

Measurements for industrial sustainability and safety

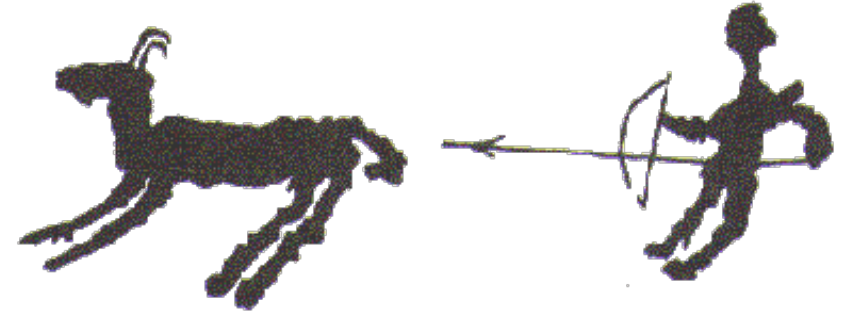
PART I Lesson 1

A.Y. 2026-27
Ludovica Apa

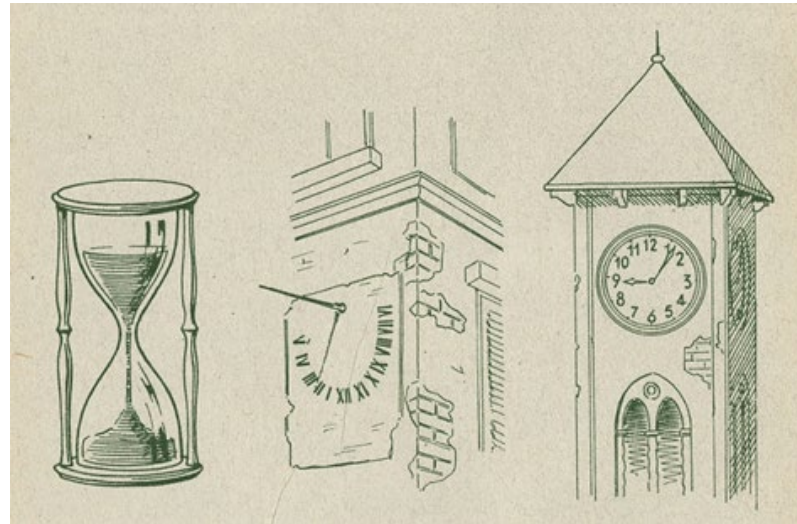


Measure and measurement history

Since ancient times, human have always "measured" ...
the distance between themselves and the things (length),
the size of things (weight) and the time it takes to do things ...



These are still the fundamental measurements in the modern world!!!



Measure and measurement history

Egyptian length units:

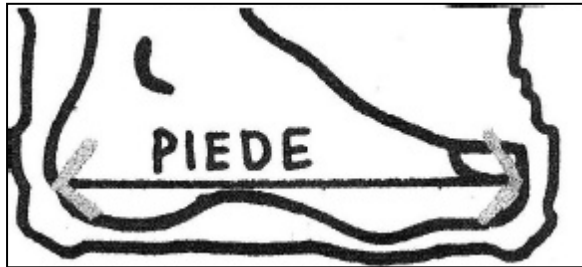


With these units egyptian build their pyramids!!!

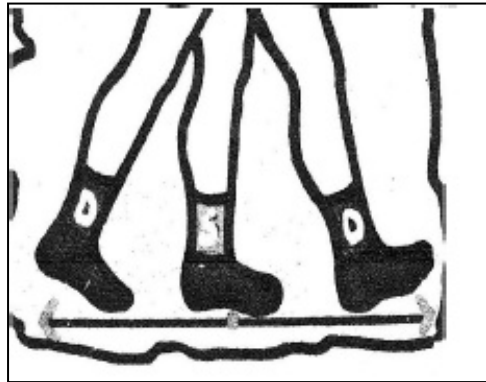


Measure and measurement history

Roman and British length units:



FOOT



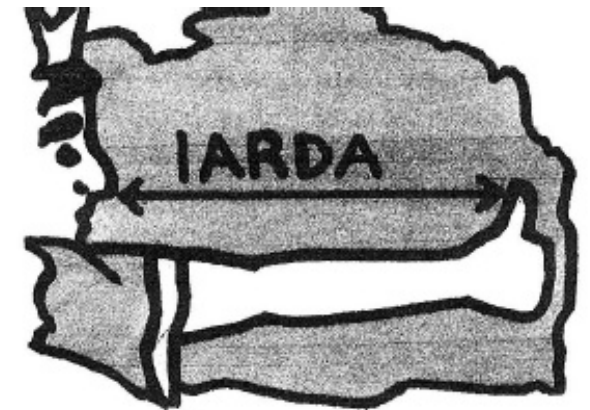
**DOPPIO PASSO
(DOUBLE STEP)**

Milestone



MIGLIO (MILE)

For romans : 1000 double steps
= 1 mile



The first *measurement unit* to be defined: The «yard»
was imposed by king Henry the 1st of England in year
1100...

