

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 ...**

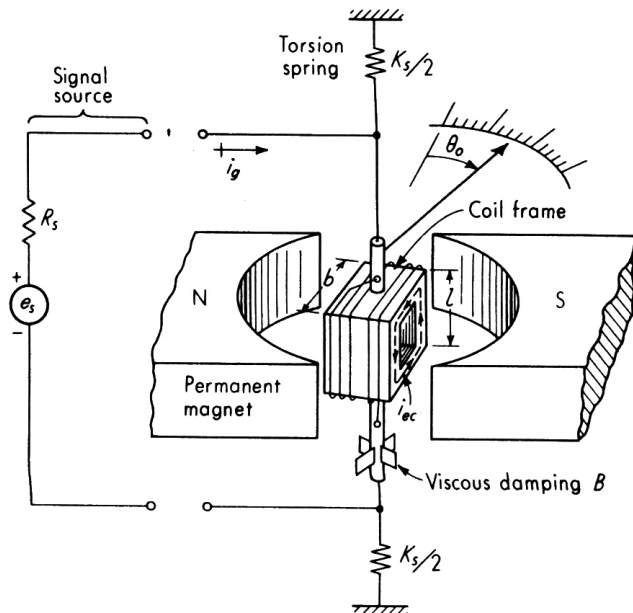
Direct instruments : (they do not transform the physical quantity - only very few)

