Chlorine is an oxide, heat causes molecules to melt, and sodium reacts badly in chlorine: a survey of the background knowledge of one A level chemistry class.

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Abstract:

Teachers are advised to start from what the learners already know, and to teach them accordingly. If enrolment on a course is conditional on passing earlier examinations, as with Science A levels, it may be tempting to assume that the class will share some common background knowledge at the start of the course (that being the purpose of having entry requirements.) With significant pressure to complete syllabuses there is little time for systematically exploring what students already know. This paper argues that - despite the time constraints - some attempt at surveying what new students understand about the basics of a subject can be very illuminating. The argument is illustrated by an example: a case study of a single group of new A level Chemistry students. It is suggested that although the details of what was uncovered are idiosyncratic, the paucity of understanding of fundamental principles may be common. If this is so the foundations for advanced work are not in place. Some suggestions are made for responding to such a situation.

Introduction

This paper is organised into three sections:

In the first section an argument is presented that although A level science teachers have limited time to complete syllabuses, an effort should be made at the beginning of a course to investigate the extent of a group's mastery of the fundamentals that will be assumed as prerequisite knowledge for the course. It is suggested that the extent of ignorance of basics, and the range of misconceptions uncovered can be enlightening for the teacher about the embark on presenting 'advanced' material.

The central section illustrates the argument by presenting examples of the ideas of students in a single class embarking on A level chemistry. It is in the nature of such a case study that the *specific* data collected relates to the *particular* probes used, and the *particular* individuals making up that group. The purpose of presenting the results in some detail is to demonstrate

a) the variety of 'misconceptions' to be found in a single class;

b) the lack of understanding of a range of very basic concepts and terms that would commonly be used (and taken for granted) in classroom discourse during A level lessons;

and

c) how such information may be collected in any classroom using simple techniques.

The final section of this paper briefly considers how the information collected in such an exercise could be used in order to facilitate more effective learning.

Section 1: The importance of testing prerequisite knowledge

A level science courses assume significant prerequisite knowledge and understanding, so that enrolment is usually conditional upon achieving a high grade in an appropriate G.C.S.E. science examination. In practice whatever subject-specific entrance requirements are set, a class of students commencing an A level course will show considerable variation in what they know and what they understand. Some will have forgotten things they memorised for the examinations; some will have been lucky to guess some answers correctly, or to be awarded marks for responses that suggested deeper understanding than was actually present. Examinations do not always cover all aspects of syllabuses; students having studied different syllabuses would have been taught different things; and - of course - you do not have to get *everything* right to pass an examination. Many teachers will be aware that the range of ignorance in a class at the start of the A level course can be vast: and the variety of misconceptions a seemingly unending source of surprise.

Despite a general awareness among teachers that examination grades do not guarantee learners have desired prerequisite knowledge, there is a temptation to get on with teaching the syllabus. This is partly because of a belief that committed students will pick up the appropriate meanings for words, and the fundamental principles of the subject, as the course progresses; and partly the belief that time constraints do not allow the luxury of revisiting and re-teaching what are meant to be elementary topics.

It is argued here that this temptation to 'get on' should be resisted, if only because such a move is likely to prove a 'false economy'. The work of Ausubel and others has emphasised that effective learning needs to be *meaningful* learning. A student who has sound foundation knowledge has something on which to build new understanding. A student who is unable to relate presented material to existing knowledge will have difficulty making sense of even the most skillful explanation. Learners take time to assimilate abstract ideas, and to construct integrated conceptual frameworks, and the acquisition of basic scientific concepts at an early stage may often be essential before more advanced notions can be understood. Time is needed for the fundamental ideas to become familiar and be made 'concrete' before they may act as the foundations for advanced learning.

Whilst ignorance may be one barrier to advanced learning, misconceptions may often prove to be an even more serious block. This has been demonstrated by the vast literature on science education research which has been undertaken following 'constructivist' premises. This shows that many 'alternative conceptions' that have been elicited from learners are resistant to change. Where learners hold their own versions of scientific ideas they will relate presented material to their existing errant frameworks of ideas. Learners can be most creative in their attempts to make sense of new information in terms of their existing 'knowledge'. The result may be a reinforcement of their existing alternative conceptions by virtue of having a wider area of application, and an extension of their alternative conceptual framework to include the new learning. Unfortunately this learning may well have become seriously distorted as it has been reinterpreted through the learner's existing ideas. Such 'mis-learning' can result in the student apparently applying the concept correctly in some contexts, but reaching completely the wrong conclusions in other cases.

To summarise, ignorance of basics may be a barrier to the meaningful learning of advanced ideas, and deep-seated misconceptions may lead to 'mis-learning' of new material. Consequently it is argued that time spent exploring the students' ideas at the outset can actually save time later in the course by allowing the teacher to plan more effective teaching. Some ideas about how this may be done are presented in Section 3.

In order to illustrate the type of information that may readily be collected in any classroom Section 2 presents some results from a case study of a single group. The class was one of two new A level groups commencing their course at a College of Further and Higher Education in September 1994 . Chemistry staff at the College had been concerned at the large apparent conceptual leap between G.C.S.E . courses and A level. Although the College has produced excellent A level Chemistry pass rates for many years, the course team were aware that some students found the transition to A level very difficult. Indeed some first year students do not make sufficient progress to proceed to the second year. It was decided that it was important to commence the A level course with an appropriate period of induction, where basic chemical concepts would be revisited, so that the new students should be 'eased' into A level work. For the class discussed below the constructivist principle that the teacher should start by finding out what the learners already think was followed. There are many techniques available for eliciting learners' ideas in science - although not all are suitable for classroom use - and a recent book by White and Gunstone provides an excellent introduction . In the present case a few simple tasks were set. These included:

- giving definitions of some basic chemical terms (*element, compound, atom, molecule, ion*);
- drawing a concept map for 'chemical bonding';
- explaining how and why chemical reactions occur.