Measure and measurement history

- “Things should not be multiplied beyond what is required” [William of Ockham, 1288-1347] → **Minimum degree of complexity of the Law (Occam's razor)**
- “Count what can be counted, **measure** what is **measurable**, and make measurable what is not.” [Galileo Galilei, 1564-1642] → **Scientific method**
- “[...] when you can measure what you are speaking about and express it in numbers **you know** something about it; but when you cannot measure it when you cannot express it in numbers your **knowledge is** of a **meager** and **unsatisfactory** kind: it may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the stage of science whatever the matter may be.” [Lord Kelvin, 1824-1907] → **Measure is to Know**

Measure and measurement history

- “Measurement is the process of assigning **numbers to represent qualities**: the object of measurement is to enable the powerful weapon of mathematical analysis to be applied to the object of science” [Norman Robert Campbell, 1880–1949]
 - Implication of a mathematical formalism
- “Measurement, in a broad sense, is defined as the **assignment of numbers to objects and events according to a rule**” [S. Stevens, Science, Vol. 103, No. 2684 (Jun. 7, 1946), pp. 677-680]
 - What is normally done in everyday activity is a measurement, which consists of the use of samples, which are objects compared in a material context with the object on which the quality to attribute has been identified a numerical value

Measure and measurement history

- “Measurement is the process of **empirical, objective** assignment of numbers or symbols to the properties of objects and events of the real world in such a way as to describe them” [L. Finkelstein, Theory and philosophy of measurement in: Handbook of Measurement Science, vol. 1, John Wiley, Chichester, 1982, pp.1–30.]
 - This definition makes explicit the measurement is an empirical, rather than an a priori process.

Measure and Measurement definitions

- “Quantity”: the property of a phenomenon, body, or substance, where the property has a magnitude that can be expressed as a number and a reference [VIM3 1.1]
- “Measurement”: the process of experimentally obtaining one or more quantity values that can reasonably be attributed to a quantity [VIM3 2.1]
- “Measurement result”: the set of quantity values being attributed to a measurand (quantity intended to be measured) together with any other available relevant information [VIM3 2.9]

Measurements require experiments

Theoretical vs experimental analysis methods

Features of theoretical methods

- Often gives results that are of **general use** rather than restricted application
- Require the application of **simplifying assumptions**. Thus not the actual physical system but rather a simplified "mathematical model" of the system is studied: the theoretically predicted behaviour is *always* different from the real behaviour
- In some cases, may lead to **complicated mathematical problems**. Today, increasing availability of high-speed computing machines allows theoretical treatment of many problems that could not be treated in the past.
- **Require only pencil, paper, computing machines...** Laboratory facilities are not required: some computers are very expensive but can be used to solve several kind of problems - laboratory equipment is special-purpose.
- **No time delay** engendered in building models, assembling and checking instrumentation and gathering data.

Features of experimental methods

- Often gives results that apply **only to the specific system** being tested.
- No simplifying assumptions necessary if tests are run on the actual system. The **true behaviour** of the system is revealed.
- *Accurate* measurements are necessary to give a true picture. This may require **expensive and complicated equipment**. *The characteristics of all the measuring and recording equipment must be thoroughly understood.*
- **Actual system** or a scale model is **required**. If a scale model is used, similarity of all significant features must be preserved.
- **Considerable time** required for design, construction and debugging of the apparatus

Measure and measurement definition

“Measurement, in a broad sense, is defined as the assignment of numbers to objects and events according to a rule”

1. Classification:

- a) identify the characteristics or the properties of an object or a physical phenomenon;
- b) group the objects or phenomena into “classes” where the identified properties are homogeneous.

It's a *qualitative* cognitive method!

2. Ordering:

- a) consider only the properties that can be sorted according to a scale.

It's a first form of *quantification*, based on the intensity of the selected property.

3. Measurement:

- a) associate to the studied property a number that represents it each time such property manifests itself equal to itself. This position establishes a **measurement scale**.

This means establishing a correspondence between the “physical properties” of objects or phenomena and “real numbers”.