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

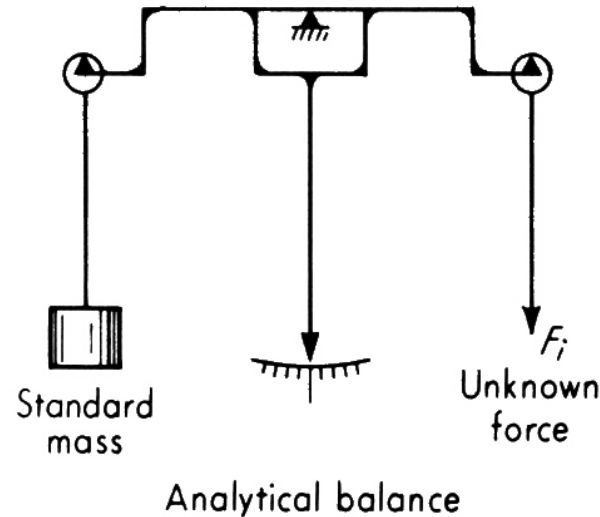
Analog instruments

Digital instruments

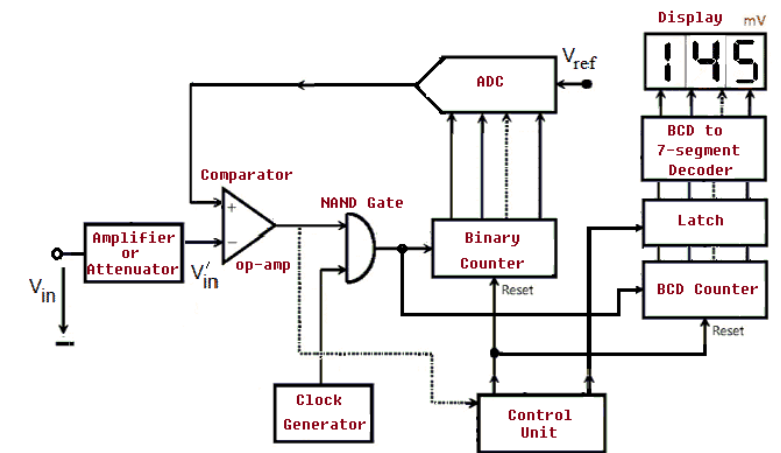
Deflection instruments



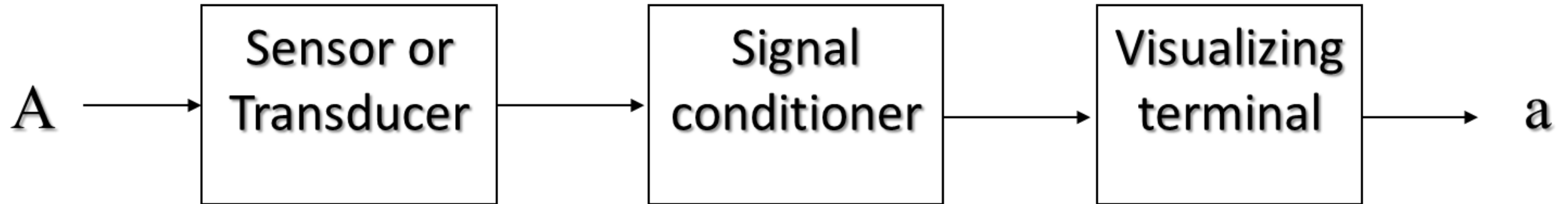
Null-out instruments



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.

