APPLIED PHYSICS• PHYS1

Physical Quantities, Measurements, and Dimensional Analysis

The quantitative foundations of biotechnological experimentation

Prof.ssa Valentina Notarstefano | Università degli Studi di Teramo

Physics in the Biomedical Lab

Key Concept: Every analytical result requires three elements: a numerical value, uncertainty, and a unit of measurement.

- **Definition of Physics:** The study of natural phenomena and their measurable properties through mathematical relationships (laws).
- **Measuring the Living World**: Every experiment involves measurement—of mass, volume, concentration, time, temperature, or absorbance.
- **Quantitative Language**: Provides fundamental and derived quantities, SI units, and the rules for combining them.
- **Experimental Validation**: Dimensional analysis helps prevent operational errors before they can compromise a culture or a dilution.

MODULE PHYS1 — QUANTITIES, MEASUREMENTS

Measuring the living world

Every experiment conducted by a biotechnologist is a measurement—of mass, volume, concentration, time, temperature, or absorbance.

Physics provides the language: fundamental and derived quantities, SI units, and the rules for combining them.

Dimensional analysis helps identify errors—in a dilution, a dosage, or the settings of a centrifuge—before they can compromise an experiment.

Every result requires a value, a unit, and an uncertainty: 4.8 ± 0.1, not simply '4.8'.

From nanometers (for a protein) to milliliters (for a culture), work is carried out across many orders of magnitude.

The Scientific Method

1. Observation of the Phenomenon: Quantitative measurement of biological or physical parameters.

2. Formulation of Questions: Identification of the critical variables involved.

3. Formulation of Hypotheses: Construction of a provisional conceptual model.

4. Experimental Phase: Execution of controlled experiments to test predictions.

5. Data Recording and Analysis: Statistical processing and error reduction.

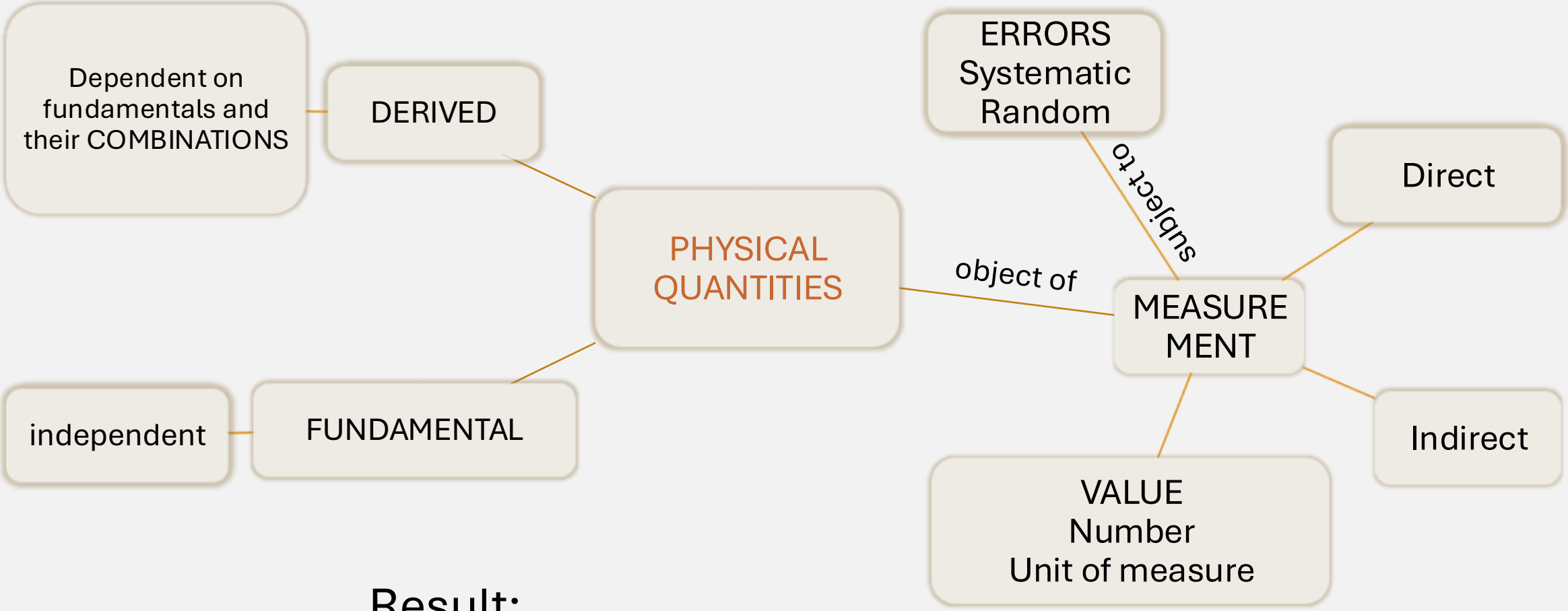
6. Drawing Conclusions: Confirmation, modification, or rejection of the initial hypothesis.



