SECTION 7

MEASUREMENT: QUANTITIES, NUMBERS AND UNITS

> In this section the language of measurement, which is central to chemistry, will be introduced. Chemists might measure a number of variables such as pressure, temperature, mass, and volume and use the experimental values to calculate some other property. The purity of a compound or the concentration of a compound in a commercial product are possible examples. The chemist needs to be able to record data and do calculations in a precise and unambiguous format. This requires a universally adopted language involving concepts, symbols and rules. While the average lay person knows little of these, knowledge of them is essential to the practising of chemistry. This section follows the recommendations of the International Union of Pure and Applied Chemistry (IUPAC), the international governing body for chemistry.

Quantity: A property that is measured [e.g. mass, length, time, volume, pressure].

Unit: A standard quantity against which a quantity is measured [e.g. gram, metre, second, litre, pascal; which are units of the above quantities].

Chemists measure various quantities. If the mass of a substance was found to be 6.0 grams this can be expressed as an equation

$$m = 6.0 \text{ g}$$

Here m is the symbol for the quantity *mass*, 6.0 is a number and g is the symbol for the gram, a standard quantity of mass. The equation is shorthand for

$$mass = 6.0 \text{ x (1 gram)}$$

In general an equation of measurement takes the form

$$quantity = \text{(number) x (unit)}$$

In print, the symbols for quantities are shown in italics and for units in regular type as is done above.

The equation may be manipulated by the normal rules of algebra. Thus the heading of a table or the axis of a graph could be labelled m/g (i.e. mass in grams) and numbers only tabulated or shown on the axis.

It is important to realise that the magnitude of a quantity expressed as a number without units for the quantity is meaningless unless the quantity is in fact a ratio and is dimensionless (i.e. has no units since the units in the numerator and denominator cancel).

Many quantities are defined in terms of other quantities. Thus **density**, symbol ρ, is defined as mass per unit volume. Thus if the mass and volume of a sample of a substance are known, the density is calculated by dividing the mass by the volume, density = mass/volume or $\rho = m/V$.
[e.g. a 5 cubic centimetre sample has a mass of 15 grams. Calculate its density.
$\rho = m/V = 15 \text{ g}/5 \text{ cm}^3 = 3 \text{ g cm}^{-3}$.]

For many quantities there are different systems of units. It is essential that one can convert from one set of units to another. This is simply done by replacing the units in the equation by their values in terms of the desired unit [e.g. If the velocity of a particle is 200 miles per hour

what is it in metres per second? 1 mile = 1609 m. 1 hour = 3600 s

The velocity is 200 miles per hour

v = 200 miles/hour = 200 miles (hour)$^{-1}$ = 200 x (1609 m) x (3600 s)$^{-1}$ = 89.4 m s^{-1}].

Units

International System of Units (SI units): The internationally adopted system which defines or expresses all quantities in terms of seven basic units, the six used by chemists being:

length	metre	m
mass	kilogram	kg
time	second	s
temperature	kelvin	K
amount of substance	mole	mol
electric current	ampere	A

Other quantities commonly used in chemistry, and which have special names for the units derived from these basic units are:

frequency	hertz	Hz	s^{-1}
energy	joule	J	kg m^2 s^{-2}
force	newton	N	kg m s^{-2} = J m^{-1}
pressure	pascal	Pa	kg m^{-1} s^{-2} = N m^{-2}
power	watt	W	kg m^2 s^{-3} = J s^{-1}
electric charge	coulomb	C	A s
electric potential difference	volt	V	kg m^2 s^{-3} A^{-1} = J A^{-1} s^{-1}

Further quantities used in chemistry but without special names for the derived units are:

area, m^2; *volume*, m^3; *density*, kg m^{-3}; *absorbance*, dimensionless (therefore no units).

Coherent SI units: The base units, and those derived from them. Thus all the units shown above are coherent SI units. Note that the base unit of mass is the kilogram. This is the only base unit which has a multiple prefix (see below). If, in a calculation of a quantity involving several other quantities, only coherent SI units are used, the units of the required quantity will be coherent (i.e. the appropriate base unit).

