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BASIC CHEMICAL CONCEPTS

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ABSTRACT: Precise definitions are given of basic chemical concepts (matter, material; solid, liquid, gas, vapour; mixture, substance, solution, solvent, solute; physical, physicochemical, chemical, radiochemical; element, compound, allotropy, stoichiometric, nonstoichiometric). These definitions are formulated entirely at a macroscopic level, and are suitable for presentation to beginners. [*Chem. Educ. Res. Pract.*: 2003, 4, 19-24]

KEY WORDS: *basic chemical concept; matter; material; solid; liquid; gas; vapour; mixture; substance; solution; solvent; solute; physical; physicochemical; chemical; radiochemical; element; compound; allotropy; stoichiometric; nonstoichiometric*

INTRODUCTION

Most teachers find the basic concepts of chemistry (“matter”, “substance”, “element”, “compound”, “solution”, etc.) difficult to teach (see, e.g., Barker, 2000). This is partly because the definitions of these concepts given in textbooks either lack precision, or invoke ideas that beginners are not familiar with, and have to accept on trust. For example, some introductory texts cite the IUPAC definition of an element (Leigh, 1990): “matter, all of whose atoms are alike in having the same positive charge on the nucleus”. This plunges beginners immediately into the world of atoms and atomic structure. As Alex Johnstone (1999, 2000) has explained, this goes against the psychology of learning. Chemistry is only fully intelligible to beginners if it is taught progressively, starting with observations at the macroscopic level, and deriving atomic and subatomic ideas from these (Nelson, 2002, and refs. therein).

In this paper, I develop a set of definitions of basic chemical concepts that can be presented to beginners. These definitions are formulated entirely in macroscopic terms. They can be explained at an atomic or subatomic level later in a course, but they stand up without this. They are all based on experimental observations that can be made with suitable equipment. A summary in alphabetical order is given at the end. The definitions are as simple and precise as I could make them. Suggestions for improvement would be welcomed.

EXPOSITION

In the following exposition, I keep to language that can be understood by beginners. Where complications arise at a more advanced level, I comment on these in numbered notes. I do not intend that these comments should be given to beginners unless they raise the issues themselves.

Matter

Chemists are interested in different kinds of *matter* (air, water, sand, salt, steel, petrol, sugar, aspirin, etc.). Matter occupies space, has mass, and so can be weighed. This distinguishes it from light and similar radiation.¹

A particular kind of matter (e.g. air) is called a *material*. Here I use the word in its broadest sense, to cover all kinds of matter, not just useful kinds. The popular meaning can be indicated by defining a material as “a particular kind of matter, especially one that is intended for some use”.

There are three main states of matter: *solid*, *liquid*, and *gas*. A solid has its own volume and shape. A liquid has its own volume but takes the shape of the vessel it is in. A gas fills the vessel it is in — it takes up the vessel’s volume and shape. (A powder takes the shape of the vessel it is in, but the individual grains have their own shape.)

Solid materials differ from one another in size or shape (e.g. steel plate, steel rod, steel wire, and steel wool), and in what they are made of (e.g. steel wire and copper wire). Materials differing only in size or shape are said to be made of the same *basic material* (e.g. “steel”).²

There are two main types of basic material: *homogeneous* and *heterogeneous*. The former appear uniform under an optical microscope, the latter not.³ The latter are *mixtures* of the former.

Basic materials can be made from other basic materials. Students can be shown examples of this in the laboratory, and be taken to see some industrial processes (e.g. smelting of iron and manufacture of steel).

Chemistry may be defined as the study and practice of making basic materials and determining their character. This embraces “pure” chemistry (“the study...”) and “applied” chemistry (“the practice...”) (cf. Nelson, 1983). It also includes the preparation of mixtures, other than by simple mixing of components. The ability of basic materials to change into other, often quite different, basic materials is what makes chemistry both interesting and useful.

Substances and solutions

Homogeneous basic materials can be divided into *substances* and *solutions*. I am here using “substance” in a technical sense; in popular usage most homogeneous materials are called substances.⁴

A solution is a combination of substances in varying proportions. The principal component [the one that gives the solution its state (solid, liquid, or gas), or, if more than one component does this, the one that is in the larger amount] is called the *solvent*; minor components are called *solutes*. Ranges of composition always start at 0% of solute; solutions can thus always be diluted by adding more solvent (cf. below).

Chemists separate components of solutions by distillation, crystallization, solvent extraction, chromatography, and other methods. A homogeneous basic material is a substance if it cannot be separated into components that can be recombined in varying proportions as for a solution.⁵

Substances may be pure or impure. Impure substances contain small quantities of other substances, either mixed with them or dissolved in them. Pure substances melt and boil at a constant temperature,⁶ impure substances generally do not.⁷

Substances can be distinguished from one another by their state at room temperature and atmospheric pressure (solid, liquid, or gas), colour, density, melting point, boiling point, solubility in different solvents, action on other substances, and other properties.