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PHYSICAL QUANTITIES

Any entity involved in the description of a phenomenon and that can be measured



Result:

VALUE ± ERROR (unit of measure)

Fundamental Quantities of the International System (SI)

PHYSICAL QUANTITY	QUANTITY SYMBOL	UNIT NAME	UNIT SYMBOL
Length	*L*	Meter	m
Mass	*M*	Kilogram	kg
Time	*T*	Second	s
Amount of substance	*N*	Mole	mol
Temperature	Θ	Kelvin	K
Electric current	*I*	Ampere	A
Luminous intensity	*J*	Candela	cd

Quantities and units in the biotech lab

Amount & concentration: mole (mol); molarity (M = mol/L) and its submultiples mM, µM, nM; % (w/v).

Volume: litre and millilitre (mL); microlitre (µL) — the working volume of a micropipette.

Mass: gram, milligram, microgram; drug dose often expressed per body mass (mg/kg).

Enzyme activity: unit (U) and katal (kat = mol/s); optical density / absorbance (dimensionless).

Centrifugation: dialled in rpm, but the quantity that matters is the RCF, in multiples of g.

Operations between Physical Quantities



Sum and **subtraction** are permitted only between identical physical quantities



Multiplication and **division** are permitted also between different physical quantities→ **DERIVED physical quantities**

DERIVED PHYSICAL QUANTITIES (AND UNITS OF MEASUREMENT)

The units of measurement of derived physical quantities can be expressed as combinations of the fundamental ones.

Volume = $[L^3] = m^3$	Density = $[M] / [L^3] = kg/m^3$
Speed = $[L] / [t] = m/s$	Force = $[M]\cdot[L] / [t^2] = kg\cdot m/s^2$ = Newton

Label of derived quantities:

PHYSICAL QUANTITY	QUANTITY SYMBOL	UNIT NAME	UNIT SYMBOL	BASE SYMBOL EQUIVALENCE	BASE UNIT SYMBOL EQUIVALENCE
Density	ρ	—	kg/m^3	$[M] \cdot [L]^{-3}$	kg/m^3
Energy	E	Joule	J	$[M] \cdot [L]^2 \cdot [T]^{-2}$	$N \cdot m$

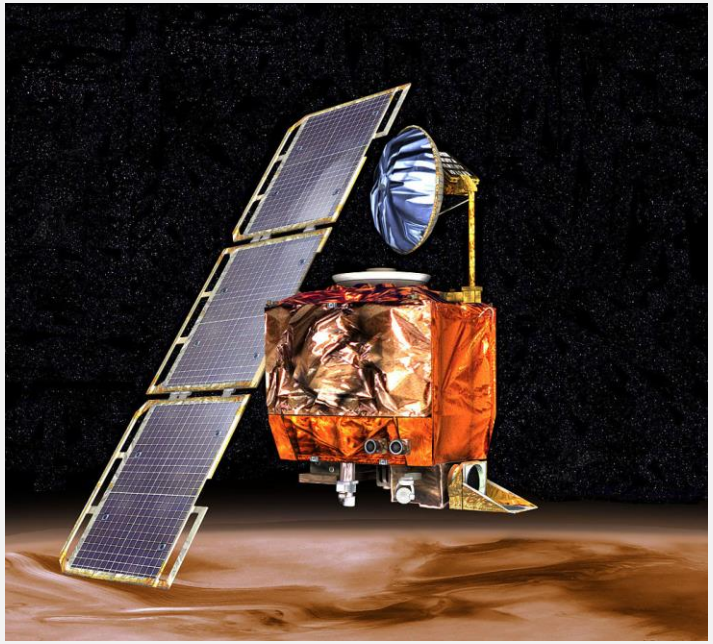
DIMENSIONAL ANALYSIS

- Analysis that allows to check the correctness of the used mathematical formulas
- If the result of a calculation is a speed and the units that we obtain are [L]*[T], the steps performed are CERTAINLY wrong

