$\bar{q} = \frac{1}{n}\sum_{k=1}^{n} q_k$$

⇒ The best *estimate* of the **uncertainty** is

$$u = s_{\mathrm{p}} \big/ \sqrt{n}$$ with $$s^2(q_k) = \frac{1}{n-1}\sum_{j=1}^{n}\left(q_j - \bar{q}\right)^2$$

Uncertainty Type B

If the quantity is not determined from repeated observations, the uncertainty is evaluated by **scientific judgement** based on **all of the available information** on the possible variability.

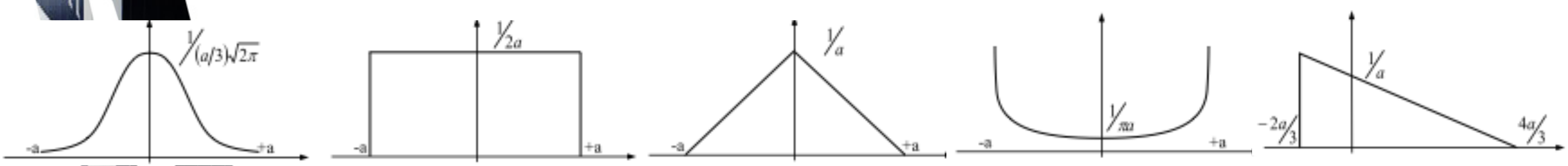
Examples:
- manufacturer's specifications
- data provided in calibration and other certificates
- uncertainties assigned to reference data taken from handbooks

Uncertainty Type B

⇒Use the existing knowledge

⇒Assume a distribution law of the variations

⇒Calculate the uncertainty

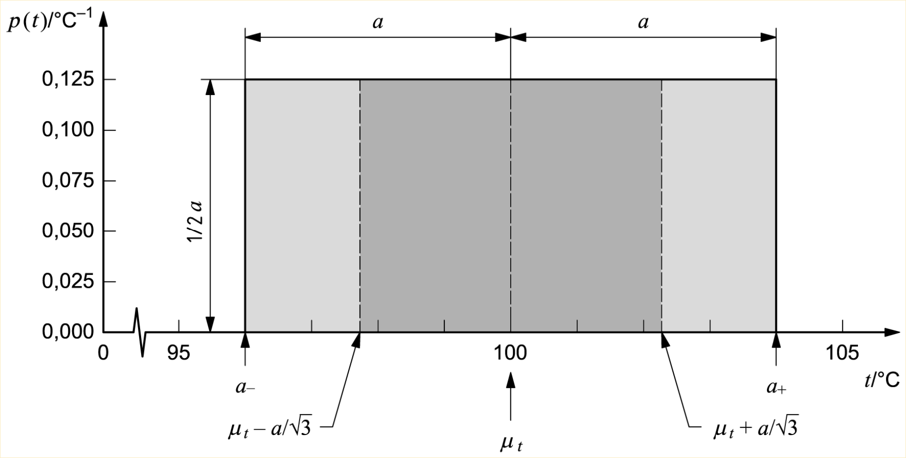


$\frac{a}{\sqrt{3}}$ $\frac{a}{\sqrt{6}}$ $\frac{a}{\sqrt{2}}$ $\frac{a}{\sqrt{4,5}}$

Uncertainty Type B

- For a numeric display ±a
- For a hysteresis ±a

$$u(\mu_t) = a/\sqrt{3}$$



Uncertainty evaluation

- Method:
  1. Describe the measurement: list all the influence quantities
  2. Determine each quantity
  3. Determine the uncertainty for each quantity
  4. Calculate the combined uncertainty
  5. Calculate the expanded uncertainty

Combined uncertainty

- We have the law $Y = f\left(X_1, X_2, ..., X_N\right)$
- We have the X_i and their uncertainties

$u = s_\mathrm{p} / \sqrt{n}$

$u(\mu_t) = a / \sqrt{3}$

=> The combined uncertainty is (uncorrelated quantities)