Substances can exist in different *forms* depending on the temperature and pressure. These are typically: crystalline solid, liquid, and gas (or, for substances that are solid or liquid at room temperature and atmospheric pressure, *vapour*⁸). Additionally, some substances can exist in more than one crystalline form (*polymorphism*), or in forms of other kinds (e.g. vitreous).⁹

That the same substance can exist in different forms is suggested by the fact that many coloured substances keep their colour when they change from one form to another (e.g., chlorine keeps its yellow colour when it condenses to a liquid or freezes to a solid; metals retain their colour when they melt).

Substances commonly keep their colour when they change form. There are, however, exceptions, especially among changes taking place at high temperatures or pressures (e.g., when mercury boils it gives a colourless gas). In these cases, the question arises, has the substance changed form, or into another substance? Chemists do not have an agreed answer to this question, but by the colour criterion for differentiating substances,¹⁰ the second answer is surely correct (i.e. mercury vapour is a different substance from liquid mercury).¹¹

The above discussion relates to coloured substances. It can be extended to colourless ones by analogy.¹² If a colourless substance melts or boils at relatively low temperatures (<200 °C), it is likely to be changing in form. If it does so at relatively high temperatures, it may be changing in substance.

Another form of a substance is as a solute in a solution. Coloured substances often keep their colour in solution (e.g. chlorine in water, gold in silver). This implies that they somehow retain their identity in solution. There are, however, many exceptions (e.g. chlorine in alkali, metals in acids). In such cases, dissolution involves a change of substance. This shows itself (usually) when the resulting solution is re-separated into components: the solute turns out to be a new substance or mixture of substances, formed by action of the solvent on the original solute (e.g. chlorine in alkali gives hypochlorite and chloride).

By analogy, colourless substances giving colourless solutions may or may not retain their identity in solution. Change of substance may be indicated by a property other than colour (e.g. hydrogen chloride in water gives conducting solutions), or if re-separation of the solution gives a new solute or solutes (e.g. carbon dioxide in alkali gives carbonate).¹³

Substances can thus undergo three kinds of change: *physical*, *physicochemical*, and *chemical*. In a physical change (e.g. compression of air) there is no change in substance or form; in a physicochemical change (e.g. melting of lead, dissolution of chlorine in water) there is a change in form but not of substance; in a chemical change (e.g. rusting of iron, boiling of mercury, dissolution of chlorine in alkali) there is a change of substance.¹⁴ Properties relating to the three kinds of change are likewise called physical, physicochemical, and chemical. The first two categories are usually conflated, but it helps to distinguish them.

Substances can also undergo a fourth kind of change: *radiochemical*. In this there is a change of substance and absorption or emission of high-energy radiation.¹⁵

Elements and compounds

Substances can be divided into *elements* and *compounds* on the basis of the chemical changes they are involved in. Compounds decompose into other substances, elements do not.¹⁶ Likewise, compounds can be made by combination of other substances, elements cannot. Compounds ultimately decompose into, and can be made from, elements.

These considerations are helped by weighing the substances involved. When a compound decomposes, the masses of the products sum to the mass of the compound (an instance of the law of conservation of mass). Masses likewise balance when a compound is made by the combination of other substances. The conclusion from such studies is that the

mass of a compound is equal to the sum of the masses of the elements of which it is composed.

Some elements exist as more than one substance (this is over and above any change in substance with change of state, as discussed above for mercury). For example, carbon exists as graphite, diamond, buckminsterfullerene, etc. This phenomenon is called *allotropy*, and the different substances are called *allotropes*. They can be interconverted without change in mass, and combine with other substances to give the same compounds (e.g., the allotropes of carbon all burn in oxygen to give carbon dioxide). Different crystalline forms of an elementary substance (e.g. α - and β -sulfur) are also called allotropes.

Many compounds have a fixed composition, i.e., the proportions by mass of the elements comprising them are constant (the phenomenon of constant composition). Such compounds are called *stoichiometric* compounds or *Daltonides*. Compounds of variable composition [e.g., ferrous oxide (wüstite), which, when made at 1000 °C and atmospheric pressure, can contain from 23.1 to 24.6% by mass of oxygen (Hansen, 1958)] are called *nonstoichiometric* compounds or *Berthollides*. They differ from solutions in that the range of composition does not start at 0% for any component.¹⁷

SUMMARY OF DEFINITIONS

Allotropy: existence of an element as more than one solid, liquid, or gaseous substance, or in more than one crystalline form.

Basic material: what a material is made of as opposed to its size or shape.

Chemical change: one in which there is a change of substance.

Chemical property: one relating to chemical change.

Chemistry: the study and practice of making basic materials and determining their character.

Compound: a substance that can be made from or decomposed into elements.

Element: a substance that does not undergo chemical decomposition into, and cannot be made by chemical combination of, other substances.

Form of a substance: crystalline solid, liquid, gas, in solution, etc., depending on the substance.