$$V = \frac{5\ (m)}{10\ (s)} = 0.5\,\frac{m}{s} \rightarrow Unit\text{à is}\,\frac{[L]}{[T]}, OK$$

$$V = 5\ (m) \times 10\ (s) = 50\ m \cdot s \rightarrow [L][T], \text{wrong!}$$

THE VALUE OF THE CORRECT UNITS OF MEASUREMENT



Mars Climate Orbiter

Mission cost: 328 million dollars

Mission outcome: FAILED

From wikipedia

The Mars Climate Orbiter was destroyed when, instead of positioning itself at an altitude of 140-150 km from the surface of Mars, it entered the Martian atmosphere at an altitude of only 57 km. The probe was destroyed by the stresses caused by friction present at that altitude with the atmosphere. It was discovered that some data had been calculated on Earth based on the unit of measurement of the US customary system, and reported to the navigation team, which instead expected the data expressed in units of measurement of the International System. The probe was not able to perform conversions between the two units of measurement.

Example — dimensional analysis in the centrifuge

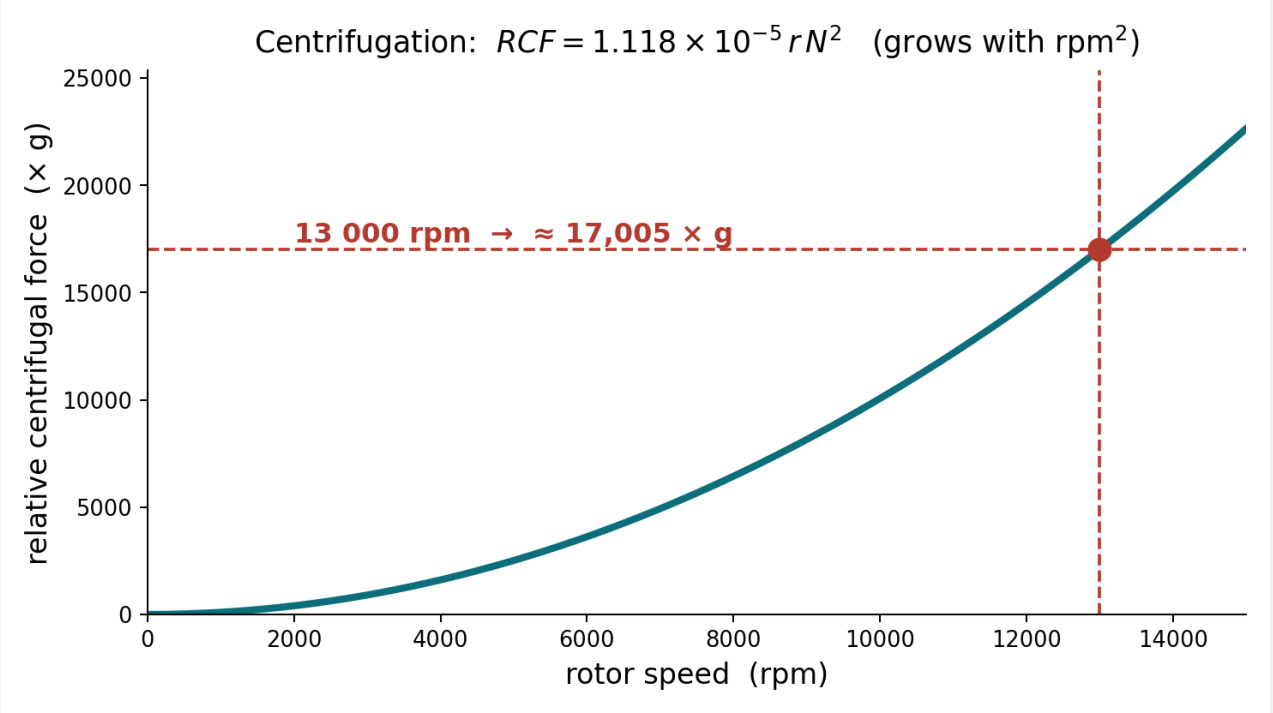
A centrifuge dial shows rpm, but what separates your sample is the g-force (RCF).

