

# Measurements for industrial sustainability and safety

## PART I Lesson 2

A.Y. 2026-27  
Ludovica Apa



$$\frac{A}{U} = a$$

- The property **A** is called: «**measurand**», the reference property **U** is the «**measurement unit**»
- the ratio between **A** and **U** today is *always* performed by a calibrated instrument !
- the measurement **a** expresses the amplitude or intensity of the property **A** we are studying

*Direct* measurements: when there is a direct comparison between the **measurand A** and the **unit U**

*Indirect* measurements: when a physical law is applied to measure quantities other than the one we are interested in:

i.e. measuring a velocity  $v = x/t$  by measuring a distance  $x$  and time  $t$

Measurements with **calibrated instruments**: by far the majority of the measurements performed today. **The instrument has the unit U memorized inside ...**

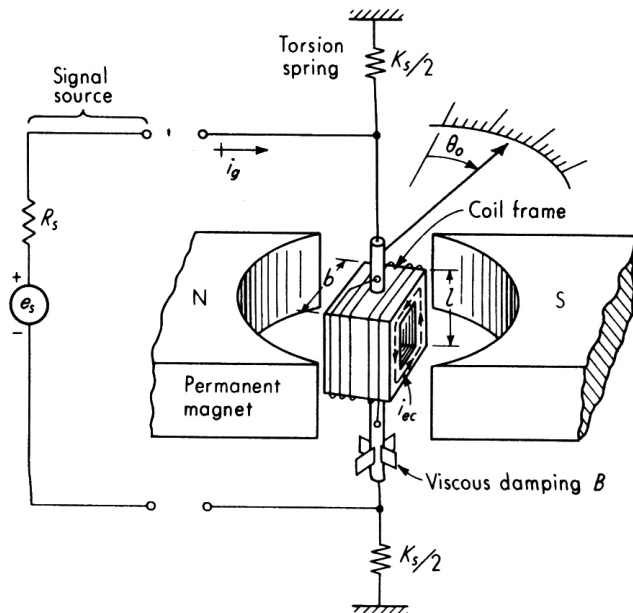
*Direct* instruments : (they do not transform the physical quantity - only very few)

*Indirect* instruments : they always transform the physical quantity they acquire in input ...

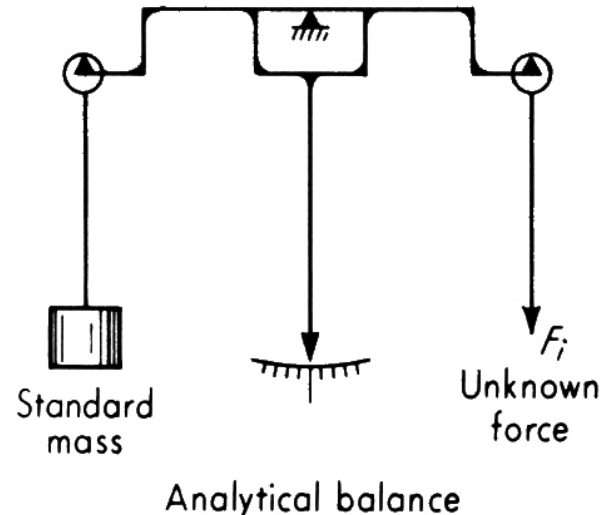
Analog instruments

Digital instruments

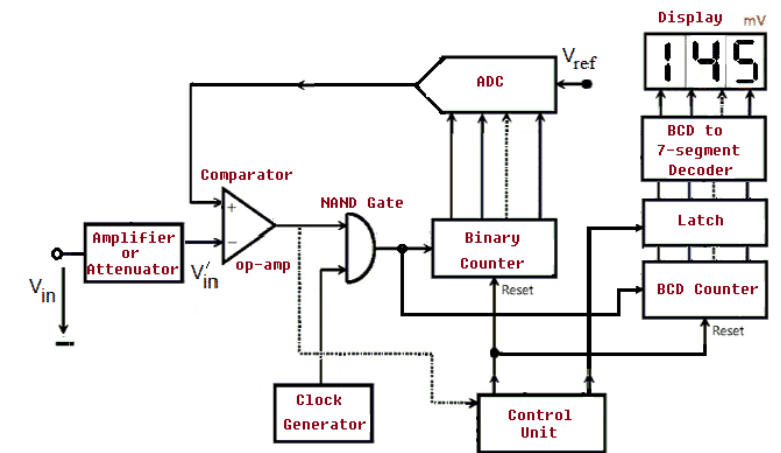
Deflection instruments



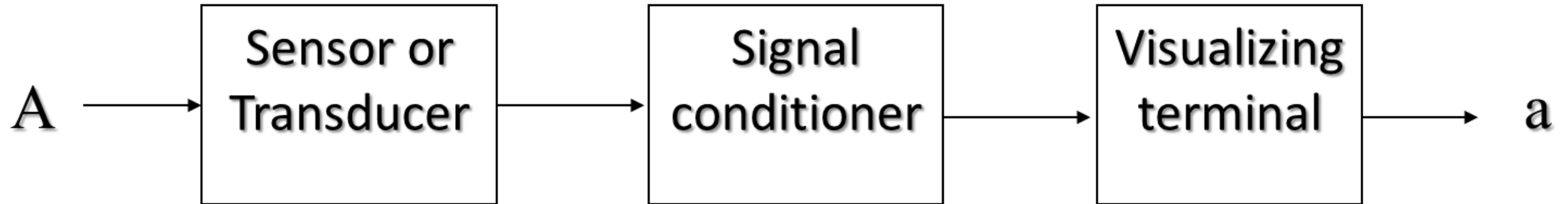
Null-out instruments



Recording instruments



# Basic MEASUREMENT CHAIN:



| Measurement chain component | Definition                                                                                                                                   |
|-----------------------------|----------------------------------------------------------------------------------------------------------------------------------------------|
| $A$                         | Physical quantity to be measured                                                                                                             |
| Sensor or transducer        | Devices capable of detecting the physical quantities to be monitored are called sensors / transducers.                                       |
| Signal conditioner          | Devices that processe the sensor's signal by amplifying, filtering, or converting it to ensure accurate and compatible data for further use. |
| Visualizing terminal        | A display or interface that presents the processed measurement data in a readable format for analysis or monitoring.                         |
| $a$                         | Measurement of the physical quantity $A$ (raw...)                                                                                            |

# Devices detecting physical quantities: sensors and transducers

Are "sensor" and "transducer" the same? They seem similar, but they serve different functions.