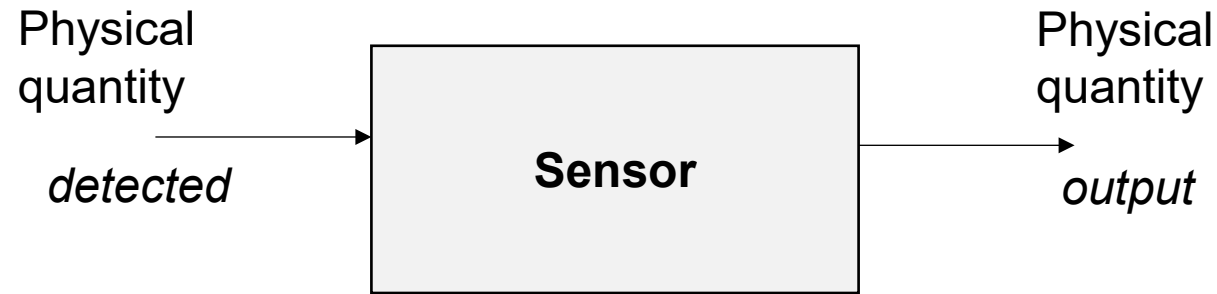
Sensor

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

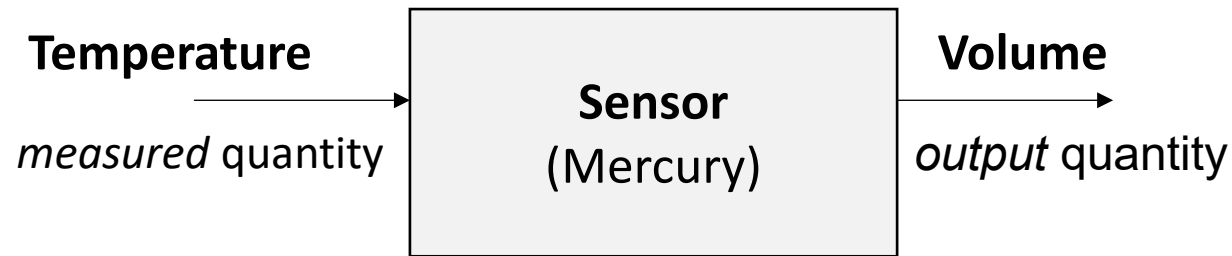
Transducer

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

Sensor: block diagram and example



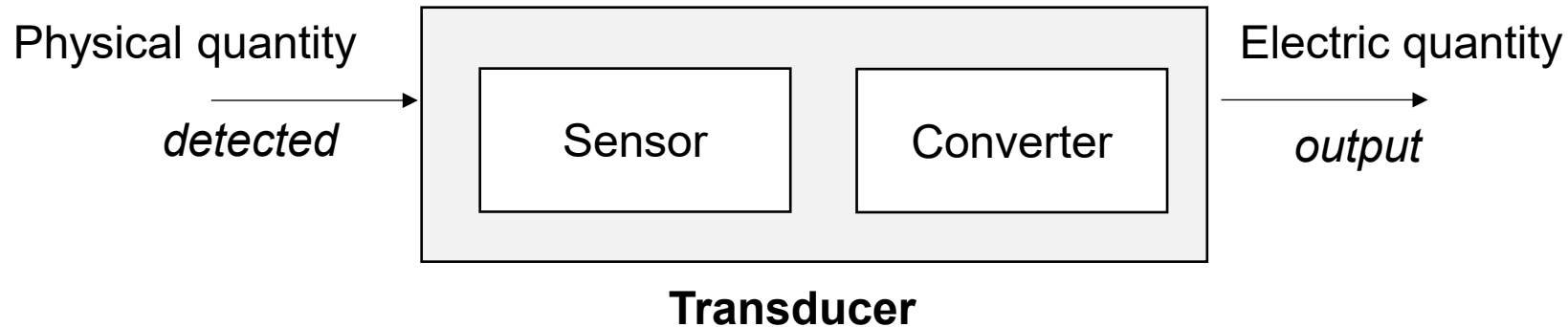
Example



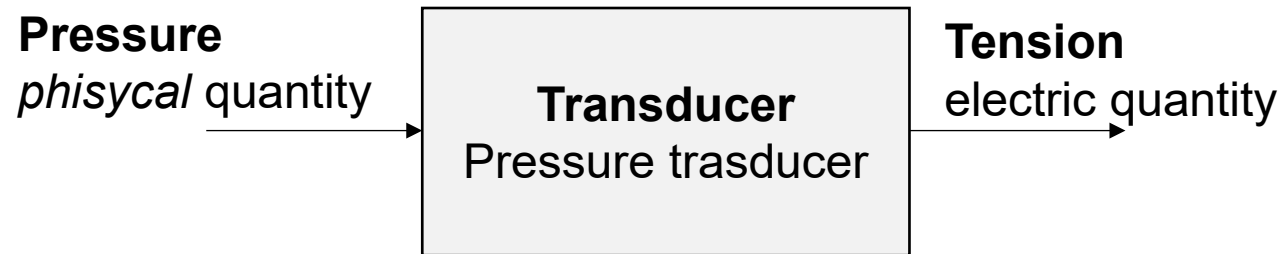
!!: mercury in thermometers is a sensor because a temperature change causes a proportional volume change.

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 ?



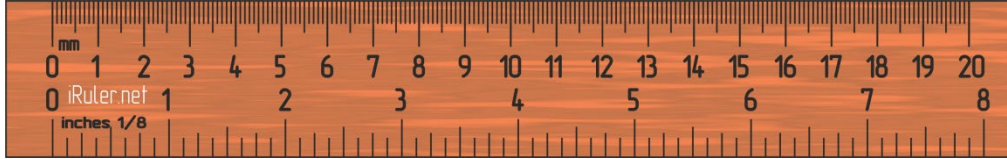
Quality of the measurement

Eg.

Length and displacement measurement

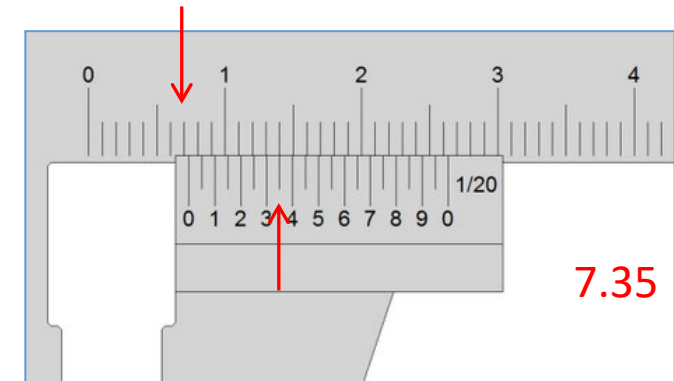
Many instruments are available to measure length and displacement in modern technology ...

