SCIENTIFIC MEASUREMENTS

A BRIEF HISTORY OF MEASUREMENT

Measurement was among one of the first intellectual achievements of early humans. People learned to measure centuries before they learned how to write and it was through measurement that people learned to count.

People of the Peking and Neanderthal periods had implements constructed from materials individually determined to be the right length or weight for a particular purpose. A tool that worked well became the model and standard for another. (See Figure 1) To measure distance, they used their fingers, hands, arms, legs, etc... Measurement of weights were based on use of certain containers or what a person or beast could haul. Each unit was separate and unrelated since their ability to count was not developed.

Figure 1. A stone ax and stones cut to the same size by comparison measurements from the Hittite Museum in Cappadocia, Turkey.

Since humans have ten fingers, we learned to count by tens, and ways were soon found to relate units to each other. Some of the most well known of the early units of measurement were:

inch -	the width of the thumb.
digit -	the width of the middle finger (about 3/4 inch)
palm -	the width of four fingers (about 3 inches)
span -	the distance covered by the spread hand (about 9 inches)
foot -	the length of the foot. Later expressed as the length of 36 -barleycorns taken from the middle of the ear (about 12 inches).
cubit -	distance from the elbow to the tip of the middle finger (about 18 inches).
yard -	distance from the center of the body to the fingertips of the outstretched arm (about 36 inches).
fathom -	distance spanned by the outstretched arms (about 72 inches).

Of course, these units varied from person to person, creating many difficulties. When individuals worked together, the leader would use his body as the sole authority. Measurements would be matched to samples made by him. As measurement and tools became more sophisticated, measuring sticks were made.

Many early civilizations tried to set up systems of weights and measures:

> Shih Huang-Ti, a founder of the Chinese Empire has the Great Wall built during his rule. His design for Chinese unity was: one law, one weight, one measure. Only the Great Wall continues to stand.

The Egyptians had a strong system of measurement. The royal cubit was 524 millimeters (20.62 inches) in the Great Pyramid at Giza. Variations, however, have been found in the Egyptian empire.

The Greeks and Romans had strong systems of measurements, but these disintegrated with the empires.

Through the medieval period, people used measurements which became accepted in particular trades, but no standards existed. Generally, measurements standards for a region would be embedded in the wall of the city hall or in the central square of a town. (See Figure 2.) Finally, in an effort to introduce a standard into the measuring system, in the eleventh century, King Henry I, of England, defined the standard yard from the tip of his nose to the end of his thumb on his outstretched arm. In 1490, King Henry VII adopted an octagonal yard bar which was distributed as the national standard. Although the yard was changed about 100 years later, by Elizabeth I, the idea of a standard yard remained.

Figure 2. *Above:* Measurement standards embedded in the wall of the city hall in Assisi, Italy. The measurements are the foot, the cubit, and the yard. *Right:* Measurements in the wall of the city hall in Regensburg, Germany. The measurements are the foot, the yard, and the fathom.

A parliamentary Committee undertook the job of clearing away the medieval weights and measures, setting up a standard system of weights and measures in 1824. The Americans, already accustomed to the English system of weights and measures, set up their system which became standardized in the mid-1900's.

While the British and Americans were trying to standardize their weights and measures, the National Assembly of France called upon the French Academy of Science, on May 8, 1790, to “deduce an invariable standard for all of the measures and all weights”.

In 1791, the French National Assembly approved the report of the French Academy of Sciences outlining the metric system. On June 19, 1791, a committee of 12 mathematicians, geodesists, and physicists met with Louis XVI and received his formal approval, one day before he tried to escape from France and was arrested.

The metric system was adopted by France in 1795, but it existed along with use of the old medieval units until 1840 when it proclaimed as the exclusive system of weights and measures.

In 1875, the metric system was universally accepted at the International Metric Convention in France and provisions were made to set up an International Bureau of Weights and Measures in Paris.

At the 11th General Conference on Weights and Measures, in Paris in October 1960, the definitions of the original metric standards were redefined to 20th-century standards of measurement and a new International System of Units was formulated.