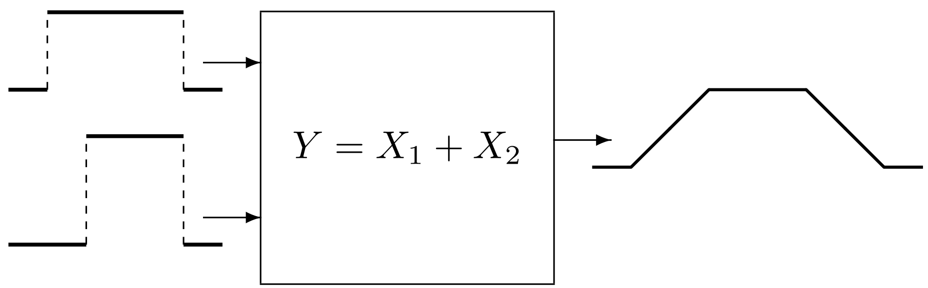
$$u_\mathrm{c}^2(y) = \sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i} \right)^2 u^2(x_i)$$

The partial derivatives $\partial f / \partial x_i$ are equal to $\partial f / \partial X_i$ evaluated at $X_i = x_i$

Combined uncertainties

- Example:

    additive measurement of 2 quantities with equi-probable distributions



Combined uncertainties

$$u_{\mathrm{c}}^{2}(y) = \sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i} \right)^{2} u^{2}(x_i)$$

Sensitivity coefficients

Absolute uncertainty
NOT relative values

Uncertainty evaluation

- Method:
  1. Describe the measurement: list all the influence quantities
  2. Determine each quantity
  3. Determine the uncertainty for each quantity
  4. Calculate the combined uncertainty
  5. Calculate the expanded uncertainty

Expanded uncertainty

- u(Xi) describes the uncertainty
- But we would like to say: *the length is 12,5 m ± 0,1 m with 95 % confidence*

=> Expanded uncertainty ***U***

=> Coverage factor ***k***

$$U = k u_{\mathrm{c}}(y)$$

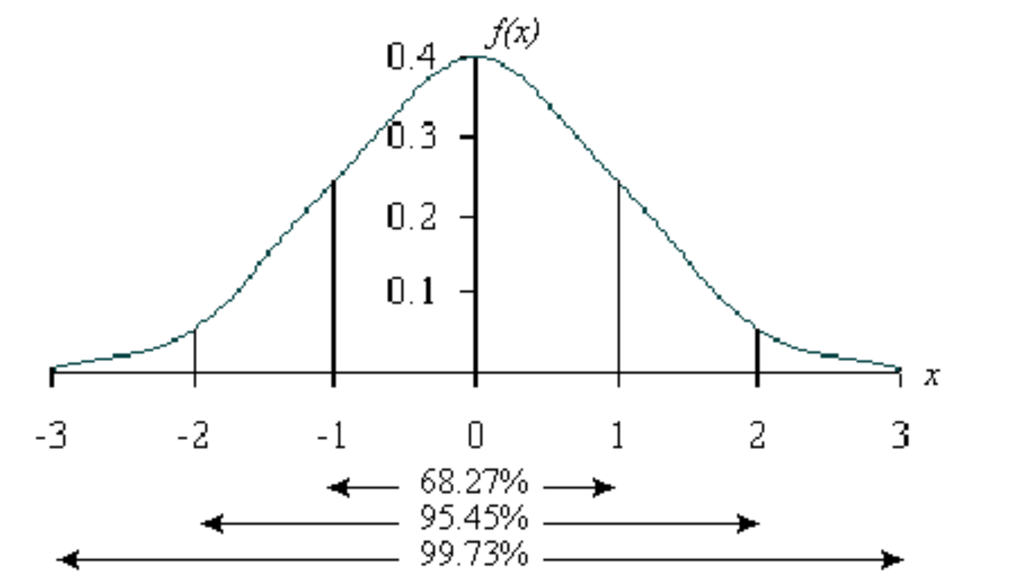
Expanded uncertainty

- Assuming a few things (normal distributions…)

  => For 95% confidence ***k* = 2**

  => For 99% confidence ***k* = 3**

$$U = k u_{\mathrm{c}}(y)$$



Assumptions

- Normal distributions
- Large number of observations
- No correlations between quantities

Measurement techniques

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Instrument properties

- Measurement range
- Linearity — *accuracy of response within range*
- Stability — *short and long term drift*
- Response time
- Accuracy
- Precision
- Hysteresis
- Quantization — *signal and sampling rate*
- Cost — *money, time, complexity*
- …

Measurement range

- How wide is the possible measurement range?
- Examples:
  - Size of a ruler
  - Starting and destruction speed of an anemometer
  - Freezing and boiling points of a thermometer

Linearity

- How many corrections to apply along the measuring range?