$RCF = 1.118 \times 10^{-5} \cdot r \cdot N^2$ (r in cm, N in rpm)

The units combine so that RCF is a pure multiple of g — a dimensionless number.

Because it depends on N^2, doubling the rpm quadruples the force.

Reporting a spin as '× g' (not rpm) lets any lab reproduce it on a different rotor.



In practice — from rpm to g-force

Protocols quote the force as '× g', because rpm alone is ambiguous between rotors.

For r = 9 cm at 13 000 rpm: RCF = $1.118 \times 10^{-5} \cdot 9 \cdot 13000^2 \approx$ 17 000 × g

Halving the radius (r = 4.5 cm) at the same rpm halves it to ≈ 8 500 × g.

So always convert rpm → × g to reproduce a spin on any centrifuge.



Laboratory centrifuge — Ivangiesen, CC0

EQUIVALENCES: MULTIPLES AND SUBMULTIPLES

Each quantity, whether fundamental or derived, may have associated with it a series of multiples and submultiples (e.g., meter):

Tm	Gm	Mm	km	hm	dam	m	dm	cm	mm	μm	nm	pm
10^{12}	10^{9}	10^{6}	10^{3}	10^{2}	10^{1}	10^{0}	10^{-1}	10^{-2}	10^{-3}	10^{-6}	10^{-9}	10^{-12}

Multiples:	Submultiples
da = deca	d = deci
h = hecto	c = centi
k = kilo	m = mili
M = mega	μ = micro
G = giga	n = nano
T = tera	p = pico

EQUIVALENCES: MULTIPLES AND SUBMULTIPLES

Expression of speed:

km/h → m/s

1 km/h = 1000 m / 3600 s

= 0.28 m/s

m/s → km/h

1 m/s = 0.001 km / (1/3600) h

= 3.6 km/h

CONVERSION FACTORS

n km/h → n · 0.28 m/s

n m/s → n · 3.6 km/h

10 m/s = 10 · 3.6 km/h = 36 km/h

120 km/h = 120 · 0.28 m/s = 33.6 m/s

DIRECT AND INDIRECT MEASUREMENTS

- **Direct measurements**

For example, the measurement of a mass on a balance*, or of a length with a ruler, or of a time with a clock.

- **Indirect measurements**

The unknown quantity is obtained by carrying out the direct measurement of another quantity, linked to the unknown one through a known mathematical law.

In this case, the quantity to be determined can be either fundamental (for example, the distance between the Earth and the Sun, which obviously cannot be measured directly with a ruler) or derived (for example, atmospheric pressure, for which the height of a mercury column in a vertical tube is measured: this height is directly proportional to the pressure, according to a well-known law).

*valid only for a pan balance!

HOW A NUMERICAL RESULT IS REPRESENTED

- A numerical result is not complete unless it consists of
- VALUE, ACCURACY and UNIT OF MEASURE

SCIENTIFIC NOTATION AND SIGNIFICANT FIGURES

Prefix (abbreviation)	Power ofl 10
peta (P)	10^{15}
tera (T)	10^{12}
giga (G)	10^{9}
mega (M)	10^{6}
chilo (k)	10^{3}
hecto (h)	10^{2}
deci (d)	10^{-1}
centi (c)	10^{-2}
milli (m)	10^{-3}
micro (μ)	10^{-6}
nano (n)	10^{-9}
pico (p)	10^{-12}
femto (f)	10^{-15}

The significant figures of a measurement are the certain digits and the first uncertain digit.

Identify the number of significant figures

(a) 409.8 s

(b) 0.058700 cm

(c) 9500 g

(d) 950.0×10^{1} ml

Using scientific notation

(a) 4.098×10^{2} s (4 digits)

(b) 5.8700×10^{-2} cm (5 digits)

(c) 9.500×10^{3} g or 9.5×10^{3} g (4 or 2 digits)

(d) 9.500×10^{3} ml (4 digits)