THE INTERNATIONAL SYSTEM OF UNITS (SI)

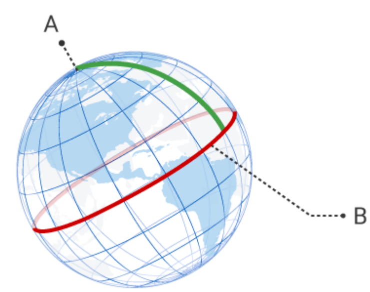
The International System of Units, as amended in 1971, consists of seven base units as listed in Table 1.

Table 1. SI Base Units

Quantity Measured	Unit	Symbol
Length	meter	m
Mass	kilogram	kg
Time	second	s
Thermodynamic temperature	kelvin	K
Amount of substance	mole	mol
Electric current	ampere	A
Luminous intensity	candela	Cd

The five base units that are useful in general chemistry are defined below:

1. The **meter** (m) was originally measured to be one ten-millionth of the distance from the north pole to the equator along the meridian running near Dunkirk, Paris, and Barcelona. It was redefined in 1971 as the length of path traveled by light in a vacuum during the time interval of 1/299 792 458 second.



2. The **kilogram** (kg) is the mass of a particular cylinder of platinum-iridium alloy, called the International Prototype Kilogram, kept at the International Bureau of Weights and Measures in Serves, France. The kilogram, the only unit defined by an artifact, was derived from the mass of a cubic decimeter of water.

In 2018, the kilogram was defined by taking the fixed numerical value of the Planck constant *h* to be $6.62607015 \times 10^{-34}$ when expressed in the unit J·s

(Joule·second), which is equal to kg·m^2·s^{-1}, where the meter and the second are defined in terms of *c* (the speed of light) and $\Delta\nu_{Cs}$ (a specific atomic transition frequency). This is almost exactly the same as the mass of one liter of water.

3. The **second** (s) was originally defined as 1/86,400th of a mean solar day. It was redefined in 1967 as the duration of 9,192,631,770 periods of the radiation corresponding to the transition between two hyperfine levels of the fundamental state of a cesium-133 atom.

4. The **kelvin** (K) is 1/273.16 of the temperature interval between absolute zero and the triple point of water (the temperature at which ice, liquid water, and water vapor are in equilibrium). The Celsius scale is derived from the Kelvin scale. An interval of 1 K is equal to 1°C.

5. The **mole** (mol) is the amount of substance which contains as many entities as there are atoms in exactly 0.012 kg of carbon-12. This number is known as Avogadro's Number which has a value of 6.0220943 x 10^{23} per mole *6.3 x 10^{17} (determined by U.S. National Bureau of Standards in 1974).

Instead of having a large number of units of different sizes, such as inches, feet, years, fathoms, furlongs, and miles in the English system, it was decided to use prefixes which would multiply base units by multiples of tens for larger measurements and decimal fractions for smaller measurements. The prefixes used for multiples and submultiples of SI units are listed in Table 2. The prefixes commonly used in chemistry are printed in bold print.

Table 2. The SI prefixes

These prefixes multiply base units for larger measurements			These prefixes are decimal fractions that multiply base units for smaller measurements		
Prefix	Symbol	Multiple	Prefix	Symbol	Submultiple
exa	E	10^{18}	**deci**	d	10^{-1}
peta	P	10^{15}	**centi**	c	10^{-2}
tera	T	10^{12}	**milli**	m	10^{-3}
giga	G	10^{9}	**micro**	μ	10^{-6}
mega	M	10^{6}	**nano**	n	10^{-9}
kilo	k	10^{3}	**pico**	p	10^{-12}
hecto	h	10^{2}	femto	f	10^{-15}
deka	da	10	atto	a	10^{-18}

Prefix symbols are printed in Roman type with no space between the prefix symbol and the base unit symbol.

Examples: millimeter is mm
microsecond is μs

It should be noted that **the first letter of the SI abbreviation represents the prefix and the second letter represents the base unit.**

Among the base units, the kilogram has a prefix built into its name. The names of the decimal fractions and multiples of the kilogram are constructed using the appropriate prefix with the stem word "gram" (symbol: g).