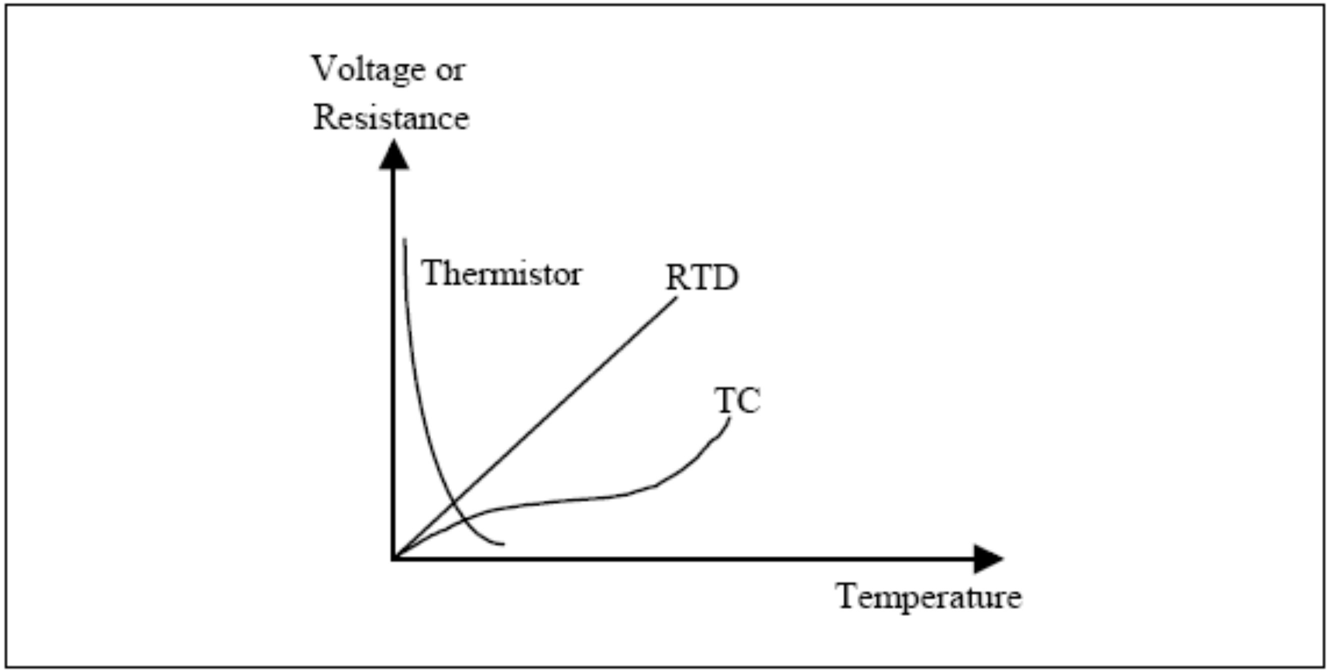


Figure 7-19. Comparison of TC, RTD, and thermistor

Stability

- How much drift of the measurement evaluation:
  - short term
  - long term
  - Example for a temperature measurement by thermocouple:
    - Short term drift: thermal sensitivity of the ADC
    - Long term drift: chemical alteration of the TC