Example — orders of magnitude in biology

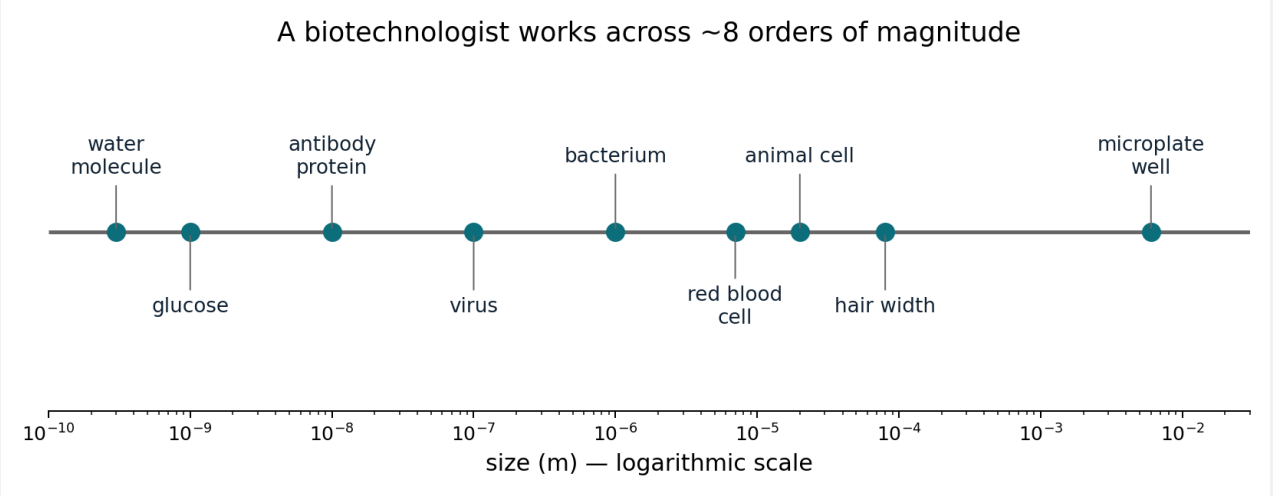
Biological objects span from sub-nanometre molecules to millimetre-scale plate wells.

Prefixes and scientific notation keep these numbers manageable:

$1\ \text{nm} = 10^{-9}\ \text{m},\quad 1\ \mu\text{m} = 10^{-6}\ \text{m},\quad 1\ \text{mm} = 10^{-3}\ \text{m}$

A protein (~10 nm), a bacterium (~1 µm) and a plate well (~6 mm) differ by about 10^6.

Choosing the right prefix is the first step of any quantitative estimate.



In practice — counting and sizing cells

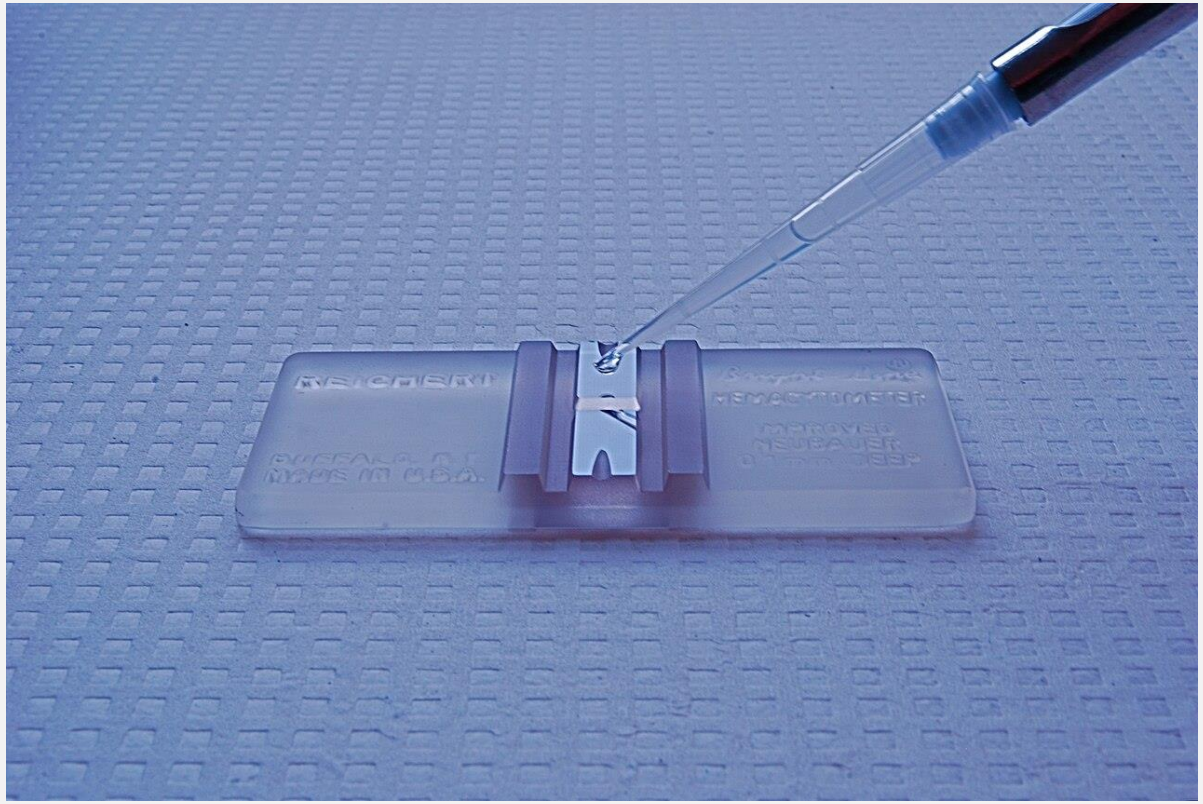
A haemocytometer is a glass slide with a grid of precisely known volume.