The most ancient is the *graduated ruler*:



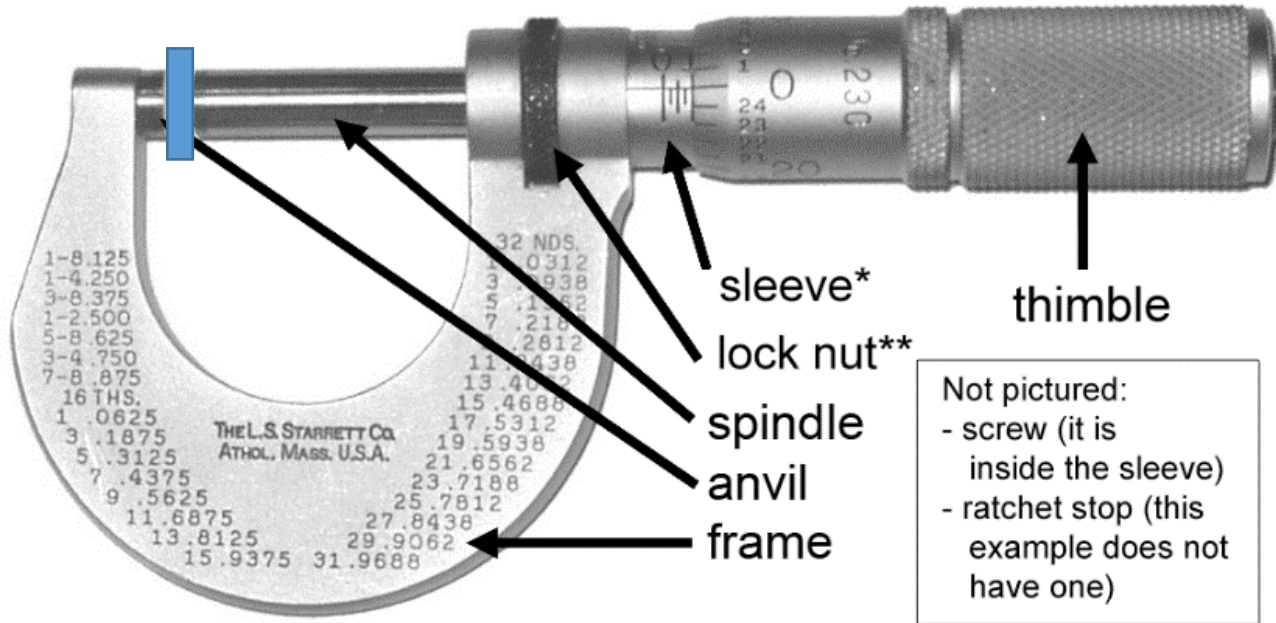
Rulers have an approximation of 1 mm,

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.

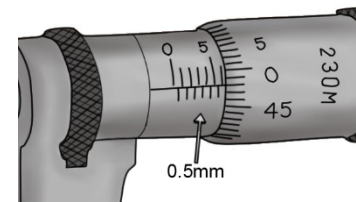
Micrometer (Palmer): it is based on a “micrometric screw” with a *pitch* of 0.5 mm (*sleeve*). It has an approximation of 0,01 mm



*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:

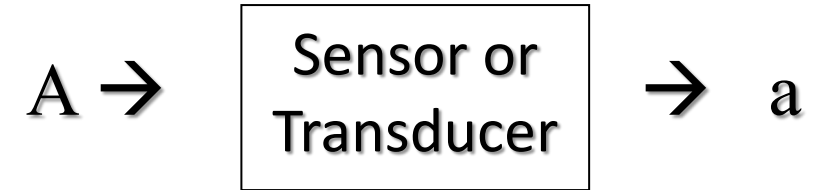


$$\frac{1}{2} \cdot \frac{1}{50} = \frac{1}{100} \text{ mm,}$$

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: $\mathbf{A} = \mathbf{a} \times \mathbf{U}$
4. at this point we still only have a *raw measurement* of the physical quantity **A**. We have to identify the *many uncertainties* ϵ associated with the raw data, correct the data we obtained and then switch to the final measurement: $\mathbf{A} = (\mathbf{a} \pm \epsilon) \times \mathbf{U}$
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)

