Measurements and Units
Accuracy, Precision, and Errors

Measurements and Units

A measurement is a **quantitative** observation that consists of two parts: a **number** and a **unit**. Why are units important?

• 45,000	has little meaning – just a number
• 45,000 dollars	has some meaning – money
• 45,000 dollars/year	has more meaning – a person's salary

The SI System

Scientists realized long ago that standard systems of units had to be adopted if measurements were to be useful and they were to communicate their results. For this reason, the SI System (International System of Units - Système Internationale d'Unités) was set up as the scientific system of measurement. These are some fundamental quantities in the SI system:

Physical Quantity	Unit	Abbreviation
Length	meter	m
Mass	kilogram	kg
Time	second	s
Temperature	kelvin	K
Amount of substance	mole	mol
Electric amount	ampere	A
Luminous intensity	candela	cd

All other physical quantities have units that can be derived from the SI base units.
e.g. velocity = displacement / Δ time - Derived SI units: $m\ s^{-1}$
e.g. acceleration = Δ velocity / Δ time - Derived SI units: $m\ s^{-2}$

SI is a decimal system. Quantities differing from the base unit by powers of ten are noted by use of prefixes. Changing the prefix alters the size of a unit. e.g. 1 <u>kilo</u>meter = 1000 m. The most common SI prefixes can be found in any first year chemistry or physics textbook.

tera	T	1 000 000 000 000
giga	G	1 000 000 000
mega	M	1 000 000
kilo	k	1 000
hecto	h	100
deca	da	10
(none)	(none)	1
deci	d	0.1
centi	c	0.01
milli	m	0.001
micro	µ	0.000 001
nano	n	0.000 000 001
pico	p	0.000 000 000 001

Dimensional Analysis

It is often necessary to convert a given result from one SI unit to another (e.g. km to m). We use dimensional analysis and conversion factors to get the result in the units we want.

Conversion Factors

Consider: 1 m = 100 cm
Thus, the ratio 100cm/1 m is a conversion factor that, when multiplied by any length in meters, converts that length to centimeters.

$$4.2 \; m \; \text{x} \; \frac{100 \; cm}{1 \; m} = 420 \; cm$$

Essentially conversion factors are the ratio between two units.

Dimensional Analysis

To convert a quantity with one set of units to a different set of units, we set up a conversion pathway by multiplying by one or more conversion factors.

EXAMPLE: Creatinine is a substance found in blood. In an analysis of blood serum sample that detected 0.58 mg of creatinine, how many micrograms were present?

$$0.580 \; mg \; \text{x} \frac{1 \; g}{1000 \; mg} \; \text{x} \; \frac{1 \; x \; 10^6 \; \mu g}{1 \; g} = 580 \; \mu g$$

There are cases where the units of both the numerator and denominator must be converted.

> *EXAMPLE: A nerve impulse in the body can travel as fast as 400 feet/second. What is its speed in meters/ min? Given: 1 m = 3.3 ft.*

$$Desired\ units\ \frac{m}{min} = \frac{400\ ft}{1\ s}\ \text{x}\ \frac{1\ m}{3.3\ ft}\text{x}\ \frac{60\ s}{1\ min} = 7273\ \frac{m}{min}$$

Cancelling out units is a way of checking out that your calculation is set up correctly!

More complicated situations when units are squared, cubed, etc. Use the same method.

> *EXAMPLE: How many square feet (ft²) correspond to an area of 1.00 square meter (m²), given that 1 m = 39.37 in and 12 in = 1 ft.?*

$$ft^2 =\ 1.00\ m^2\ \text{x}\ \left(\frac{39.37\ in}{1\ m}\right)^2\ \text{x}\ \left(\frac{1\ ft}{12\ in}\right)^2 = 10.8\ ft^2$$

Conversion factors can be raised to a power.

$$ft^2 =\ 1.0\ m^2\ \text{x}\ \frac{(39.37)^2\ in^2}{1\ m^2}\ \text{x}\ \frac{1\ ft^2}{(12)^2\ in^2} = 10.8\ ft^2$$

Measuring Properties of Matter

Basically, the properties of matter can be classified into two groups: **extensive** and **intensive** properties.