Each large square holds 0.1 µL (1 mm × 1 mm × 0.1 mm deep).

Count 80 cells in a square → 80 / 0.1 µL = 8×10^5 cells/mL (× dilution factor).

It works because the length scales — mm grid, µm cells — are known exactly.

Automated counters and flow cytometers do the same at higher throughput.

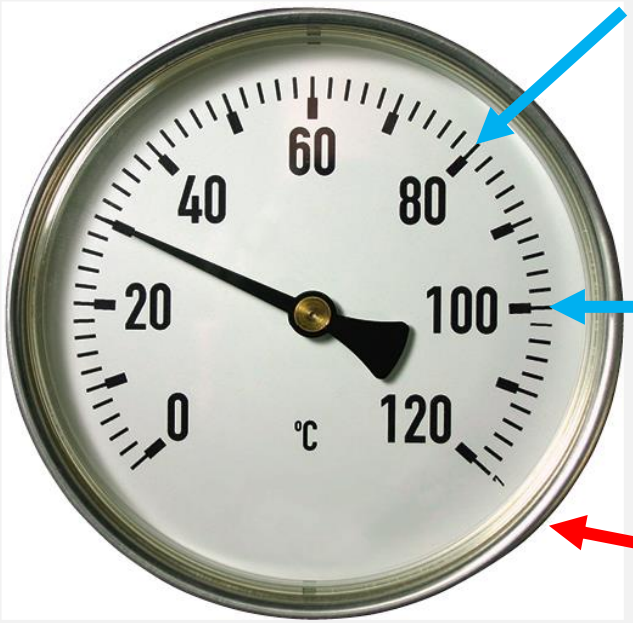


Haemocytometer being loaded — CC BY-SA 2.0

ACCURACY (OR ERROR)

- The error in a measurement has several origins. It can be random or systematic.
- It defines the precision with which we can determine the value of a physical quantity and often depends on the measuring instrument
- The error in a measurement DETERMINES the significant figures to report in a result
- It propagates in calculations

RANGE AND SENSITIVITY OF MEASURING INSTRUMENTS



SENSITIVITY (or precision):
between 80 °C and 100 °C there are 10 intervals.
The precision is therefore 2 °C

RANGE

A temperature measurement with this thermometer will be for example 64 °C ± 2 °C

RANGE AND SENSITIVITY OF MEASUREMENT INSTRUMENTS



commercial scale;
sensitivity 1 g

$m = 48 \pm 1$ g

$m = 4.8(1) \times 10^1$ g



laboratory scale;
sensitivity 0.01 g

$m = 47.74 \pm 0.01$ g

$m = 4.774(1) \times 10^1$ g



analytical laboratory scale;
sensitivity 0.0001 g

$m = 47.7438 \pm 0.0001$ g

$m = 4.77438(1) \times 10^1$ g

SOURCES OF ERRORS

- **Instrument sensitivity**
  - More accurate instruments allow this type of error to be reduced
- **Systematic error**
  - Errors that lead ALWAYS to an overestimate or an underestimate of a physical quantity (example: imperfect calibration). These errors can be ELIMINATED once identified (for example by calibrating an instrument more accurately).
- **Statistical error**
  - «Random» errors that lead SOMETIMES to an overestimate or an underestimate of a physical quantity. By repeating a measurement multiple times, on average these errors are reduced.