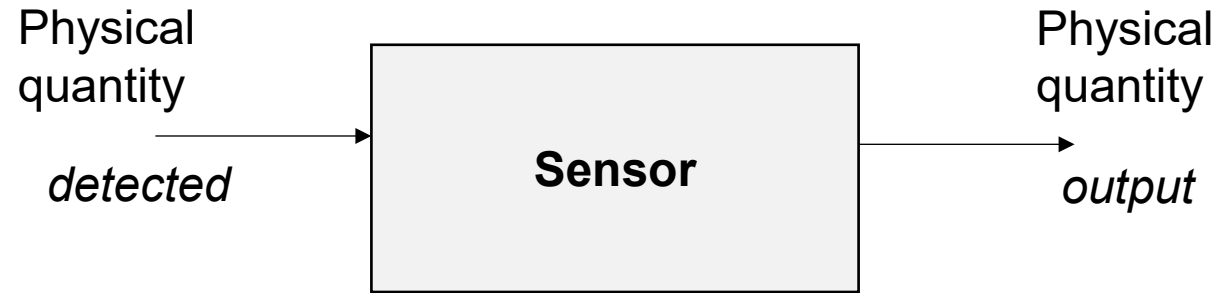
## Sensor

The sensor is a device capable of detecting changes in a physical quantity.

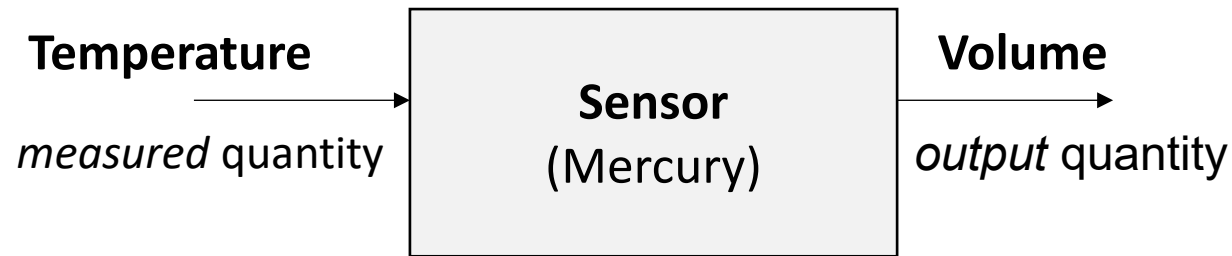
## Transducer

The transducer is a device that converts a physical quantity into an electrical quantity.

# Sensor: block diagram and example



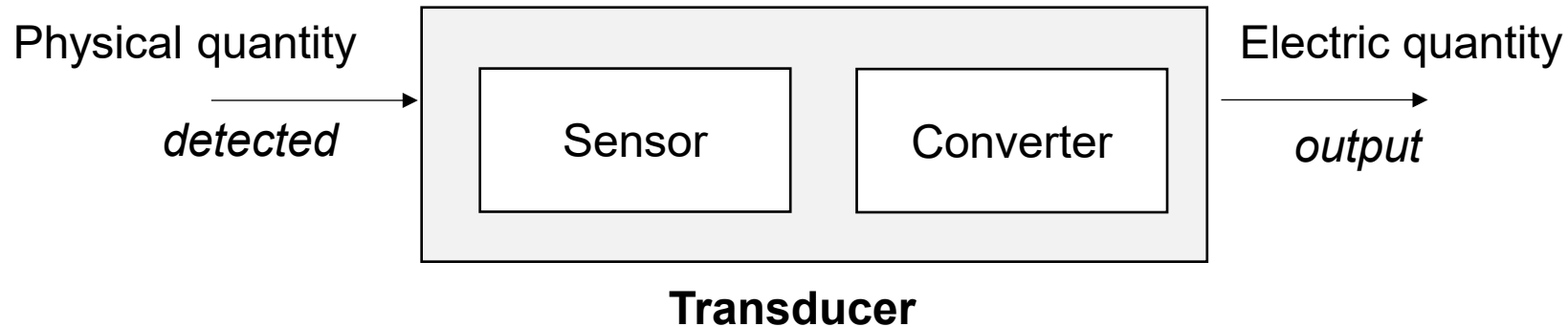
## Example



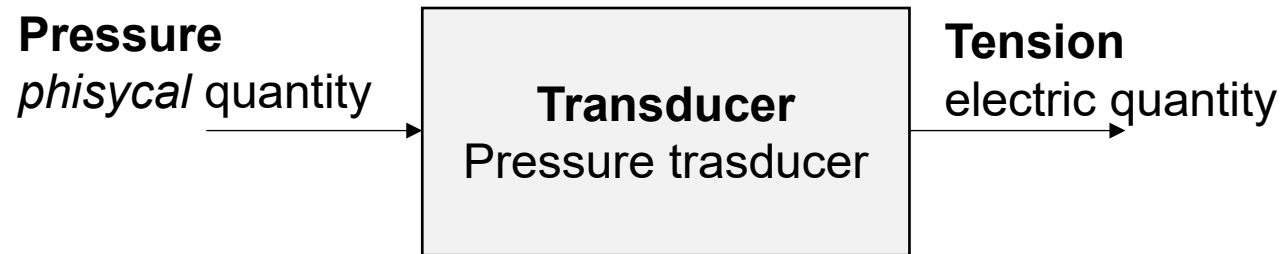
!!: mercury in thermometers is a sensor because a temperature change causes a proportional volume change.