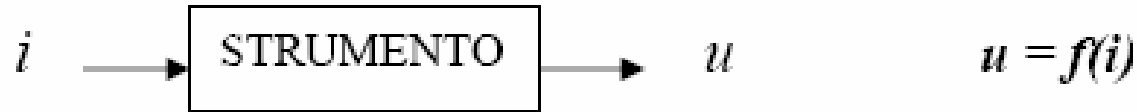
- **MEASUREMENT SPAN**

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 !

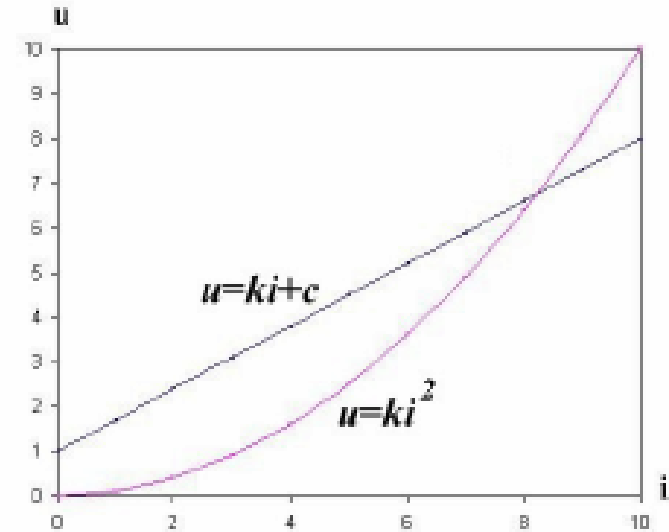
Span = high operation limit – low operation limit

..... **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):

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

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

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

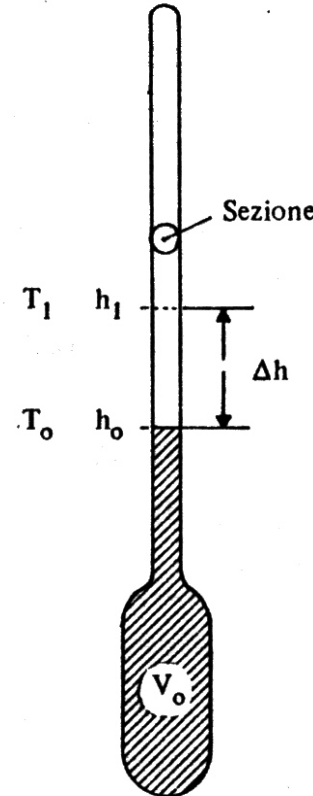
$$\Delta h = \frac{\alpha \cdot V_0}{S} \Delta T$$

output input (measurand)

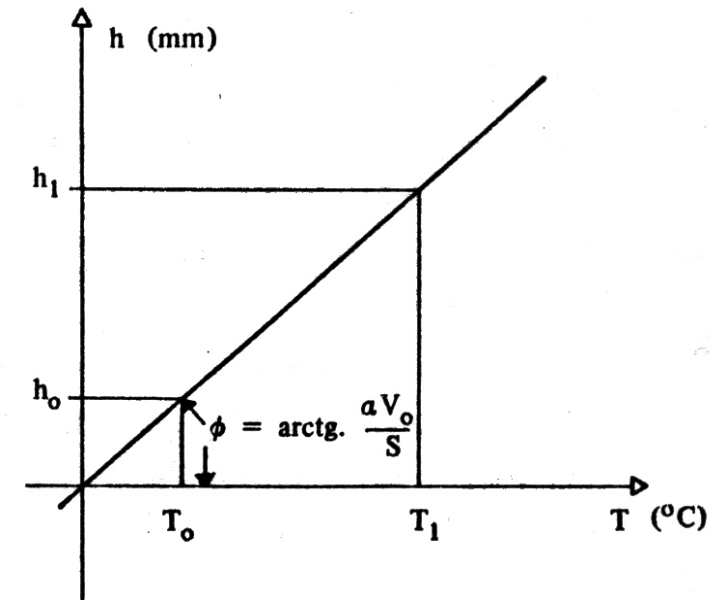
That's the *graduation curve* !