Measurement Unit System

- International commissions, which employ specialists from many fields of specific interest, establish systems of units of measurement with general criteria for the entire scientific field.
- The qualities present in measurement systems must admit of extensive scale.
- The determination of the minimum number of qualities to be included in the systems of units of measurement will remain open as long as new laws and manifestations of quality are introduced (**Occam's razor**).

$n=q-p=4$ (current determination)

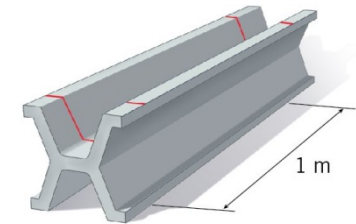
$p \rightarrow$ known laws.

$q \rightarrow$ manifestations identified within the laws

$n \rightarrow$ minimum number of qualities of a system of measurement units.

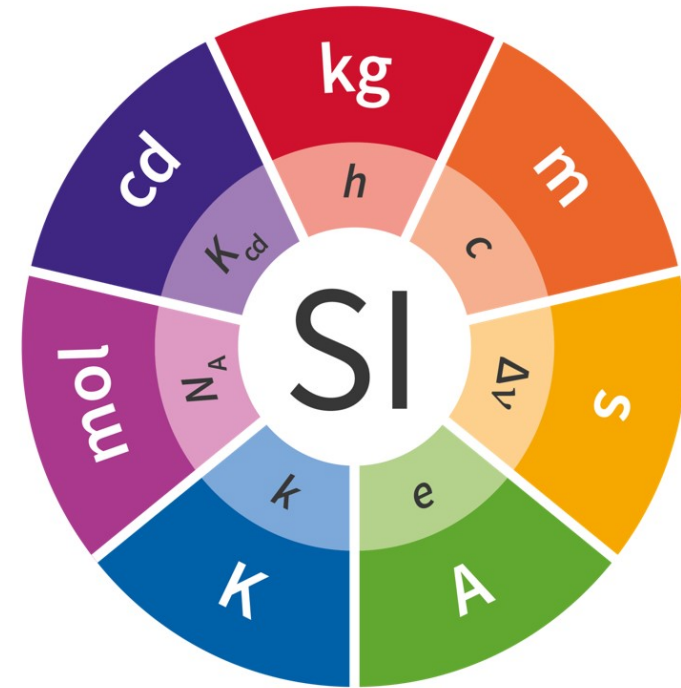
Measurement Unit System

- The «metric system» was introduced in France in 1790 with the French Revolution.
- The new units of length, weight and time required about 10 years of work and the overcoming of many contrasts to be drawn. They were attended by many famous scientists including **Borda, Lagrange, Laplace, Monge, Condorcet, Mechain, Delambre and Coulomb**.
- In 1799, the first platinum iridium samples of meter and kilogram were deposited in the archives of France !
- In 1875, 17 nations, including Italy, signed the "International Metre Convention".
- In 1889 took place the first **General Conference on Weights and Measures** (1° GFCM), which definitively established the new units ...



Measurement Unit System

- In 1960 (**11° GFCM**), the metric system was given the official symbol **SI** for *Système International d'Unités* and launched as the “modernized metric system”...
- ... until today: in November 2018 (**26° GFCM**), 60 member states and 42 associate states converged on a new SI. All the measurements units are with similar definitions and are based on physical constants (Plank, Avogadro, Boltzmann...)
- Valid from 20 May 2019, the World Metrology Day



<https://www.bipm.org/en/measurement-units/>

International System of Quantities ISQ & International System of Units SI

International System of Quantities		International System of Units	
Base quantity	Symbol for dimension	Name	Unit Symbol
length	L	metre	m
mass	M	kilogram	kg
time	t	second	s
electric current	I	ampere	A
Thermodynamic temperature	T	kelvin	K
amount of substance	N	mole	mol
luminous intensity	J	candela	cd

Definition of International System of Units SI

- second: 9.192631770×10^9 cycles of radiation from vaporized caesium 133
- meter: The length of path traveled by light in an interval of $1/299,792,458$ s
- kilogram: The mass of a platinum-iridium cylinder kept in the International Bureau of Weights and Measures, Sevres, Paris
- temperature degrees: The temperature difference between absolute zero Kelvin and the triple point of water is defined as 273.16 K.
- ampere: The current flowing through two infinitely long parallel conductors of negligible cross section placed 1 m apart in vacuum and producing a force of 2×10^{-7} N per meter length of conductor
- candela: The luminous intensity in a given direction from a source emitting monochromatic radiation at a frequency of 540 THz and with a radiant density in that direction of 1.4641 mW/str
- mole: The number of atoms in a 0.012 kg of carbon 12

A **dimensional equation** is an equation that expresses with the «Maxwell notation» every *derived quantity* or **unit U** as a function of the *fundamental quantity* or **units U_1, U_2, U_3** , with the **dimensions $\alpha_1, \alpha_2, \alpha_3$** .

$$[U] = [U_1^{\alpha_1}] \cdot [U_2^{\alpha_2}] \cdot [U_3^{\alpha_3}]$$

If we concentrate only on Mechanics, we define **10 physical quantities or units** and **7 relationships** between them: only **10 – 7 = 3** quantities or units are **fundamental**, the others are **derived** from the 3 fundamental !!!