Examples:	megagram is Mg	
	centigram is cg	

When a prefix is affixed to an SI unit, it multiplies the base unit by the appropriate factor listed in Table 2.

Examples:	millimeter:	1 mm = 10^{-3} m
	microsecond:	1 µs = 10^{-6} s
	megagram:	1 Mg = 10^{6} g
	centigram:	1 cg = 10^{-2} g
	kilometer:	1 km = 10^{3} m

Since the SI system is based on factors of ten, there are relationships between the metric prefixes that should be noted. Each of the first three prefixes above or below the base unit either multiply or divide the base unit by ten. After that, each prefix represents a multiplication or division by 1,000. The factors that relate the more commonly used SI prefixes are shown in Table 3.

Examples: Using m as the base unit:

1,000 pm = 1 nm
1,000 nm = 1 µm
1,000 µm = 1 mm
10 mm = 1 cm
10 cm = 1 dm

To convert between units with difference prefixes, multiply by the factors that occur between them. Some examples, using m as the base unit, are shown below.

To convert from nm to mm, we first note that there are 1,000 nm in 1 µm and 1,000 µm in 1 mm, then, to convert, multiply the two factors of 1,000 together to get:

1,000,000 nm = 1 mm

To convert from µm to cm, multiply the factors of 1,000 µm in 1 mm and 10 mm in 1 cm together to get:

10,000 µm = 1 cm

To convert from cm to km, multiply the factors of 100 cm in 1 m and 1000 m in 1 km to get:

$$100,000 \text{ cm} = 1 \text{ km}$$

Table 3. Relationship between SI prefixes

			Prefix	**Symbol**	**Multiple**
			mega	M	10^6
		1000			
			kilo	k	10^3
Base unit to mega: 1 000 000 units	Base unit to kilo: 1000 units	10			
			hecto	h	10^2
		10			
			deka	da	10
		10			
			[base unit]		
		10			
			deci	d	10^{-1}
micro to base unit: 1 000 000 units	milli to base unit: 1000 units	10			
			centi	c	10^{-2}
		10			
			milli	m	10^{-3}
		1000			
			micro	μ	10^{-6}
		1000			
			nano	n	10^{-9}
		1000			
			pico	p	10^{-12}

Table 4 lists SI-derived units with special names. The most commonly used units in general chemistry are listed in bold print. A number of these units are named in honor of individuals who did significant work in the area where the unit is often used.

Table 4. SI-Derived units with special names

Physical Quantity	Unit	Symbol	Formula
Frequency	**hertz**	Hz	(cycles) s^{-1}
Force	newton	N	kg · m s^{-2}
Pressure	**pascal**	Pa	N · m^{-2}
Energy	**joule**	J	N · m
Power	watt	W	J · s^{-1}
Electric potential difference	volt	V	W · A^{-1}
Electric charge	**coulomb**	C	A · s
Electric resistance	ohm	Ω	V · A^{-1}
Electric capacitance	farad	F	C · V^{-1}
Electric conductance	siemens	S	A · V^{-1}
Magnetic flux	weber	Wb	V · s
Magnetic flux density	tesla	T	Wb · m^{-2}
Inductance	henry	H	Wb · A^{-1}
Luminous flux	lumen	lm	cd · sr[(a)]
Illuminance	lux	lx	lm · m^{-2}
Activity (radionuclide)	becquerel	Bq	(disintegration) s^{-1}
Absorbed dose (radiation)	gray	Gy	m^2 · s^{-2}

(a) sr = steradian

Table 5 lists units that are derived from either SI base units or from the SI derived units with special names. The units from which each is derived are shown in the column labeled "Symbol"