The sizes of these units are often unsuitable for some measurements and the decimal multiples, shown below with the name and symbol of the prefix, are used:

10^{-18}	atto	a		10	deca	da
10^{-15}	femto	f		10^2	hecto	h
10^{-12}	pico	p		10^3	kilo	k
10^{-9}	nano	n		10^6	mega	M
10^{-6}	micro	μ		10^9	giga	G
10^{-3}	milli	m		10^{12}	tera	T
10^{-2}	centi	c		10^{15}	peta	P
10^{-1}	deci	d				

Some multiple units have their own name, the three relevant for chemists being:

mass	tonne	t	$1 \text{ t} = 10^3 \text{ kg} = 1 \text{ Mg}$
volume	litre	L	$1 \text{ L} = 10^{-3} \text{ m}^3 = 1 \text{ dm}^3 = 10^3 \text{ cm}^3$
length	ångström	Å	$1 \text{ Å} = 10^{-8} \text{ cm} = 10^{-10} \text{ m} = 100 \text{ pm}$

Units may be written out in full or the symbol used. A mixture of full word and symbol is not permitted [e.g. kgram is not permitted]. The letter s is never added to the symbol to indicate a plural. A full stop is not written after symbols except at the end of a sentence. Those symbols named after a person have a capital first letter, but when the name of the unit is written out in full a lower case first letter is used [e.g. J, joule].

When two or more symbols are combined to indicate a derived unit, a space is left between them. A space is also left between the number and the symbol for the unit, but no space is left between the prefix indicating powers of ten and the symbol to which it applies. When symbols are combined as a quotient, [e.g. metres per second], either power to the minus one or the solidus may be used [e.g. m s^{-1} or m/s]. But the solidus may only be used once in a derived unit to avoid ambiguity [e.g. writing kg/m/s^2 for pascal could be interpreted as kg m^{-1} s^{-2} or as kg m^{-1} s^{2}].

Quantity calculus: The manipulation of the mathematical equations relating quantities and their measured values using the rules of algebra. All calculations in this manual follow the rules of quantity calculus. When one quantity is multiplied by another, no space is left between their symbols, [e.g. $m = \rho V$]. In calculations prefixes for multiples can be replaced by their numerical values. [eg. Convert the density of 3 g cm^{-3} into coherent SI units. The coherent units for density will be kg m^{-3}. $1 \text{ g} = 10^{-3} \text{ kg}$, and $1 \text{ cm} = 10^{-2} \text{ m}$. $\rho = 3 \text{ g cm}^{-3} = (3 \times 10^{-3} \text{ kg}) \times (10^{-2} \text{ m})^{-3} = 3 \times 10^3 \text{ kg m}^{-3}$.]

Some non-SI units are commonly used by chemists:

temperature	degrees Celsius	(the temperature intervals 1 $^{\circ}$C and 1 K are identical)
		0 $^{\circ}$C = 273.15 K
		0 K = -273.15 $^{\circ}$C
time	minute	min = 60 s
	hour	h = 60 min = 3600 s
	day	d = 24 h
pressure	atmosphere	atm = 1.013 x 10^5 Pa = 760 torr
	bar	bar = 10^5 Pa
	torr (mmHg)	torr = 133.3 Pa
energy	calorie	cal = 0.2390 J or J = 4.184 cal
	electron volt	eV = 1.602 x 10^{-19} J
	kilowatt hour	kWh = 3.6 x 10^6 J

The calorie, still widely used in USA, is the energy required to raise the temperature of 1 g of liquid water 1 $^{\circ}$C. Electron volts are useful at the atomic or molecular level, and kilowatt hours are the common unit for power consumption.

EXERCISES

Write the equations for the following statements using powers of 10 in place of prefixes.

1. *Example*: The density, ρ is 3 micrograms per cubic millimetre

    Answer: $\rho = 3 \times \mu g \ mm^{-3}$ (replacing micrograms with μg) $= 3 \times 10^{-6} \ g \ (10^{-3} \ m)^{-3}$ (replacing μ with 10^{-6} and m with 10^{-3}) $= 3 \times 10^{3} \ g \ m^{-3}$

2. The velocity, v, is 50 millimetres per second

3. The pressure, p, is 64 meganewtons per square centimetre

4. The concentration, c, is 2.8 nanograms per microlitre

Express the following numbers under the given heading in a table as a normal equation for the quantity.

5. *Example*: 4.2 under the heading $10^{5} \ m/g$ *Answer*: $10^{5} \ m/g = 4.2$ $m = 4.2 \times 10^{-5} \ g$

6. 23 under the heading $10^{-2} \ t/s$ 7.   7.   8 under the heading $10^{5} \ p/Pa$

Convert the following quantities to coherent SI units.

8. *Example*: $q = 230$ cal   *Answer*: $q = 230 \ (4.184 \ J) = 962 \ J$

9. $T = 27 \ ^{o}C$ 10. $t = 32$ h   11. $p = 61$ mmHg (mmHg = 133.3 Pa)

12. $\rho = 34 \ lb \ ft^{-3}$ (lb = 454 g, ft = 12 in, in = 2.54 cm)