$[L] = [L]$	$\rightarrow$	m	(fundamental)
$[A] = [L^2]$	$\rightarrow$	m ²	(derived)
$[V] = [L^3]$	$\rightarrow$	m ³	(derived)
$[t] = [t]$	$\rightarrow$	s	(fundamental)
$[v] = [L][t^{-1}]$	$\rightarrow$	m/s	(derived)
$[a] = [L][t^{-2}]$	$\rightarrow$	m/s ²	(derived)
$[M] = [M]$	$\rightarrow$	kg	(fundamental)
$[F] = [M][L][t^{-2}]$	$\rightarrow$	kg·m/s ² = N	(derived)
$[J] = [M][L^2][t^{-2}]$	$\rightarrow$	kg·m ² /s ² = J	(derived)
$[W] = [M][L^2][t^{-3}]$	$\rightarrow$	kg·m ² /s ³ = W	(derived)

$$\frac{A}{B} = \alpha$$

measurement of A with respect to B

α always exists and it is a ***real number!***

When we choose a ***reference property*** or ***unit*** $B \equiv U$ then we associate uniquely a number to the physical quantity and we can introduce the ***measurement of the quantity A!***

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

measurement of A !

To express «physical properties» with numbers we have to find and associate them with a suitable measurement unit!

Examples :

Length : $\frac{A}{m} = a$

meters ...

Temperature:

$$\frac{B}{^{\circ}\text{C}} = b$$

Celsius degree ...

What if I choose a new unit U' for the same physical property A ???

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

The property stays the same, but the *number a* changes in *a'* (of course)!

There is a simple rule to pass from *a* to *a'* :

$$\frac{A}{U'} = \frac{A}{U} \times \frac{U}{U'} = \frac{A}{U} \times \tau \quad \text{or} \quad a' = a \times \tau$$

The ratio of the two *units U* and *U'* is of course dimensionless :

$$\tau = \frac{U}{U'}$$

This rule accounts for the «***change of the measurement units***» in science and technology !

Example:

$$\tau = \frac{U}{U'} = \frac{1mm}{1km} \quad \begin{array}{l} \nearrow \frac{1mm}{10^6 mm} = 10^{-6} \\ \searrow \frac{10^{-6} km}{1km} = 10^{-6} \end{array}$$

$$[v]=[L][t^{-1}]$$

$$5 \text{ m/s} \rightarrow v' \text{ km/h}$$

$$v' = v \times \tau_v$$

$$\tau_v = \tau_l \times \tau_t^{-1}$$

$$\tau_l = \frac{m}{km} = \frac{1m}{1000m} = \frac{0.001km}{km} = 10^{-3}$$

$$\tau_t = \frac{s}{h} = \frac{1s}{3600s} = \frac{0.000278h}{1h} = 2.78 \times 10^{-4}$$

$$\text{so} \quad \tau_v = \left(\frac{1}{1000} \right) \left(\frac{1}{3600} \right)^{-1} = \frac{1}{1000} \times 3600 = 3.6$$

$$v' = 5 \times 3.6 = 18 \text{ km/h}$$

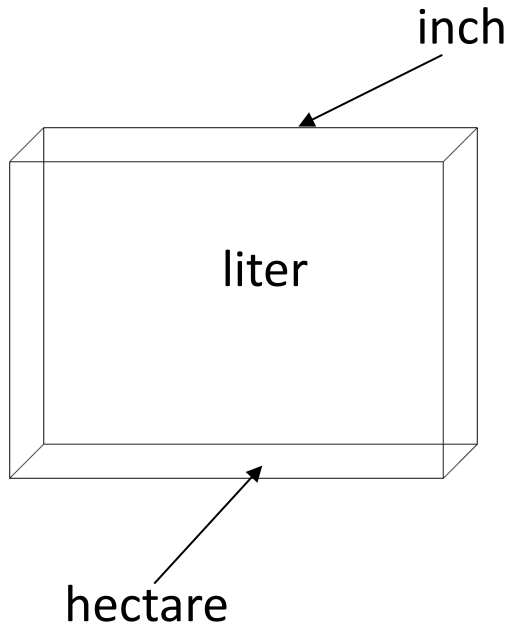
Are we going to choose for every physical quantity or property an *arbitrary measurement unit* ?