Repeatibility and Reproducibility

Repeatability

Variability on an occasion

With-in run precision

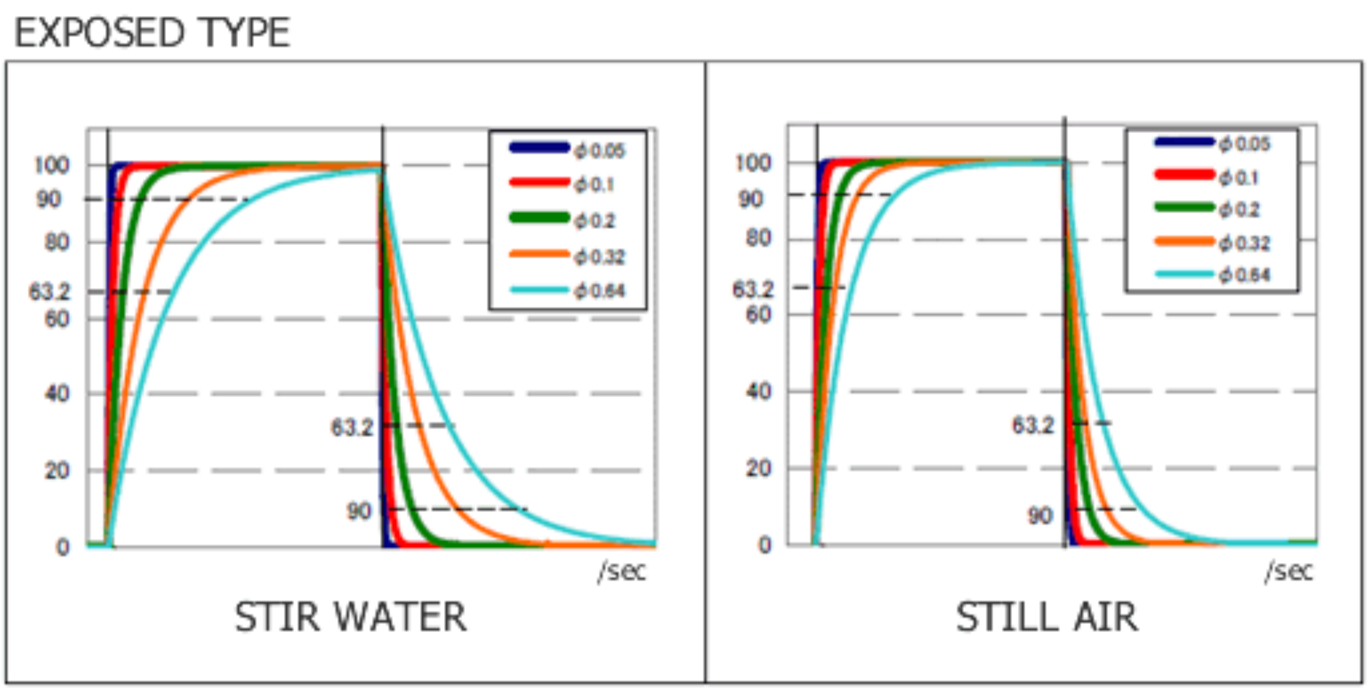
Reproducibility

Variability on different occasions

Between-run precision

Response time

- How fast the output signal changes?



Thermocouples: Speed vs Diameter

Accuracy and Precision

Accuracy (Justesse)

The closeness of the experimental mean value to the true value.

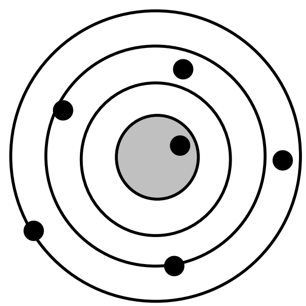
High accuracy = Small systematic error.

Precision (Fidélité)

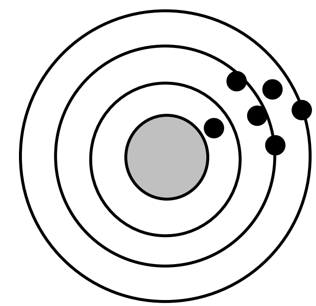
The degree of scatter in the results.

High precision = Small random error.