# Transducer: block diagram and example

A transducer is composed of **two parts**: a sensor and a signal conditioner



## Example



!!:es. A pressure transducer converts the pressure in an electric signal: the pressure is «sensed» by the physical deformation of the strain gauges connected to the sensor inner membrane – the output of the Wheatstone bridge returns the transduced electric quantity (V)

# Sensor and Transducer

| Sensor                                                                        | Transducer                                                                                                       |
|-------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------|
| A sensor detects a change in a physical environment.                          | A transducer converts one form of energy into another.                                                           |
| A sensor is not necessarily a transducer.                                     | Every transducer includes a sensor as a component.                                                               |
| A sensor is a standalone component.                                           | Electrical transducers consist of a sensor and a signal emission circuit.                                        |
| A sensor converts physical quantities or energy into non-electrical signals.  | A transducer converts physical quantities or energy into an electrical signal.                                   |
| The output of a sensor cannot be directly applied to another system.          | The output of a transducer can be directly connected to another system.                                          |
| A sensor is a simple device.                                                  | A transducer has a complex electrical circuit used for energy conversion.                                        |
| Examples: thermometer, pressure sensor, ultrasonic sensor, light sensor, etc. | Examples: pressure transducer, thermistor, potentiometer, piezoelectric transducer, Hall effect transducer, etc. |

**First question to be answered: WHAT do we want to measure and WHY ?**

**It's a "KNOWLEDGE PATH" that leads to new *quantitative* INFORMATION about the world surrounding us !**

- want we to have an approximate control of a physical quantity ?
- want we to do a rigorous scientific measurement ?
- want we to use the value of the measure for an automatic control ?
- want we to know to what extent can a physical parameter vary to set an alarm signal ?



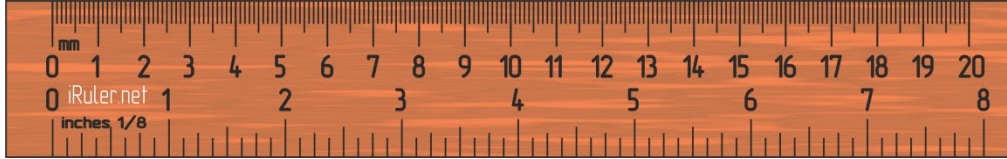
**Quality of the measurement**

Eg.

## Length and displacement measurement

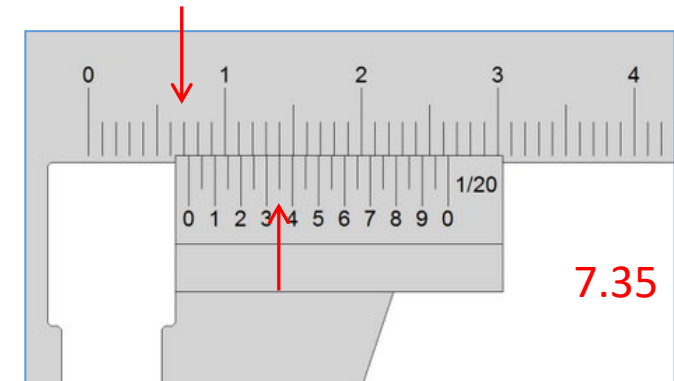
Many instruments are available to measure length and displacement in modern technology ...

The most ancient is the *graduated ruler*:



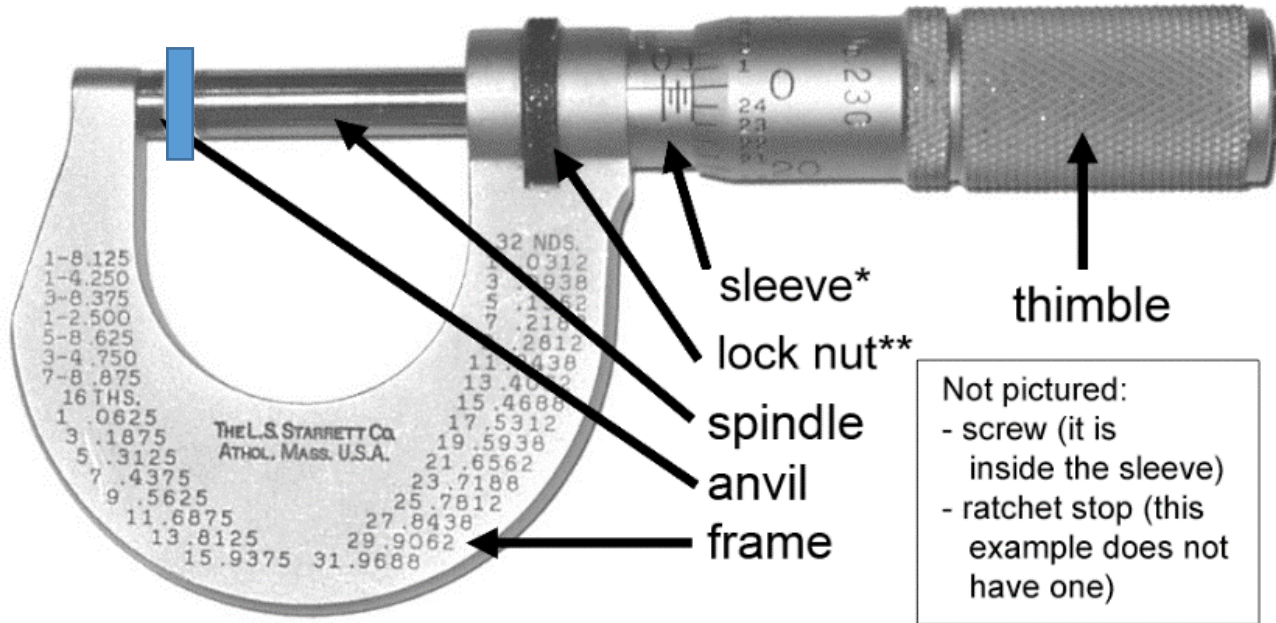
**Rulers** have an approximation of 1 mm,