Span ?

[-38 °C / +365 °C; ...]



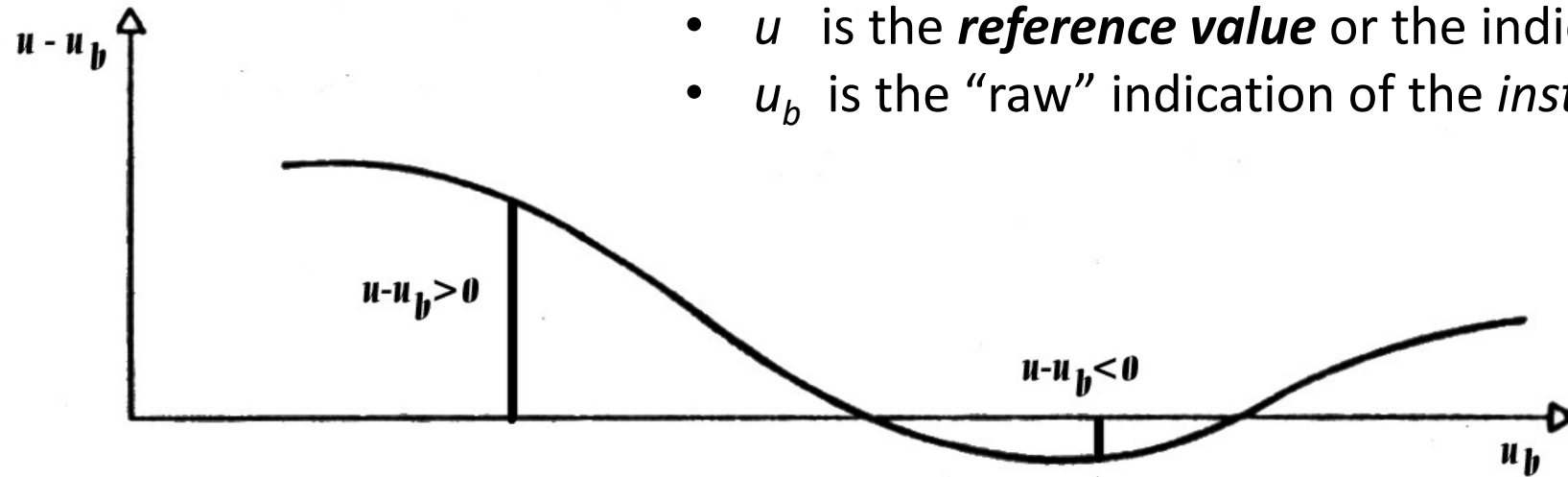
$$\Delta V = S \Delta h$$



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

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)