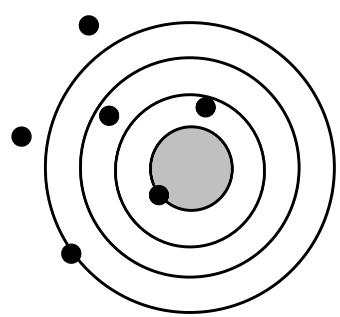
Accuracy and Precision



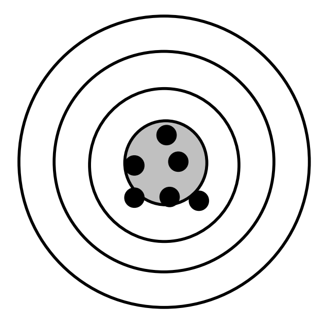
ACCURATE



PRECISE



whatever…

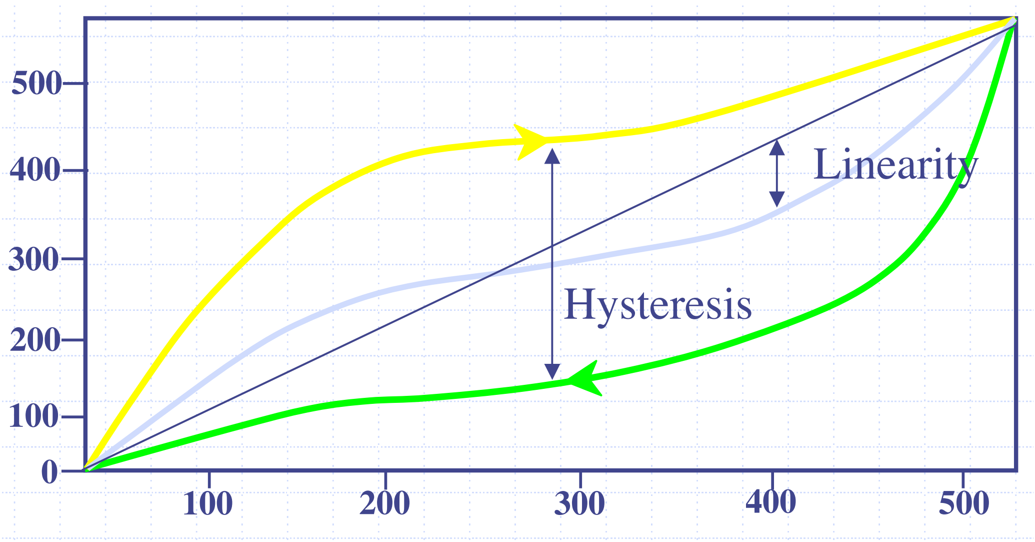


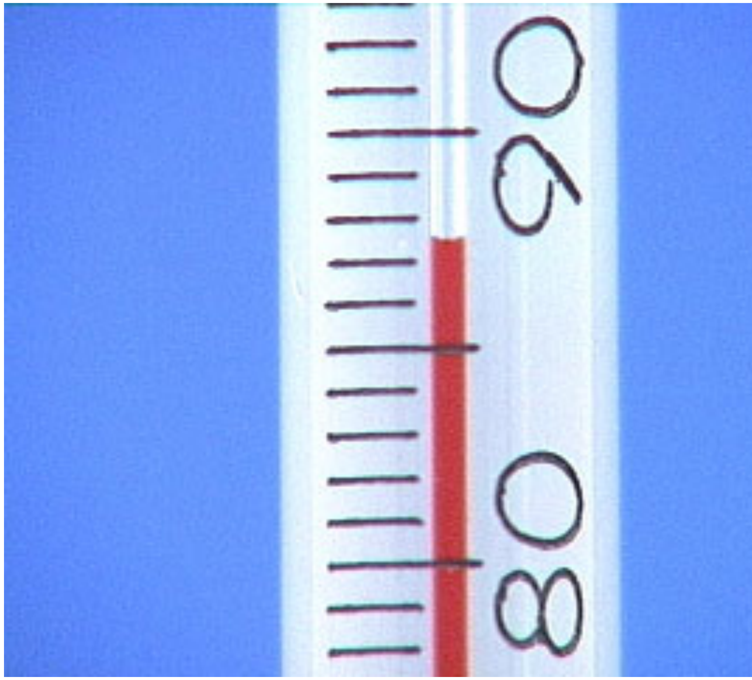
ACCURATE and PRECISE

Hysteresis

- Does the output depends on past environment?