**Vernier Calipers** have an approximation of 0,05 mm (1/20 caliper) or 0.1 (1/10 caliper), over an average range of 200 mm !



Eg.

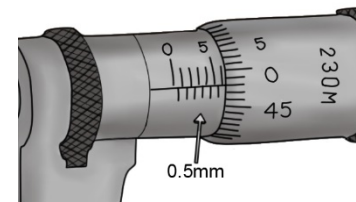
**Micrometer (Palmer):** it is based on a “micrometric screw” with a *pitch* of 0.5 mm (*sleeve*). It has an approximation of 0,01 mm



\*Sleeve is the most prevalent name. May also be called the *barrel* or *stock*.

\*\*Aka *lock-ring*. Some mics have a *lock lever* instead.

There are 50 notches on the rotating screw (*thimble*), therefore for every notch the screw advances:

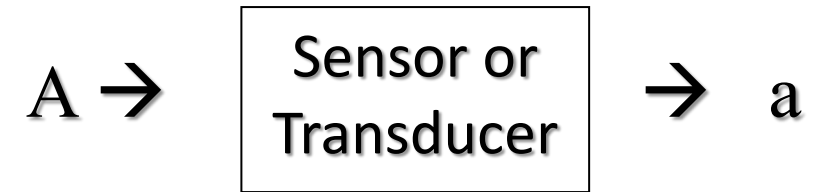


$$\frac{1}{2} \cdot \frac{1}{50} = \frac{1}{100} \text{ mm,}$$

which is also the approximation of the instrument !

Of course the range is limited by the instrument screw opening ...

First question to be answered: WHAT do we want to measure and WHY ?



1. we choose the instrument according to the “extension range” of the physical quantity to be measured, based on the *amount of variation* that is expected for the quantity and also on *how fast* the quantity changes its value during the measurement;
2. we read the numeric data on the output device of the instrument;
3. by means of the *graduation of the instrument* we associate the numeric data  $a$  with the  $U$  units, performing actually the real measurement:  $A = a \times U$
4. at this point we still only have a *raw measurement* of the physical quantity  $A$ . We have to identify the *many uncertainties*  $\epsilon$  associated with the raw data, correct the data we obtained and then switch to the final measurement:  $A = (a \pm \epsilon) \times U$
5. with the diffusion of digital instrumentation is now possible to acquire many repeated measurements of a physical quantity  $a_1 a_2 \dots a_n$ . This raises the question of identifying the *true magnitude* of the value. We have to go through a statistical analysis of the data ...

# We have to establish the QUALITY of a measurement

*High quality measurements* means being able to get *data with low uncertainty*; most of the times, this is also an *expensive procedure* !

To quantify the quality of a measurement we have to quantify first the quality of the instrument !

To this extent we can define 5 general metrological characteristics that apply to every measuring instrument or measuring system and completely describe its performances !

- Measurement Span
- Sensitivity
- Stiffness
- Accuracy
- Measurement Rapidity (Dynamic Response)

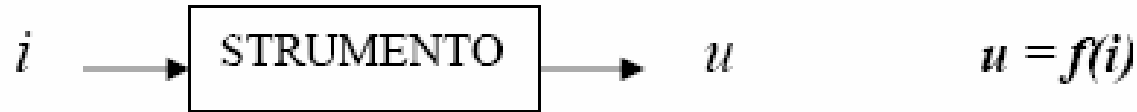
- **MEASUREMENT SPAN**

The *measuring span* is the numerical *range* between the minimum and maximum values of the “measurand” the instrument can appropriately measure and within which the other four instrument characteristics are valid !

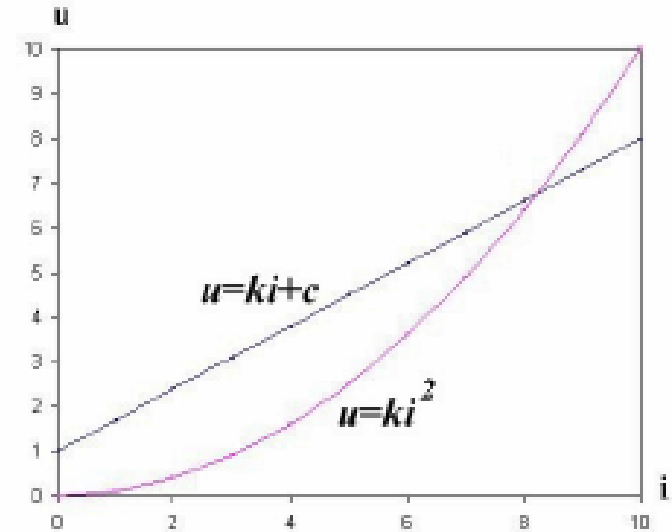
***Span = high operation limit – low operation limit***

..... overload

**Graduation curve :**



The operation of every instrument is based on a *physical law*, this law is described by an equation; the same equation is also *the equation representative of the graduation curve* !



if this equation is of 1st degree, the instrument is said *linear instrument* !

if this equation is of 2nd degree, the instrument is said *quadratic instrument* !

