Using waste and recycling as a way in to the periodic table

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Abstract The periodic table is for elements, but can we make sense of the millions of compounds in our environment? The answer explained here is to classify them according to their physical properties, the same properties we use when we recycle – metals, ceramics (glass), plastic and organic waste, paper, plus the volatile waste we send up the chimney or down the drain. Add in ionic substances like ash and we have just five different sorts of compound. We find the same five groups when we look at the ways elements bond. Forget classifying substances into solid, liquid or gas and go, instead, for these five types: metals, ceramics, life polymers (both biodegradable and plastics), volatile and ionic, and learn about elements and compounds from the things we throw away.

Sorting rubbish

We sort materials for recycling into glass, paper, biodegradable, plastics and metal. We also throw away our waste gases into the air and our dirty water down the drain. These materials are made from:

- metals and alloys (made from metallic elements only) such as steel, brass and aluminium;
- volatile substances (formed entirely from non-metallic elements) – gases and liquids, such as nitrogen, water, carbon dioxide, oxides of nitrogen, oil, water, wax and alcohol;
- carbon (or life-) polymers (formed from a backbone of carbon with other non-metallic elements):
  - **a** biodegradable, such as food scraps, garden waste and paper;
  - **b** non-biodegradable such as polythene and other synthetic polymers;
- rocks and ceramics (giant structures based on silicon) such as glass, pottery and concrete;
- ionic substances (formed when reacting a metal with a non-metal) such as salt, cement and baking powder.

Each of these has its own properties, making it essential that they are sorted separately when we recycle our rubbish. Let's now explore the link with the periodic table.

All possible combinations of elements in the periodic table

Elements range from the very reactive metals such as potassium and caesium on the left and at the bottom of the periodic table, to the very reactive non-metals such as oxygen and fluorine on the right and at the top of the table. Twist the table 45° clockwise and squash it down to form a line and you have the elements arranged pretty much according to their electronegativity, from caesium (0.7) to fluorine (4) (see the top of Figure 1). Electronegativity is a measure of how metallic or non-metallic they are in behaviour. In the middle we have elements such as silicon and germanium, which are neither one nor the other. You can see this animated in the second of the two Fuse School videos mentioned at the end.

Caesium, (the most reactive metallic element) reacts with fluorine (the most reactive non-metallic element) forming the stable, unreactive compound 'caesium fluoride', which is totally unlike its constituent elements – it is the most extreme compound if you will. We now construct a triangle by drawing lines from Cs and F to meet at the apex, which represents CsF (see lower part of Figure 1). All other possible compounds are located within the triangle at the place where the lines that are drawn from the two elements parallel to the sides of the big triangle meet. To map compounds made from more than two elements, take a weighted average of the points created by each single pairing. We will see that this 'structure triangle' divides into four regions: metals, giant structures, volatile and ionic. Try yourself and see that it does work for aluminium silicate (rock) and calcium carbonate (ionic).

Metals and alloys

When two metallic elements combine, the 'compound' will fall within the top left region of the triangle labelled metals and alloys; for example, copper and zinc 'react' to form the alloy brass.

Giant structures, rocks and polymers

Compounds formed from elements from the middle of the table are giant covalently bonded rock-like structures with similar properties to the element; for example, silicon carbide and gallium arsenide are like the element silicon. Carbon tends to form chains, sealed off along its length by hydrogen, rather than the three-dimensional structures associated with the rock-like silicon–oxygen systems. Thus the inner triangle is filled with giant structures typified by silicon–oxygen (rock-like) and carbon–hydrogen (life-like).