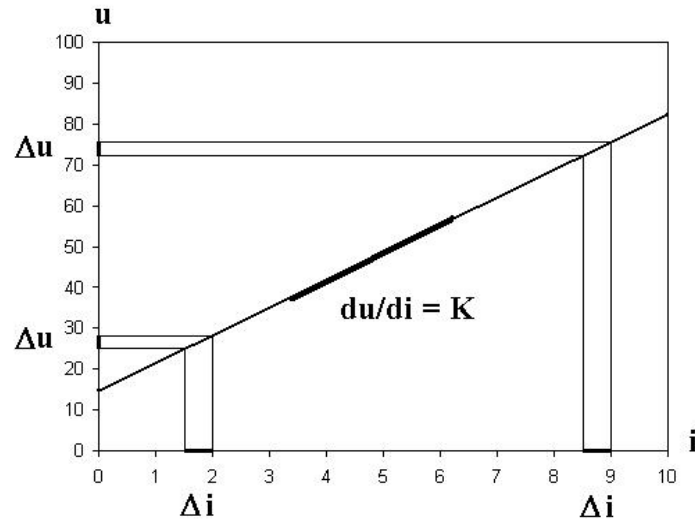
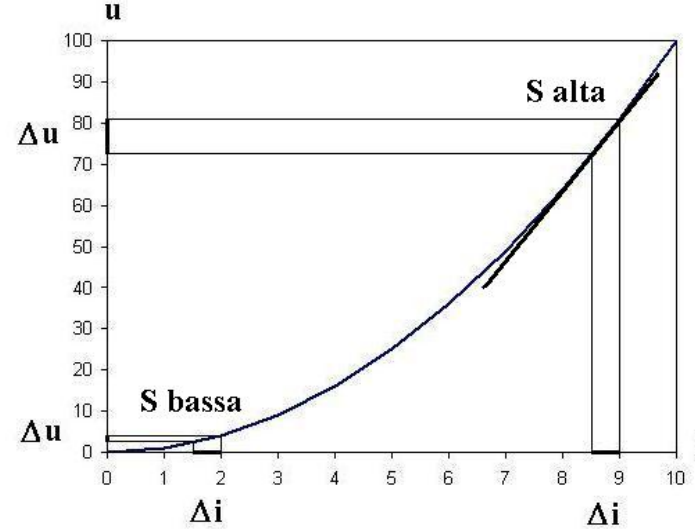
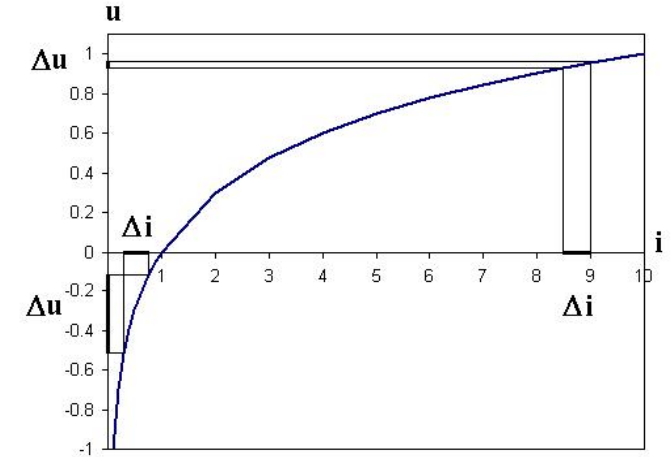
how small can a variation Δi of the input be, to get from the instrument an *appreciable* output Δu ?

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** !

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

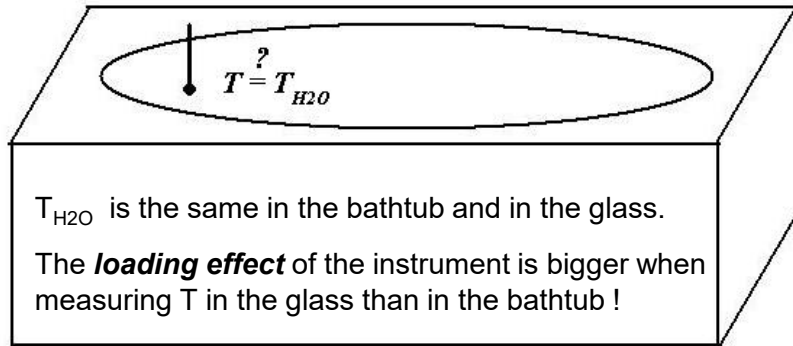
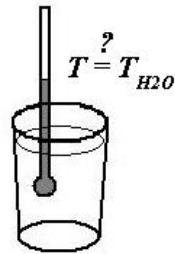
Do not confuse the *sensitivity* with the **resolution** of an instrument, which actually is a more appropriate concept for **digital instruments** !