Extensive properties depend on the **quantity** of sample observed, such as mass and volume.

Mass vs. Weight

Mass (m) is the quantity of matter in an object. The SI base unit is the kilogram (kg); however, the gram (g) is more commonly used in Chemistry. The mass of an object is fixed and *independent* of where or how it is measured.

Weight is the force of gravity on an object, directly proportional to mass: $W \propto m$ and $W = Mass \times Gravity$). The weight of an object may vary because gravity varies slightly from one point on Earth to the other.

Volume

Volume is the amount of space than an object occupies. The more common non-SI unit to use is the liter (L). The most common unit used in the lab is the milliliter (mL). Recall that:

$$1 \text{ mL} = 1 \text{ cm}^3 \text{ (cubic centimeter)}$$
$$1 \text{ L} = 1 \text{ dm}^3 \text{ (cubic decimeter)}$$

Intensive properties <u>do not depend on the quantity of sample</u> observed; they are characteristics of the substance itself being measured, regardless of quantity, and can be used to identify substances. Some examples of intensive properties are temperature, density, melting and boiling points.

Temperature

Temperature is the measure of the thermal energy of a system. Three common scales are used: Fahrenheit (°F), Celsius/Centigrade (°C), and Kelvin (SI temperature scale). The Kelvin (K) scale assigns a value of zero to the lowest conceivable temperature, 0 K unit (comes at -273.15 °C).

EXAMPLE: Converting °F to °C - If the temperature outside is 20 °F, what is the temperature in °C?

$$T \text{ (°C)} = [T \text{ (°F)}] - 32 \,] \times \frac{5}{9}$$

$$T \text{ (°C)} = [20 \text{ °F} - 32 \,] \times \frac{5}{9} = -6.7 \text{ °C}$$

EXAMPLE: Converting between Kelvin and Celsius Scales - If the temperature outside is 20.10 °C, what is the temperature in K?

$$T \text{ (K)} = T \text{ (°C)} + 273.15$$
$$T \text{ (°C)} = T \text{ (K)} - 273.15$$

$$T \text{ (K)} = 20.10 \text{ °C} + 273.15 = 293.25 \text{ K unit}$$

Note some common temperatures:
- 0 °C = 273.15 K (often rounded off to 273 K)
- 0 K = -273.15 °C (often rounded off to -273 °C)
- 25 °C = 298.15 K (often rounded off to 298 K)

Density

Density (d) is an intensive property of a substance based on two extensive properties: mass and volume.

$$Density \ (d) = \frac{mass \ (m)}{volume \ (V)}$$

SI derived unit: kg/m^3. More common units used in the lab are g/cm^3 and g/mL

Dependence of density on temperature: Density is a function of temperature because volume varies with temperature, whereas mass remains constant. e.g.

$$d(H_2O) = 1.000 \text{ g/mL } \underline{\text{at 4 °C}}$$
$$d(H_2O) = 0.9982 \text{ g/mL } \underline{\text{at 20 °C}}$$

EXAMPLE: What is the density of 5.00 mL of a fluid if it has a mass of 5.23 g?

$$d = \frac{m}{v}$$

$$d = \frac{5.23 \ g}{5.00 \ mL} = 1.05 \ \frac{g}{mL}$$

EXAMPLE: What would be the mass of 1.00 L of this sample?
$$m = V \ x \ d$$

$$m = \ 1.00 \ L \ x \ 1000 \ \frac{\cancel{mL}}{L} \ x \ 1.05 \ \frac{g}{\cancel{mL}} = 1.05 \ X \ 10^3 \ g$$