## Example: find the *graduation curve* of the Hg thermometer

the fundamental physical law (starting point) is the law of *volumetric thermal expansion* of all materials (fluids):

$$V = V_0(1 + \alpha \cdot \Delta T)$$

$$V - V_0 = \alpha \cdot V_0 \Delta T \quad \frac{\Delta V}{V_0} = \alpha \cdot \Delta T$$

$$\text{with } \Delta V = S \cdot \Delta h \quad \frac{S \cdot \Delta h}{V_0} = \alpha \cdot \Delta T$$

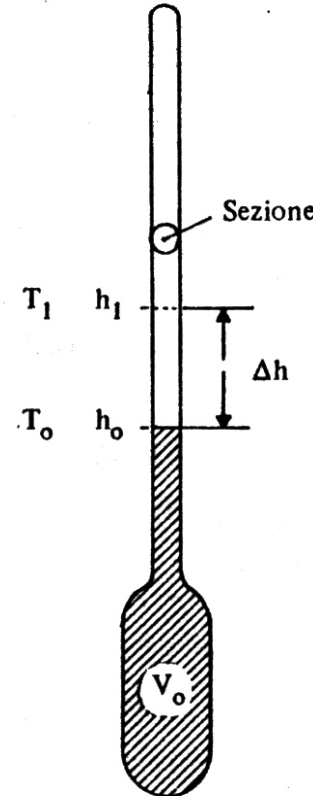
$$\Delta h = \frac{\alpha \cdot V_0}{S} \Delta T$$

output                      input (measurand)

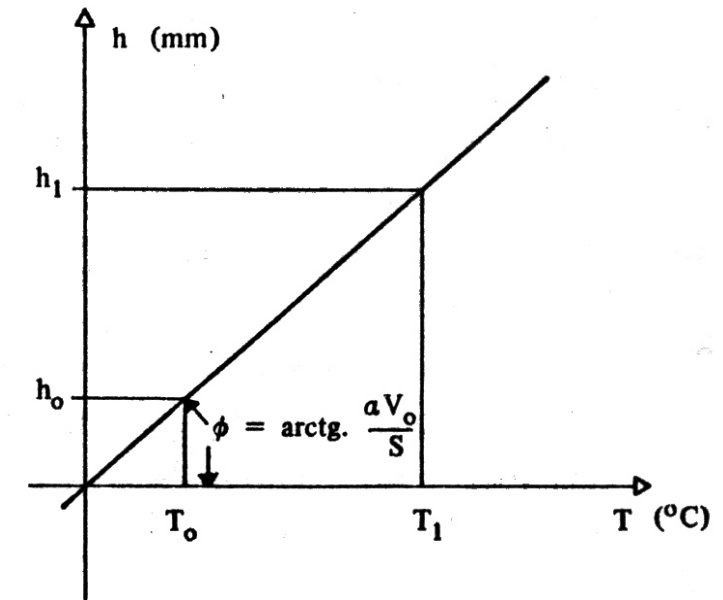
That's the *graduation curve* !

*Span ?*

*[-38 °C / +365 °C; ...]*



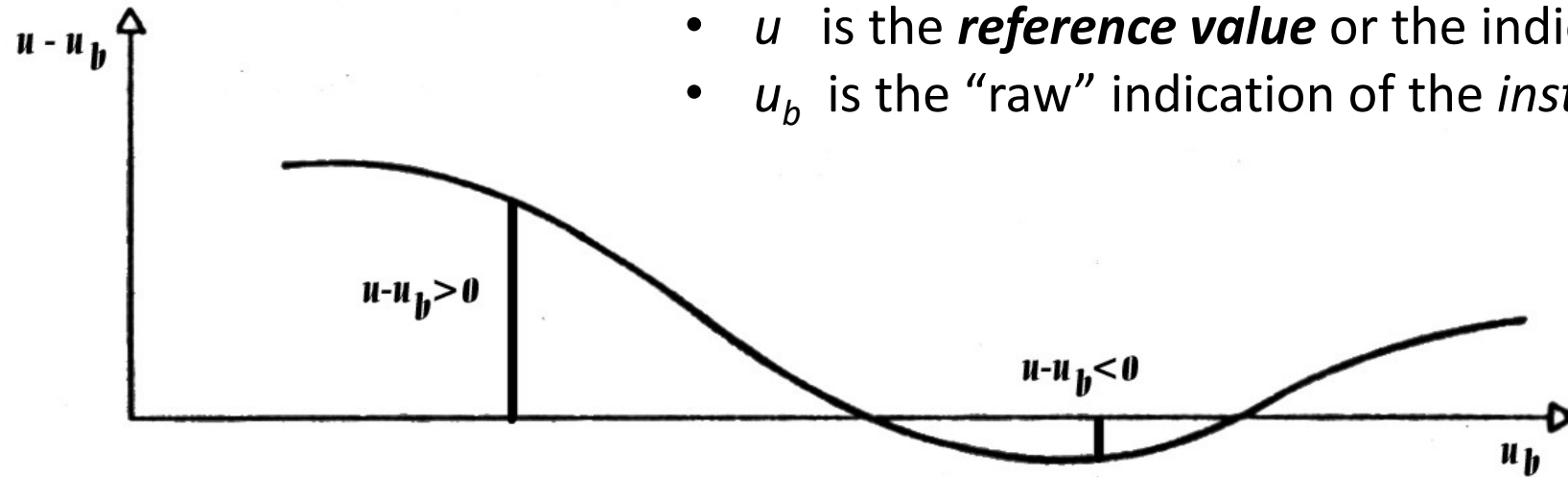
$$\Delta V = S \Delta h$$



$$\Delta h = \frac{\alpha V_0}{S} \Delta T$$

**Graduation curve** should NOT be confused with the **CALIBRATION** (*taratura*) **curve** :

- $u$  is the **reference value** or the indication of a **reference instrument**
- $u_b$  is the “raw” indication of the *instrument under calibration*



$u - u_b = f(u_b)$  is the **calibration curve**: the curve of the *differences* between the *reference value*  $u$  and the *raw instrument indication*  $u_b$ , for every instrument output  $u_b$ .

if  $u - u_b < 0$  magnitude  $\longrightarrow$   $u < u_b$  the instrument under calibration “overestimates” the measurand (input) so we have to **subtract** the indicated deviation from  $u_b$ .

if  $u - u_b > 0$  magnitude  $\longrightarrow$   $u > u_b$  the instrument under calibration “underestimates” the measurand (input) so we have to **add** the indicated deviation to  $u_b$ .