• 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*.

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 !

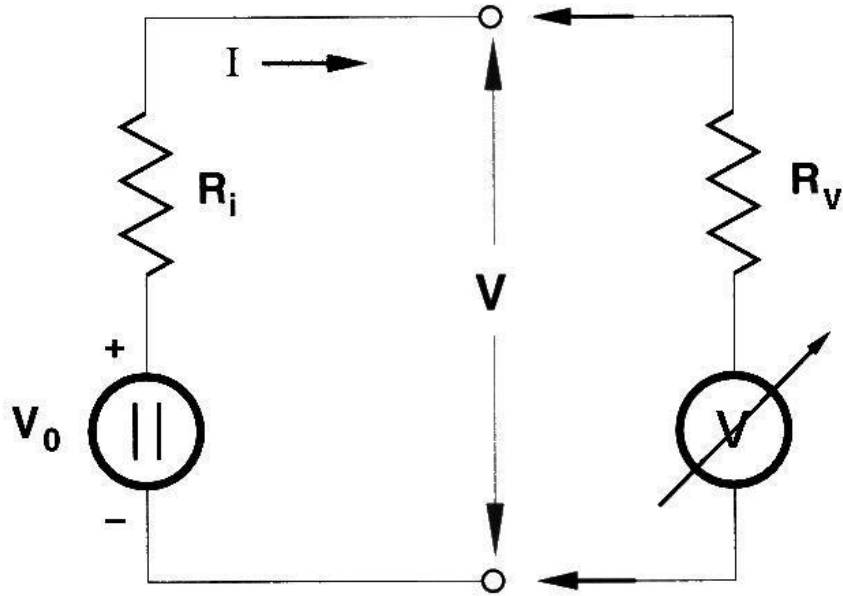
One parameter could be the **insertion or connection error** done by the instrument when connecting with the measurand:

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

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:
 $V = R_v \cdot I \neq V_0$

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

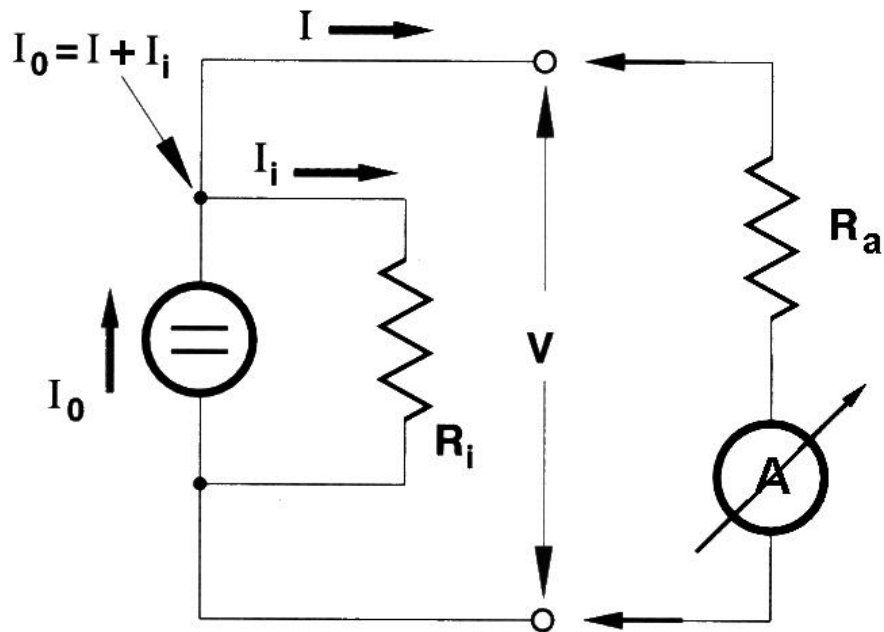
We do a “**connection error**”

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

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

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 !