Gas: matter not having its own volume or shape.

Liquid: matter having its own volume but not shape.

Material: a particular kind of matter, especially one that is intended for some use.

Matter: that which occupies space and has mass.

Mixture: a heterogeneous basic material.

Nonstoichiometric compound: a compound of variable composition.

Physical change: one in which there is no change in substance or form.

Physical property: one relating to physical change.

Physicochemical change: one in which there is a change in form but not substance.

Physicochemical property: one relating to physicochemical change.

Polymorphism: existence of more than one crystalline form of a substance.

Radiochemical change: one in which there is a change of substance and absorption and emission of high-energy radiation.

Solid: matter having its own volume and shape.

Solute: minor component of a solution.

Solution: a homogeneous basic material that can be separated into components that can be recombined in varying proportions starting with 0% of one.

Solvent: principal component of a solution.

Substance: a homogeneous basic material that cannot be separated (by the methods chemists usually employ) into components that can be recombined in varying proportions as for a solution.

State of matter: solid, liquid, gas, etc.

Stoichiometric compound: a compound of constant composition.

Vapour (ordinary meaning): gaseous form of a substance that is a solid or liquid at room temperature and atmospheric pressure.

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NOTES

¹ At an advanced level, matter has to be distinguished from antimatter.

² Here “steel” refers to ordinary, “mild” steel, containing 0.1–0.3% by mass of carbon.

³ There is also an intermediate type: *colloidal*. Colloids appear uniform under an optical microscope when illuminated from below, but not from the side (see, e.g., Partington, 1954).

⁴ Chemical usage in the past has varied (see, e.g., Partington, 1949; Simpson & Weiner, 1989). Some chemists have used “substance” in a broad sense and divided substances into “pure substances” and solutions. Others have defined “substance” to exclude solutions. The editor and a reviewer tell me that current practice is to exclude solutions.

⁵ A complication at this point is that many substances that cannot be separated into components of a solution by the methods chemists usually use can be so separated by special methods (e.g. fractional distillation of a large quantity, repeated many times). The components obtained by these methods have very similar properties except in their ability to absorb or emit high-energy radiation. For example, water can be separated into components having densities (at 25 °C) of 0.997 and 1.104 g/cm³. Their freezing points are respectively 0.0 and 3.8 °C, and their boiling points 100.0 and 101.4 °C. Both turn anhydrous cupric sulfate blue, but the first absorbs neutrons 720 times more effectively than the second (see, e.g., Greenwood & Earnshaw, 1984). This difficulty can be resolved by calling the materials obtained by the methods of separation chemists usually use *ordinary* substances. This need not be made explicit until later in a course, when isotopes are introduced (Nelson, 2002).

⁶ As far as can be ascertained by ordinary methods: by special methods isotopic variation can be detected (cf. previous note).

⁷ Constant melting point is shared by some mixtures (“eutectic”) and constant boiling point by some solutions (“azeotropic”).

⁸ A more advanced definition is “a fluid below its critical temperature” (see Simpson & Weiner, 1989).

⁹ Some substances can exist in more than one liquid form, one isotropic, the others anisotropic (“liquid crystals”).

¹⁰ A change of colour does not always indicate a change of substance. For example, zinc oxide turns yellow on heating; freshly precipitated cuprous oxide changes from yellow to red on digestion. However, these colour changes are *continuous* (in the first case, with increase in temperature, in the second, with size of the particles). (Continuous colour changes also occur when coloured components of a solution are in equilibrium with each other, and the position of equilibrium shifts. In this case, however, the colour of the solution is a changing *combination* of the colours of the components, as can be demonstrated by colorimetry.)

¹¹ This is supported by considerations at an atomic level. Boiling of mercury involves breaking of metal–metal bonds, whereas boiling of chlorine only van der Waals bonds.

¹² Once spectroscopy has been introduced, simple comparison of near-infrared and ultraviolet spectra can be used.

¹³ See previous note.

¹⁴ There is no virtue in trying to define these changes more precisely at this stage. Further consideration can wait until atoms and molecules have been introduced, and changes can be analysed at this level.

¹⁵ I include this type here to delimit the scope of “chemical”. I only intend that it should be mentioned briefly, in the macroscopic terms I have used.

¹⁶ Not in a chemical change. They do in radiochemical ones.

¹⁷ At an advanced level, some nonstoichiometric compounds can be regarded as stoichiometric compounds in which components (or other stoichiometric compounds of the components) are partially soluble [e.g. $\text{CuAu}_{0.6-1.6}$ as solid solutions of Cu or Au in CuAu (Hansen, 1958)]. However, this is only possible if there is an ideal stoichiometry within the composition range [there is not for, e.g., ferrous oxide at 1000 °C and atmospheric pressure, $\text{Fe}_{0.88-0.95}\text{O}$ (Wells, 1984)]. The distinction between stoichiometric and nonstoichiometric compounds therefore still stands.

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