NO!

Then we have to establish *relationships* between every quantity or property that allows it

Example:

Geometric Units



Length [L] $\longrightarrow$ fundamental unit $U_L = m$ «meter»
(in the *International Unit System*)

Area [A] $\longrightarrow$ *derived unit* $U_A = m^2$
 $[A] = [L \times L] = [L^2]$

Volume [V] $\longrightarrow$ *derived unit* $U_V = m^3$
 $[V] = [L \times L \times L] = [L^3]$

Dimensions

Kinematic Units

Time [t] $\longrightarrow$ fundamental unit $U_t = s$ «seconds»
(in the *International Unit System*)

Velocity [v] $\longrightarrow$ *derived unit* $U_v = m/s$
 $[v] = [L \times t^{-1}]$

Kinematic relationships !

Acceleration [a] $\longrightarrow$ *derived unit* $U_a = m/s^2$
 $[a] = [L \times t^{-1} \times t^{-1}] = [L \times t^{-2}]$

Dynamic Units

Mass [M] $\longrightarrow$ fundamental unit $U_F = kg$ «kilogram»
(in the *International Unit System*)

Force [F] $\longrightarrow$ *derived unit* $U_F = kg \cdot m/s^2$ «newton»
 $[F] = [M \times L \times t^{-2}]$

Physical relationships !

Work [J] $\longrightarrow$ *derived unit* $U_J = kg \cdot m^2/s^2$ «joule»
 $[J] = [M \times L^2 \times t^{-2}]$

Power [W] $\longrightarrow$ *derived unit* $U_a = kg \cdot m^2/s^3$ «watt»
 $[W] = [M \times L^2 \times t^{-3}]$

The New SI: The International System of Units is getting a Makeover



time	The second , symbol s, is the SI unit of time. It is defined by taking the fixed numerical value of the caesium frequency $\Delta\nu_{\text{Cs}}$, the unperturbed ground-state hyperfine transition frequency of the caesium 133 atom, to be 9 192 631 770 when expressed in the unit Hz, which is equal to s^{-1} .
length	The metre , symbol m, is the SI unit of length. It is defined by taking the fixed numerical value of the speed of light in vacuum c to be 299 792 458 when expressed in the unit m s^{-1} , where the second is defined in terms of the caesium frequency $\Delta\nu_{\text{Cs}}$.
mass	The kilogram , symbol kg, is the SI unit of mass. It is defined by taking the fixed numerical value of the Planck constant h to be $6.626\,070\,15 \times 10^{-34}$ when expressed in the unit J s, which is equal to $\text{kg m}^2 \text{s}^{-1}$, where the metre and the second are defined in terms of c and $\Delta\nu_{\text{Cs}}$.
electric current	The ampere , symbol A, is the SI unit of electric current. It is defined by taking the fixed numerical value of the elementary charge e to be $1.602\,176\,634 \times 10^{-19}$ when expressed in the unit C, which is equal to A s, where the second is defined in terms of $\Delta\nu_{\text{Cs}}$.
thermodynamic temperature	The kelvin , symbol K, is the SI unit of thermodynamic temperature. It is defined by taking the fixed numerical value of the Boltzmann constant k to be $1.380\,649 \times 10^{-23}$ when expressed in the unit J K^{-1} , which is equal to $\text{kg m}^2 \text{s}^{-2} \text{K}^{-1}$, where the kilogram, metre and second are defined in terms of h , c and $\Delta\nu_{\text{Cs}}$.
amount of substance	The mole , symbol mol, is the SI unit of amount of substance. One mole contains exactly $6.022\,140\,76 \times 10^{23}$ elementary entities. This number is the fixed numerical value of the Avogadro constant, N_A , when expressed in the unit mol^{-1} and is called the Avogadro number. The amount of substance, symbol n , of a system is a measure of the number of specified elementary entities. An elementary entity may be an atom, a molecule, an ion, an electron, any other particle or specified group of particles.
luminous intensity	The candela , symbol cd, is the SI unit of luminous intensity in a given direction. It is defined by taking the fixed numerical value of the luminous efficacy of monochromatic radiation of frequency 540×10^{12} Hz, K_{cd} , to be 683 when expressed in the unit lm W^{-1} , which is equal to cd sr W^{-1} , or $\text{cd sr kg}^{-1} \text{m}^{-2} \text{s}^3$, where the kilogram, metre and second are defined in terms of h , c and $\Delta\nu_{\text{Cs}}$.