Ex: Meniscus

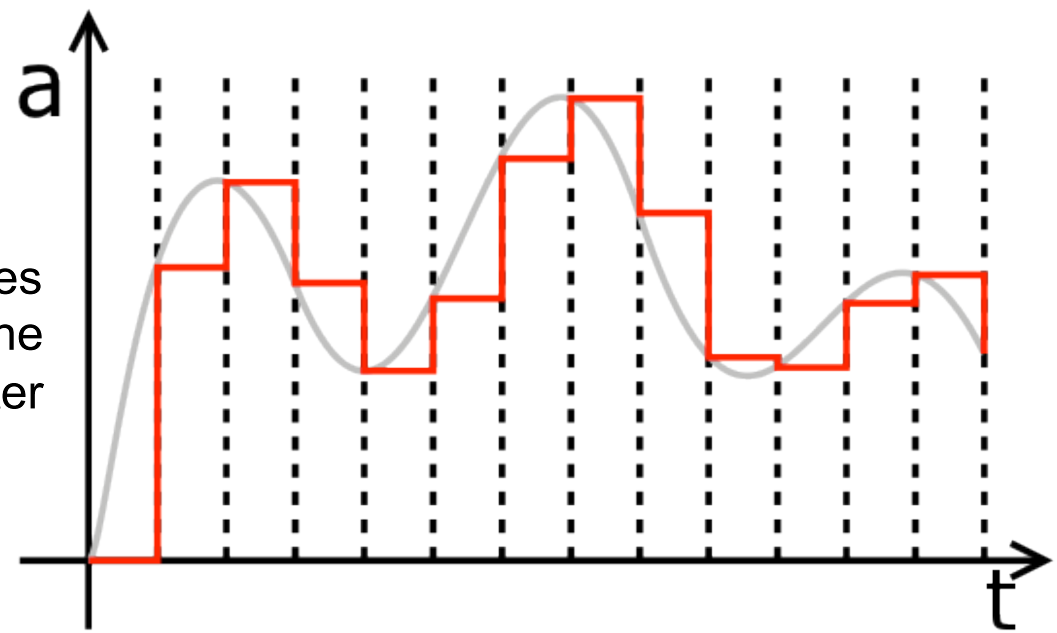




Quantization

- Quantity of steps between the analog signal and the numeric value:
  - Signal output
  - Sampling rate

Eg: 16 bits = 65536 values for the Full Scale of the converter

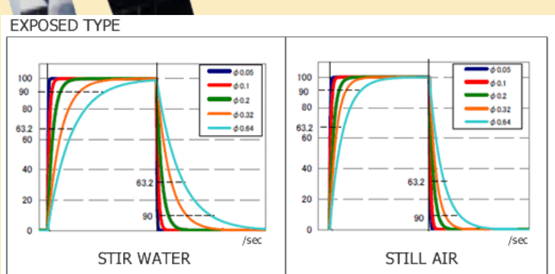


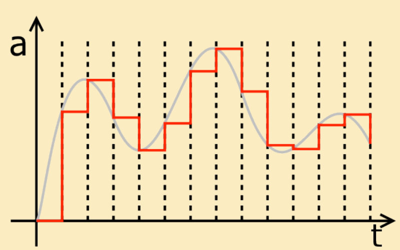
Eg: 1 ksps = 1000 values per seconds

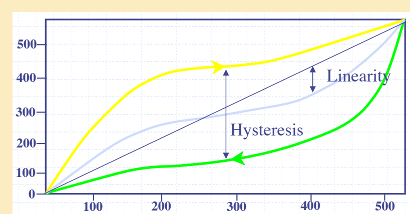
Instrument properties

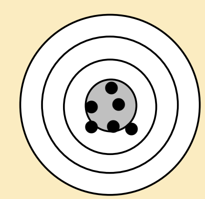
- Measurement range
- Linearity
- Hysteresis
- Stability
- Response time
- Quantization