Accuracy vs. Precision

Accuracy and precision are terms often used to describe the reliability of measurements. However, they must be clearly differentiated. **Accuracy** refers to how close a measured value is to the real or "true" value. **Precision** refers to the degree of reproducibility of a measured quantity–the closeness of agreement when the same quantity is measured several times–how close the measurements are to each other. This difference is demonstrated in the following illustration:
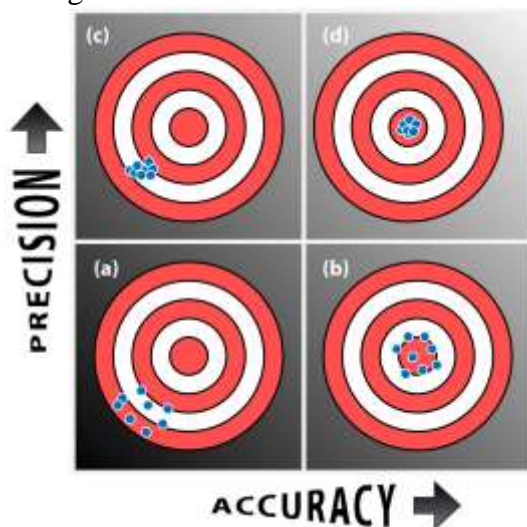
1www.extremetech.com/

Systematic Errors vs. Random Errors

Systematic error (determinate error): Built-in, inherent error. It always <u>occurs in the same direction each time</u>; it is always high or always low. A systematic error <u>can be corrected</u> by proper calibration or running controls or blanks. E.g. a thermometer consistently gives readings that are 2 °C too low. Large systematic errors <u>lower the accuracy</u> of a measurement.

Random error (indeterminate error): A measurement has an equal probability of being too high or too low. It is <u>due to limitations in an experimenter's skills</u> or ability to read scientific measurements. It <u>cannot be corrected</u>. Large random errors <u>lower the precision</u> of the measurements (e.g., the temperature in room varies "wildly").

EXAMPLE 1: Weigh a piece of brass five times on the analytical balance and obtain the following results:

Weighing	Result
1	2.486 g
2	2.487 g
3	2.485 g
4	2.484 g
5	2.488 g

Average = (2.486 g + 2.487 g + 2.485 g + 2.484 g + 2.488 g) / 5 = 2.486 g

Normally, we would assume that the true mass of the piece of brass is very close to 2.486 g, the average of the five results.

However, if the analytical balance has a defect causing it to be consistently 1.000 g too high (a systematic error of +1.000 g), then the measured value of 2.486 g would be seriously in error.

The point: high precision among several measurements is an indication of accuracy only if systematic errors are absent.

EXAMPLE 2: To check the accuracy of a graduated cylinder, fill the cylinder to the 25 mL mark using water delivered from a burette and then read the volume delivered.

Trial	Volume Shown by Cylinder Graduated (mL)	Volume Shown by Burette (mL)
1	25	26.54
2	25	26.51
3	25	26.60
4	25	26.49
5	25	26.57
Average	25	26.54

The results show good precision (for a graduated cylinder) – the student has good technique.

However, the average value measured using the burette is significantly different from 25 mL.

Thus, this graduated cylinder is not very accurate. It produces a systematic error (in this case, the result is low for each measurement).

Ways of Comparing Experimental Values

Percent Error: used to compare an unknown value with a theoretical value. It is a measure of the degree of accuracy.

$$\%Error = \frac{|Theoretical\ value - Experimental\ value|}{Theoretical\ Value} \times 100\%$$

Percent Difference: used to compare two experimental values which are expected to be the same. It is a measure of the degree of precision. It is also used to compare two values which are not necessarily expected to be the same. (Particularly useful to determine which are the best runs to use for calculations in titration experiments)

$$\%\ Difference = \frac{|Value\ 1 - Value\ 2|}{\left(\frac{Value\ 1 + Value\ 2}{2}\right)} \times 100\%$$

EXAMPLE: A % different calculation between other combinations of runs must be done and only the best two runs (e.g the ones with the smallest % difference) that are < 1% are used in further calculations.

Runs	% Difference
1 & 2	1.79 %
1 & 3	0.97 %
2 & 3	0.82 %

The best runs to use would be 2 & 3 since their % difference is smallest of those < 1%.

Percent Change (or Percent Recovery): used to compare two values which are different due to an imposed stress on a system. It is a measure of the degree of the effect caused by the stress.

$$\% \ Change = \frac{|Old \ value - New \ value|}{Old \ value} x \ 100\%$$