- **SENSITIVITY**

Capability of the instrument to «sense» *small variations* of the input variable (the measurand)



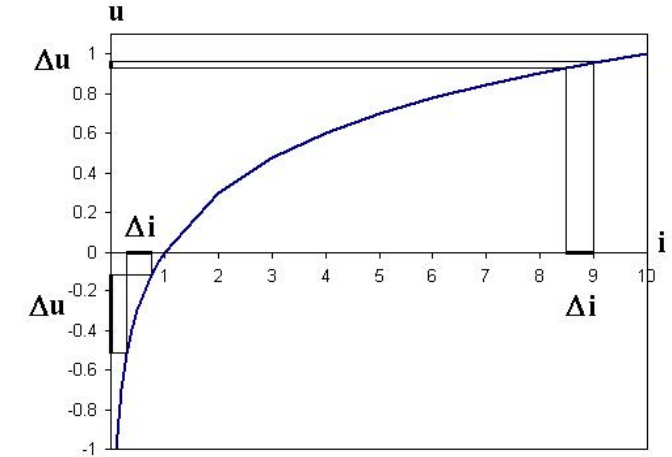
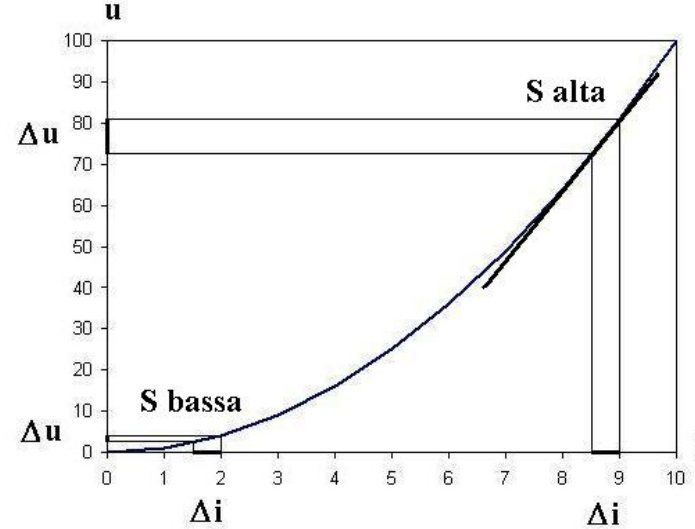
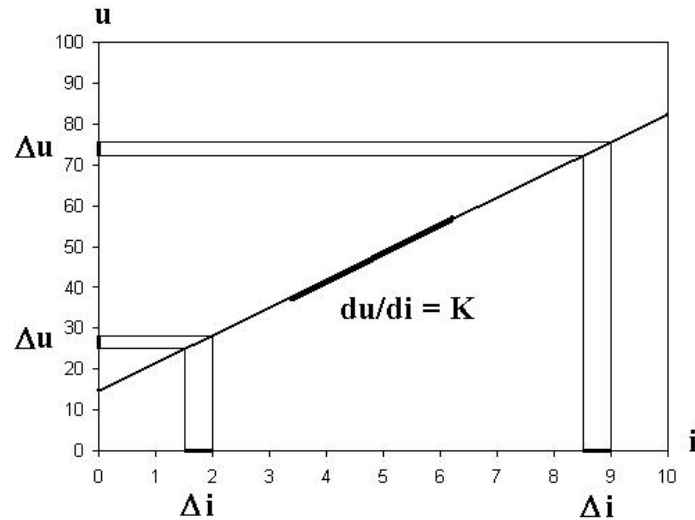
*how small* can a variation  $\Delta i$  of the input be, to get from the instrument an *appreciable* output  $\Delta u$  ?

We can certainly write  $\frac{\Delta u}{\Delta i}$  that, for variations  $\Delta i \rightarrow 0$  means  $\frac{du}{di}$  , or better  $\lim_{\Delta i \rightarrow 0} \frac{\Delta u}{\Delta i} = \frac{du}{di} = S$

It is immediately observed that, if  $u = f(i)$  is the *graduation curve*, the **sensitivity**  $S = \frac{du}{di}$  is the **derivative of the graduation curve** !

The sensitivity  $S$  can be calculated for *every point* of the *graduation curve*, by means of the differential ratio:  $\frac{du}{di}$

# Examples:



geometric meaning: it's the *slope of the tangent* to the graduation curve in the measuring point that is being considered.