Example — accuracy vs precision of a measurement

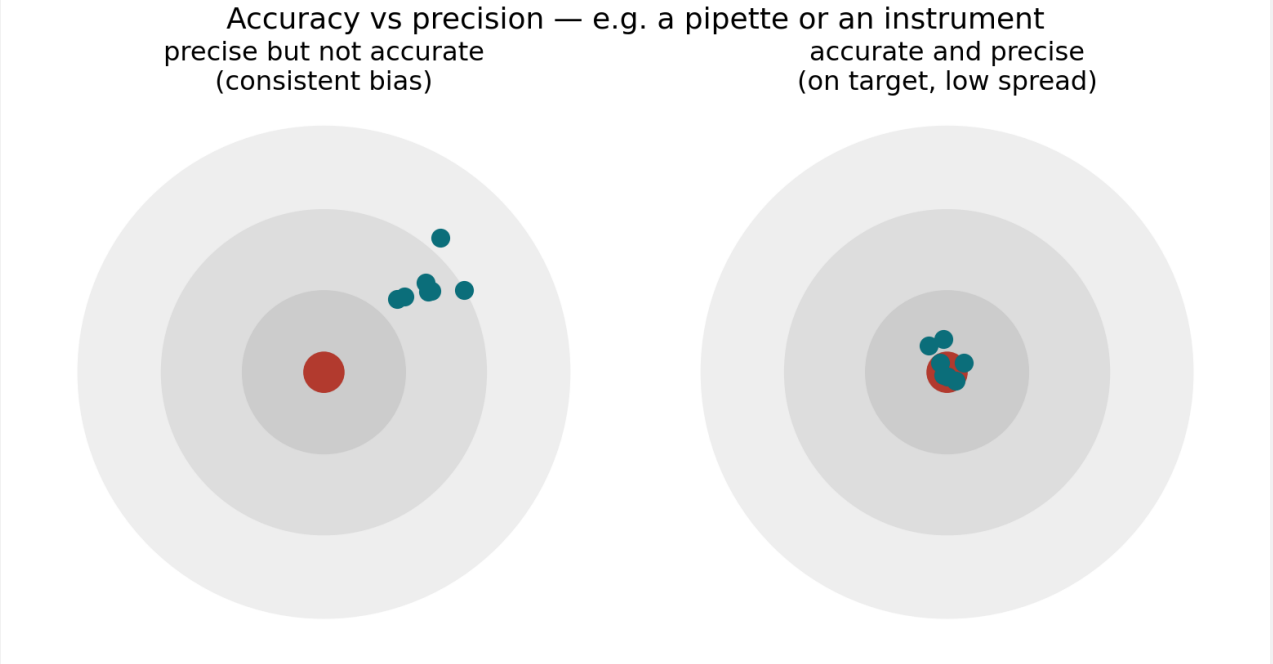
Every instrument — a pipette, a balance, a plate reader — has a limited accuracy and precision.

Precision = how close repeated measurements are to each other (small spread).

Accuracy = how close they are to the true value (small bias).

A miscalibrated pipette can be very precise yet consistently wrong — hence regular calibration.

Always report the mean with its uncertainty: value ± error.



In practice — calibrating a micropipette

A micropipette is trusted only after calibration against a known standard.

Gravimetric test: dispense water and weigh it — 1 µL of water ≈ 1 mg.

Repeat 10×: the spread (SD or %CV) is precision; the mean vs target is accuracy.

A good 100–1000 µL pipette holds ≈ ±0.8% accuracy and < 0.3% CV.

Uncalibrated or worn pipettes are a leading cause of irreproducible results.



Micropipettes — CC BY-SA 4.0

SCALAR AND VECTOR QUANTITIES

- All the examples seen so far as of now have been of SCALAR quantities, that is, characterized by a sign, number and unit. Examples: mass, temperature, length, etc. ...
- VECTOR quantities are instead characterized by number and unit (which together are called MAGNITUDE or INTENSITY), direction, sense and point of application (or origin). They are vector, velocity, force, acceleration, etc. ...