Table 5. Other SI-Derived Units

Physical Quantity	**Unit**	**Symbol**
Area	square meter	m^2
Volume	cubic meter	m^3
Velocity	meter per second	$m \cdot s^{-1}$
Acceleration	meter per second squared	$m \cdot s^{-2}$
Wave number	1 (Wave) per meter	m^{-1}
Density	kilogram per cubic meter	$kg \cdot m^{-3}$
Concentration	mole per cubic meter	$mol \cdot m^{-3}$
Molar mass	kilogram per mole	$kg \cdot mol^{-1}$
Molar volume	cubic meter per mole	$m^3 \cdot mol^{-1}$
Heat capacity	joule per kelvin	$J \cdot K^{-1}$
Molar energy	joule per mole	$J \cdot mol^{-1}$
Electric field strength	volt per meter	$V \cdot m^{-1}$
Electric dipole moment	coulomb meter	$C \cdot m$

In general chemistry, there are certain non-SI units which may be retained due to widespread use. The definitions of some of these units are given below:

The **calorie** (cal) is the amount of heat needed to raise the temperature of 1.0 gram of water by 1°C at 15°C.

The **erg** is the energy involved when a force of one dyne acts through a distance of one centimeter.

A **dyne** (dyn), is the force required to produce an acceleration of one centimeter per second squared on a mass of one gram.

The **Angstrom** (Å) is a unit of length that was commonly used in describing sizes of atoms. One Angstrom is equal to one-tenth of a nanometer.

The **tonne** or metric ton (t) is equal to 1000 kg. It is an established commercial unit of volume.

The **atmosphere** (atm) is the unit of pressure based on the Earth's standard air pressure at sea level. One atmosphere pressure is equal to a barometric pressure of 760 mm Hg.

The **liter** (L) is an established unit of volume in nations using the metric system. It is equal to one cubic decimeter. (Formerly defined as one kilogram of water.)

Two units of energy that are used with SI whose values are obtained by experiment are:

The **electronvolt** (eV) is the kinetic energy acquired by an electron passing through a potential difference of 1 volt in vacuum.

The **unified atomic mass unit** (u) is equal to the fraction 1/12 of the mass of an atom of the nuclide ^{12}C

Table 6 lists these non-SI units with conversion factors to SI.

Table 6. Non-SI units used in chemistry with conversion factors to SI

Physical Quantity	SI Unit	Non-SI Unit	Symbol	Conversion Factor
Energy	joule	calorie	cal	1 cal = 4.184 J
	erg		erg	1 erg = 10^{-7} J
	electronvolt		eV	1 eV = 1.60219 x 10^{-19} J
Force	newton	dyne	dyn	1 dyn = 10^{-5} N
Length	meter	Angstrom	Å	1 Å = 10^{-10} m = 10^{-1} nm
Mass	kilogram	tonne	t	1 t = 10^{3} kg
	atomic mass unit		amu	1 amu = 1.66057 x 10^{-27} kg
Pressure	pascal	atmosphere	atm	1 atm = 1.013 x 10^{5} Pa
			torr or mm Hg	1 torr = 1 mm Hg = 133 Pa
Temperature	kelvin		K	
	Celsius		°C	1°C = 1 K
Volume	cubic meter	liter	L	1 L = 1 dm^3 = 10^{-3} m^3
Time	second	minute	min	1 min = 60 s
		hour	hr	1 hr = 3600 s
		day	d	1 d = 86 400 s

Two conversion factors which will be extremely useful, especially in laboratory work are:

The relationship between volume in cubic centimeters and the non-SI unit of liters:

$$1\ cm^3 = 1\ mL$$

Note: A cubic centimeter is sometimes called a cc in the medical field

The relationship between volume and mass of water is:

$$1\ mL\ H_2O = 1\ g\ H_2O$$

SOME ENGLISH-SI CONVERSION FACTORS

Although modern chemistry uses only SI units, it may be useful to know some English-SI conversion factors in the event it may be necessary to convert between the English system and the SI system. There are a great number of conversion factors that apply to the large number of English units. The ones that will be most useful in everyday encounters are:

Length:	1 in = 2.54 cm
Volume:	1.057 qt = 1 L
Mass:	1 lb = 453.6 g

Since length has many English units with different names, some other useful conversion factors for length are:

39.37 in = 1 m

1 mi = 1.609 km

Another useful conversion factor for mass is:

2.2 lb = 1 kg