Instruments with a *constant sensitivity* are called **linear instruments** !

$$u = ki + c \rightarrow S = \frac{du}{di} = K$$

Instruments with a *sensitivity that is a function of  $i$*  can be **quadratic instruments** !

$$u = ki^2 \rightarrow S = \frac{du}{di} = 2ki$$

Instruments with a *sensitivity that is a function of  $i$*  can be **logarithmic instruments** !

$$u = k \log i \rightarrow S = \frac{du}{di} = \frac{k}{i}$$

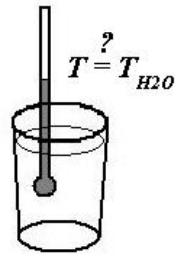
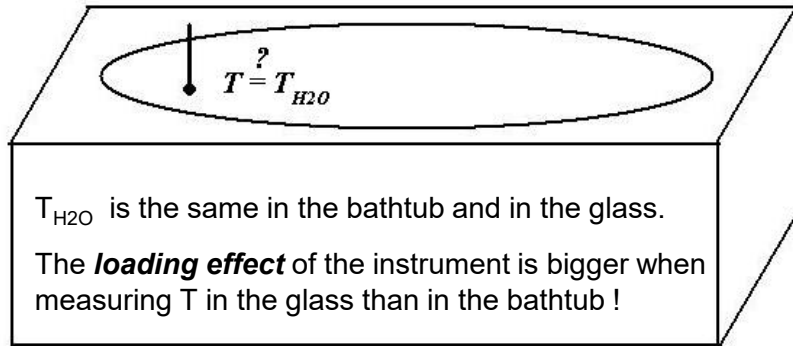
Do not confuse the *sensitivity* with the **resolution** of an instrument, which actually is a more appropriate concept for **digital instruments** !

## • STIFFNESS

The introduction of any *measuring instrument* into a *measured medium* always results in the extraction of some energy from the medium, thereby changing the value of the measured quantity from its undisturbed state !

This circumstance makes a perfect measurement theoretically impossible !

Example:



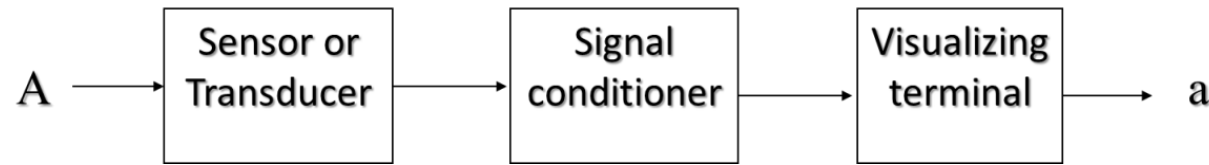
Every instrument that physically interacts with the measured quantity has a «**loading effect**» on the measurand and slightly changes its value

Instrument designer can only «*minimize*» this *loading effect*, which is called **stiffness** !

An instrument with a *low stiffness* means an instrument capable of doing measurements with a *small loading effect* !

Stiffness is a “singular characteristic” because it depends also on the *measurement environment* and *circumstances*.

Let's go to a generalized definition of ***stiffness*** and ***input impedance*** :



Energy transfers in a measuring system require the specification of two variable quantities for their description.

At the input of each component there exists a variable  $q_{i1}$ , the “***effort variable***”, that carries the “*information content*” of the measurement.

At the same input, however, there is a second variable  $q_{i2}$ , the “***flow variable***” associated with  $q_{i1}$ , in a way that the product  $q_{i1} \times q_{i2}$  has the “dimensions of power” and represents an instantaneous rate of “energy withdrawal” from the preceding element !

Now the generalized input impedance can then be defined as :  $Z_{gi} = \frac{q_{i1}}{q_{i2}}$

The power drained from the preceding element is :  $P = \frac{q_{i1}^2}{Z_{gi}}$

and a “***large***” ***generalized input impedance*** is needed to keep the *power drain small* !

These concepts can be immediately applied to an electrical example: a *voltmeter* measuring an *unknown voltage*  $V$ .

As soon as the meter is applied to the voltage terminals, the electrical circuit is changed and the value of  $V$  is no longer the same but changes to another value  $V_m$ .

For a voltmeter the input variable of interest, the *effort variable* ( $q_{i1}$ ), is the terminal voltage  $V_m$ . If we look for an *associated variable* ( $q_{i2}$ ) which, when multiplied by  $q_{i1}$ , gives the power withdrawal from the voltage terminals, we find the meter current  $i_m$  meets this requirement.

Thus, the *input impedance* in this example is: 
$$Z_{gi} = \frac{q_{i1}}{q_{i2}} = \frac{V_m}{i_m} = R_m \quad \text{the } \mathbf{meter\ resistance} \ !$$

This situation is very important indeed and applies also to the *internal stages* of a more complex instrument chain, for example, when coupling a transducer that measures a physical quantity  $A$  and outputs a voltage  $V$  or a current  $i$  to the *signal processing stage* that follows in the measurement chain ....

Some *numerical means* of expressing the *loading effect* of the instrument on the measured medium would be helpful in comparing competing instruments at the moment of their choice or purchase !

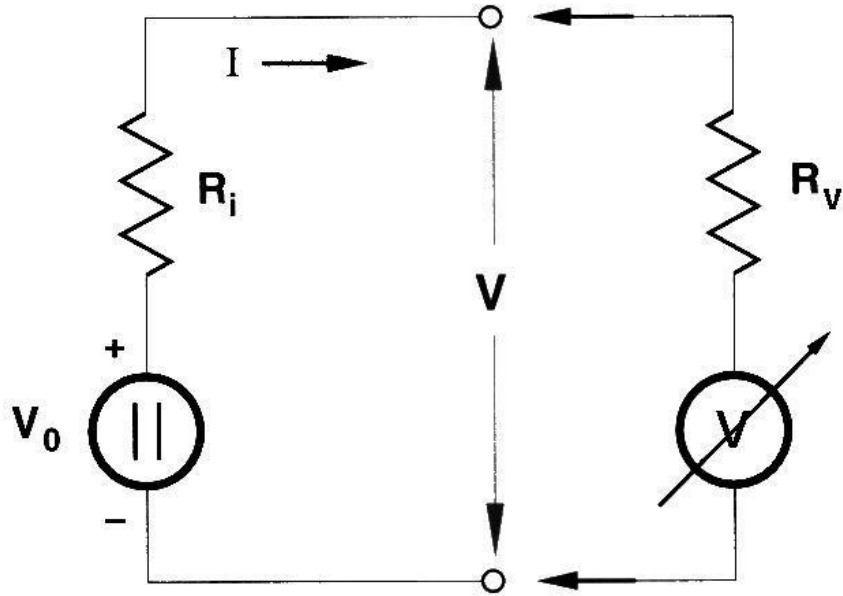
One parameter could be the **insertion or connection error** done by the instrument when connecting with the measurand:

$$\mathcal{E}_{ins} = \frac{a_b - a}{a_b} \cong \frac{a - a_b}{a}$$

where:  $a_b$  is the numerical value of the measurand “before” the instrument insertion;  
 $a$  is the numerical value of the measurand “after” the instrument insertion,  
the *actual measurement* returned by the instrument.

Because  $a_b$  is a value that can NOT be measured, this parameter may seem useless !

## Example I



Before connecting the voltmeter to the terminals we have :  
 $V = V_0$  with  $I = 0$

After connecting the voltmeter we have:  
 $V_0 = (R_i + R_v) \cdot I$  with  $I \neq 0$

But the instrument measures:  
 $V = R_v \cdot I \neq V_0$

$$\varepsilon_{ins} = \frac{V_0 - V}{V_0} \Rightarrow \frac{(R_i + R_v) \cdot I - R_v \cdot I}{(R_i + R_v) \cdot I} = \frac{R_i}{R_i + R_v} = \frac{1}{1 + \frac{R_v}{R_i}}$$

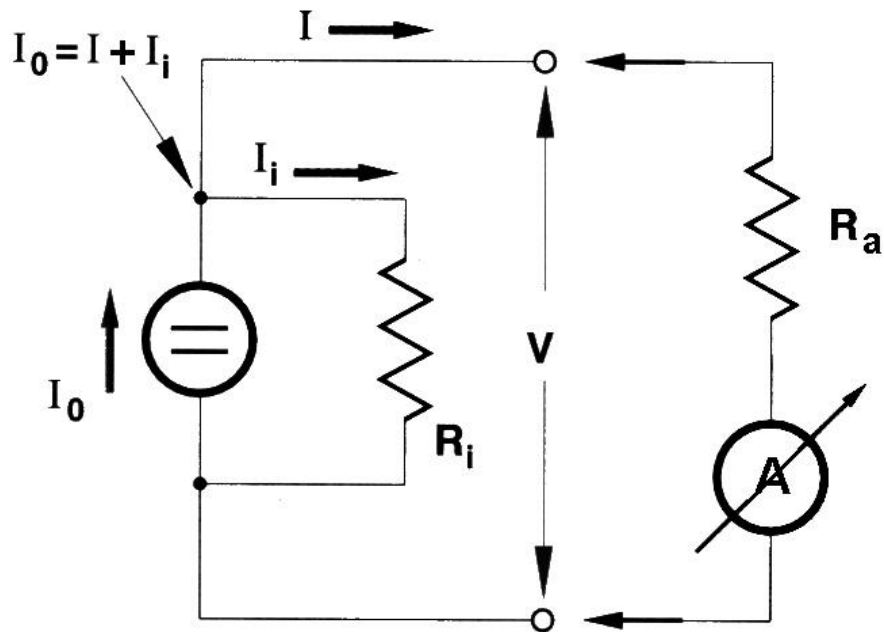
We do a “**connection error**”

If we wish to keep this error small  $\varepsilon_{ins} \rightarrow 0$  we have to design either  $R_v \rightarrow \infty$  or  $R_i \rightarrow 0$

Acting on the transducer *output resistance*  $R_i$  is not so easy therefore, the preferred way in designing the connection is making the *input resistance*  $R_v$  of the signal processing stage (voltmeter) very big !

This choice prevents the signal  $V$ , which carries the “information” about the measurement, to degrade further !

## Example II



Before connecting the ammeter to the terminals we have :

$$I_0 = I_i \quad \text{with} \quad I = 0$$

After connecting the ammeter we have:

$$I_0 = I_i + I \quad \text{with} \quad I = \frac{V}{R_a}$$

And the instrument measures:

$$I \neq I_0$$

We do a **“connection error”**

$$\varepsilon_{ins} = \frac{I_0 - I}{I_0} = 1 - \frac{I}{I_0}$$

Since the two resistors are now in a parallel configuration:

$$V = I_0 \frac{R_i R_a}{R_i + R_a}$$

Therefore : 
$$\frac{V}{R_a} = I_0 \frac{R_i}{R_i + R_a} = I$$

$$I = I_0 \frac{R_i}{R_i + R_a} \longrightarrow \frac{I}{I_0} = \frac{R_i}{R_i + R_a}$$

And the connection error becomes :

$$\varepsilon_{ins} = 1 - \frac{I}{I_0} \Rightarrow 1 - \frac{R_i}{R_i + R_a} = \frac{R_i + R_a - R_i}{R_i + R_a} = \frac{R_a}{R_i + R_a} = \frac{1}{\frac{R_i}{R_a} + 1}$$

If we wish to keep this error small  $\varepsilon_{ins} \rightarrow 0$  we have to design either  $R_i \rightarrow \infty$  or  $R_a \rightarrow 0$

Having at disposal a current generator with a big *internal short-circuit resistance*  $R_i$  is advisable but not so easy to obtain from a transducer which outputs a current therefore, the preferred way in designing the two-stage connection is making the *input resistance*  $R_a$  of the signal processing stage (ammeter) very small !

This choice prevents the signal  $I$ , that carries the “information” on the measurement, to degrade further !