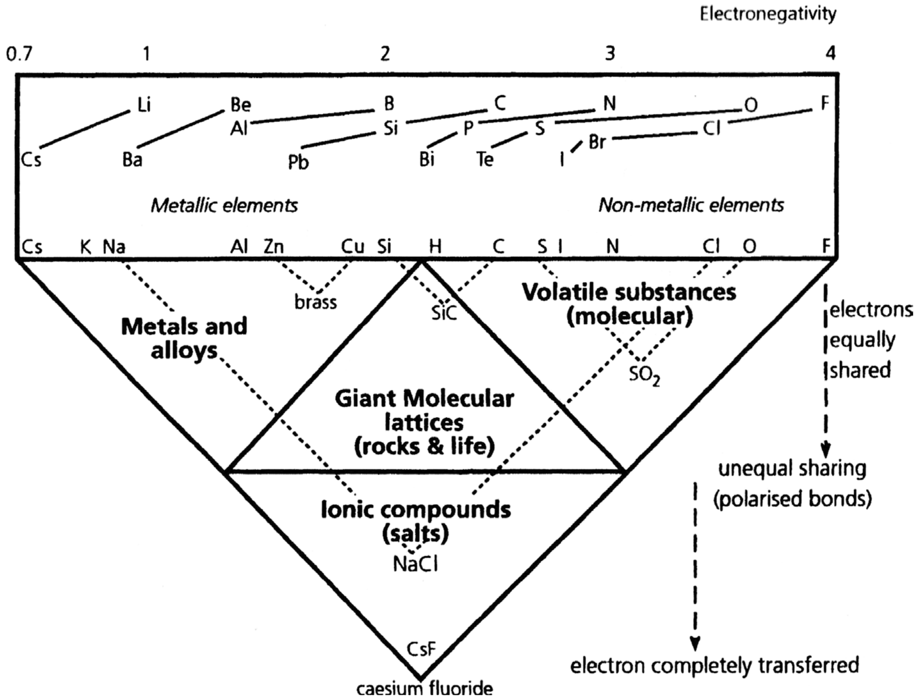

Figure 1 The structure triangle, with the 'twisted' periodic table above where electronegativity values are given along the top; diagonal lines in the top section show the first seven groups of this twisted periodic table, squashed flat to form the top line of the actual structure triangle

Volatile substances

All non-metallic elements from groups 5 to 7 are volatile (meaning they evaporate easily or are already a gas). When they react with another non-metal, they form volatile substances made of small self-contained molecules just like the original elements; for example, S and O give SO_2. This forms the top right region of the structure triangle.

Ionic

Only in the case of a metal reacting with a non-metal (as with the example of caesium and fluorine, above) do we get something completely different in structure from the elements – an (unreactive) ionic lattice exhibiting brand new properties, such as being an electrolyte. This forms the bottom of the triangle (see Figure 1) and is the only part that contains no elements, only compounds.

Bonding in these five structure types

These five types of structure represent the only ways in which atoms can bond. Let's consider them in turn, remembering that if two identical atoms approach in gaseous form they will form a covalent bond (except atoms from the inert gases). This process is animated in the first of the Fuse School videos and also explained in the *Science Issues* resource (see further reading at the end).

Metals and alloys

A sodium molecule, Na_2, can be observed in sodium vapour where two atoms share the two outer electrons. Normally, because there is plenty of space in their outer shells, more metal atoms will bond, building up a typical metallic lattice to either form the element or, with more than one metal, making an alloy. The electrons are not fixed or *localised* so the crystal conducts and the atoms can slide past each other, making metals ductile. The physical properties of the compound (alloy) are pretty much the same as the constituent elements. These are recycled as 'metals'.

Rocks and life polymers

Only four carbon atoms can surround an original carbon atom before the outer shell is full, but atoms can go on joining the structure forever, making the giant structure we call diamond. With silicon and oxygen, we get a brittle giant structure called sand, and with aluminium and other elements, other rocks are built up; however, if carbon is bonded with hydrogen, we get linear chains with a carbon backbone giving us the flexible giant structures of life and plastics. With silicon (and oxygen) we get similar flexible materials called silicones. The compounds, at least as far as the rocks are concerned, have properties similar to the element (carbon or silicon). These are recycled as 'glass', 'paper and card', 'biodegradable' and 'plastic'.

Volatile

Non-metallic elements have nearly full outer shells so only small self-contained molecules can form as the outer shells quickly become full. For example, once the two chlorine atoms are bonded, no more atoms can join, thus the bonded pair of atoms exists as a small independent molecule, making chlorine volatile, just like all other compounds made from these non-metallic elements. These are recycled in the sewage works or thrown away into the air.

Ionic

As the two atoms that are to bond become more and more different, the electrons in the bond are pulled more and more towards the more electronegative atom. The bond becomes polarised, and this polarisation increases as you go down the structure triangle. Eventually, the electrons forming the bond are essentially transferred from the metal atom to the non-metal atom, and we have ions that can take up separate existence, for example in a solid lattice or hydrated in water. If soluble, these are washed away down the drain, but if insoluble, they are recycled; for example, concrete is recycled as hardcore.

Less focus on ionic compounds and more on metals, carbon and silicon

By considering all possible combinations of two elements, we arrive at the same five categories used for recycling. Four categories (metals, rocks, polymer and volatile) contain both elements and compounds where the structure and bonding of the compounds is roughly similar to that of their constituent elements. The fifth category (ionic) contains only compounds; in this case, the structure and properties of the compound are completely different from its constituent elements. It is unfortunate that ionic chemistry has tended to dominate introductory courses in chemistry. In our everyday environment, ionic compounds hardly feature compared with the giant structures based on metals, carbon (life and plastics), silicon (rocks) and the volatile materials of fuels, air and water. It is the overemphasis on ionic chemistry that perpetuates the idea that compounds have totally different properties from those of the constituent elements. In the other three regions of the structure triangle, the compounds are bonded in the same way as their constituent elements, and properties are less differentiated.