- Accuracy
- Precision
- Repeatability
- Reproductibility
- Cost €€€-time
- …

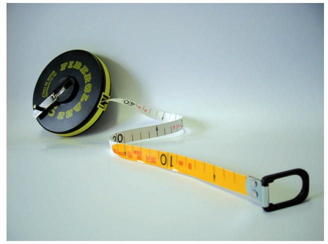






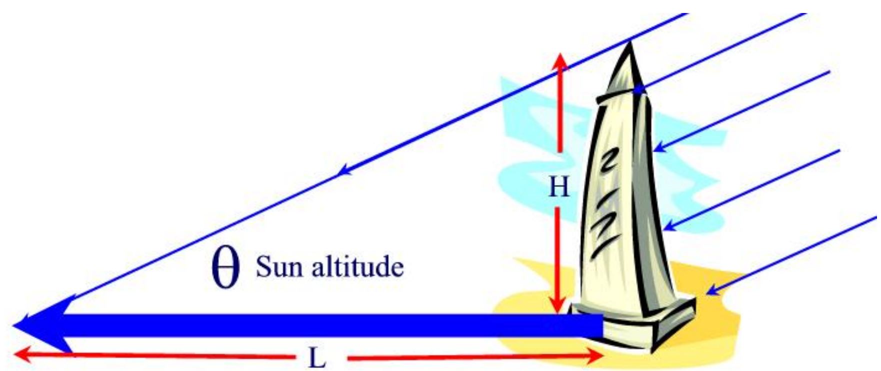


Choice of the instrument



width

***Width* of a rectangle**



Instrument properties

There are no perfect sensor which has the perfect properties for all the measurements needs.

⇒Need to adapt the technology and setup of the sensor to the actual requirement of measurement performance: “the size of the uncertainty”

⇒**In order to save time and €€€**

⇒**In order to be realistic with the environment**

Instrument properties

There are no perfect sensor which has the perfect properties for all the measurements needs.

⇒**A wished performance may be unreachable with the provided resources and the current state of the art of the Metrology**

⇒*Eg: measuring the irradiated surface temperature of a tower solar receiver at ±1 K @ 95% uncertainty: next to impossible in real field, at least for now… no ?*

Summary

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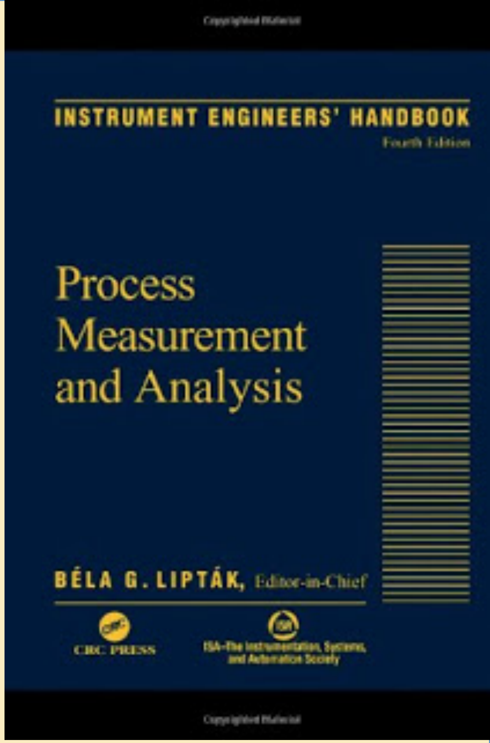
Measuring
is
Comparing

The Truth
is
Out there

Reference books about measurement techniques

- Béla G. Liptak
  CRC Press
  4th edition: 2005
  ISBN13: 978-084-931-0812



- Georges Asch
  Éditions DUNOD
  7th edition: 2010
  ISBN13: 978-210-054-9955

THE reference guide for uncertainties, terms

Bureau International des Poids et Mesures

http://www.bipm.org


BIPM

JCGM 104:2009

Evaluation of measurement data — An introduction to the "Guide to the expression of uncertainty in measurement" and related documents

Évaluation des données de mesure — Une introduction au "Guide pour l'expression de l'incertitude de mesure" et aux documents qui le concernent

ΜΕΤΡΩ ΧΡΩ

http://www.bipm.org/en/publications/guides/gum.html

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