By bringing in substances from home (see Box 1), students get an immediate feel that chemistry belongs to the real world. The substances we recycle are mostly made of metals and of compounds of carbon and silicon (metals, rocks and life polymers). The substances they meet in chemistry lessons are mostly ionic or volatile. Why not try to bring all five substances together using this simple introduction to the periodic table based on the materials we throw away.

Box 1 Ideas for teaching

To classify substances according to their physical properties rather than just as solid, liquid or gas, get students to pair up these 10 substances using our five categories. Ask them to consider how they might be grouped for recycling. (Alternatively ask them to bring in two ('clean') items of rubbish and use those instead, but make sure you have examples of all five to hand in case they are not brought in): *leather*, *cooking oil*, *wood-ash*, *glass*, *nylon*, *baking soda*, *copper*, *granite*, *steel*, *air*.

- Oil and air – *volatile*, both made of small independent molecules
- Leather and nylon – *life polymer*, both made of long carbon chains (but not recycled together because only leather is biodegradable)
- Copper and steel – both *metallic*
- Granite and glass – both giant *rock-like* structures (but glass is recycled separately!)
- Baking soda and wood-ash – *ionic*: both dissolve in water, which then conducts – wood-ash is the remains of the minerals taken up by the tree after the organic compounds (e.g. carbohydrates) join with oxygen during combustion and enter the atmosphere. (Ash is a good fertiliser and baking soda, like salt, if not needed will normally be washed down the drain.)

To show that compounds between similar elements retain the properties of the constituent elements, try these demonstrations (For *safely details* and more ideas see Ross (2018)):

1 warm a bead of sodium with a bead of potassium (they melt to form an alloy that is liquid at room temperature and behaves like an alkali metal);

2 warm an iodine crystal in a boiling tube full of chlorine (fitted with a Bunsen valve) to form the brown liquid ICl, which looks and behaves like bromine.

Here is some simple practical work that will help pupils sort out salt from sugar, show that ash is salt-like and show that water is beginning to behave like an ionic substance.

If you dip two wires from a low voltage circuit into water to test for conductivity, it fails because the resistance is too high. Try using two sheets of aluminium foil (10 cm square) and separate them with kitchen tissue paper (or filter paper). Use a 4.5 V battery, and 3.5 V bulb. You can show that no current flows when the paper is dry. Nor do you detect a current when wetted with oil, alcohol or distilled water. Now sprinkle one of the substances you want to test (ash, salt, sugar, etc.) onto the paper (which must be renewed each time, and the aluminium foil also needs to be cleaned and dried) and add a little more distilled water. The ionic materials will allow enough current to flow to light the bulb. It even works with tap water alone because of the traces of dissolved minerals. If you want to distinguish between distilled water (slight conductivity) and organic solvents such as lighter fluid, oil, or alcohol (no conductivity) then replace the bulb with an LED – it will light with the distilled water but not with the other solvents.

Resources

This article is based on the 'Matter' section of *Science Issues* – the resource we developed to reactivate an interest in and an understanding of science by primary teachers in training:

www.scienceissues.org.uk has a freely downloadable learning resource that covers pretty much the whole of the GCSE science curriculum. Look in 'Matter' and enter 'The 5 types of material' and 'The structure triangle'.

Further reading

Ross, K. A. (1997) Many substances but only five structures. *School Science Review*, **78**(284), 79–87.

Ross, K. A. (2000) Matter and life – the cycling of materials. In *Science Knowledge and the Environment: A Guide for Students and Teachers in Primary Education*, ed. Littledyke, M., Ross, K. A. and Lakin, L. Ch. 5. London: David Fulton.

Ross, K. A. (2017) Mapping compound structure and bonding: how everyday materials and compounds can be described with a 'structure triangle'. *Education in Chemistry*, 26 July. Available at: https://eic.rsc.org/3007749.article.

Ross, K. A. (2018) Laboratory demonstrations of reacting elements to form simple compounds. *School Science Review*, **100**(371), 9–12.

Websites

www.fuseschool.org has over 250 free short animated videos covering the whole of the GCSE chemistry syllabus. These two relate to the classification and bonding referred to in this article:

How Atoms Bond – Elements and Compounds Part 1(3:32 mins long)
https://www.fuseschool.org/topics/66#contents/1021

How Atoms Bond – Elements and Compounds Part 2 (5:50 mins long)
https://www.fuseschool.org/topics/66#contents/1108

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