Concept mapping is a well established technique for eliciting students' ideas and assessing their grasp of a topic. It is also a technique that students can find helpful in learning and revising their science . Students were asked to follow their concept map with an answer to the question *"Why do chemical reactions occur?"* Then in a subsequent class a more specific task was set involving two chemical and two physical processes (figure 1).

Section 2: A survey of the background knowledge of one A level chemistry class

In this section the range of misconceptions and confusion uncovered in the case study class is discussed. Of course there were also many statements made by members of the group which were credit-worthy, and demonstrated significant knowledge and understanding of chemical ideas.

A number of the students couched their answers in dubious grammar (as some of the extracts will show), and in places it is not possible to distinguish poor chemistry from poor expression - although inaccurate and imprecise statements are of concern whatever their origin. There was also a noticeable tendency for many terms to be inappropriately given upper case first letters as though proper nouns. In some cases being able to give a phenomenon a name seems to stand in place of deeper understanding. Perhaps this explains the suggested definition of an element as "a single particle which has been given a name e.g. zinc."

Confusion over basic chemical terms

An understanding of, and ability to use, certain basic chemical terminology is important for communication between students, teacher and textbook authors. It is necessary that there are shared meanings for these terms so that there is a common language for discussing chemistry. It has been pointed out that some chemical terms may be less clearly defined than is desirable from a pedagogic viewpoint , however it is expected that the distinction between the most basic chemical categories - such as elements, compounds and mixtures; atoms, molecules and ions - will be learnt in introductory chemistry classes. Although confusion has been found in national surveys of secondary pupils, it might be expected that those who progress to A level work would have mastered the basic language of the subject. This group of students showed many examples of confused use of such terms. Some definitions offered were so vague or limited as to give little evidence of whether the student understood the term - e.g. "an element is a substance" - although perhaps in some cases the problem was one of expression rather than comprehension. Other responses provided evidence of definite misconceptions or confusion, and a few could actually be described as obscure. In this last category were the definitions of an atom as "a single being", and of an element as being "made up of lots of particles + compound", and the definition of chemistry itself as "a study of emotions, to reproduce substances from the body". One hopes this particular student is not too dissatisfied with the actual content of the course.

A common mistake was to fail to understand and demonstrate the relationship between elements, compounds and mixtures. There were six different references (from five different students) to compounds being mixtures: of two or more elements, of two different substances, of different chemicals or particles, or of atoms. Similarly defining an element as a "single pure substance", implies that a compound would not be so classed, and the definition of a mixture as "two different elements (or more) mixed together without bonding" seems to exclude compounds as mixture components. Perhaps students have difficulty relating the pure chemical nature of a compound at the molar (macroscopic) level, with its literally compound nature at the molecular (microscopic) level.

There was certainly much evidence of confusion over terms at the molecular level. The atom was "a very small molecule" for one student and - intriguingly - "the smallest part of the atom" for another. Another thought columns of the periodic table represented "elements all containing the same amount of atoms in the outer shell", and a fourth student thought that "a covalent bond is when atoms are shared together in an element." Two students suggested that atoms were the smallest particles possible, and one added that "it cannot be split" which must presumably have made some parts of their G.C.S.E. science course difficult to follow. Two definitions of 'molecule' restricted it to the diatomic case, but of more concern two students thought that a molecule was "part of an atom". Ions were also thought to be "part of the Atom i.e. neutron Proton, electron", or more specifically, "a charged particle that orbits an atom". For one student "an ion is made up of molecules combined together chemically".

Student ideas about bonding

A number of misconceptions about chemical bonds were uncovered in the student responses. Two students seemed confused between the two main types of bond met prior to A level,

> Two elements form an ionic bond when they *share* an electron eg sodium chloride.
>
> [a covalent bond] involves sharing electrons either [*sic*] *one element lacks one electron and other has extra electron* ∴ both elements are unstable, to become stable they share a electron so a chemical is formed.

One student thought sugar contained ionic bonds, perhaps because it is crystalline. Another student seemed unsure about exactly what was transferred in ion formation,

> In ionic bonding the charged particles are transferred from one element to another. These charged particles are electrons, *protons* and they are sub-atomic particles called *nucleons*.

A novel form of bonding mentioned by several students was the 'atomic bond'. From the comments of one respondent this seems synonymous with 'covalent',

> Atomic bond - When electrons are shared between atoms to create a full outer shell. … Compound is a substance made from two or more atom joined in an atomic bond. … Molecule - Two atoms joined in an atomic bond.

However, another student did not consider them to be the same,

> Atomic bonds are bond which give are take a atom [*sic*] e.g sodium has 1 atom on it's [*sic*] outer shell and hydrogen also has 1 atom. So the sodium atom would join the hydrogen atom making it have a compelet [*sic*] outer shell. When this happen each element join together, to form a new substanc [*sic*]. … *Covalent bond is almost the same as atomic bond* but instead of taking atoms away they share. Also making new substance.

The other novel form of bonding was "magnetic bonding" which was apparently "similar to ionic bonding" although the comparison was not elucidated.

Other ideas referred to were that ionic bonding was stronger than covalent, single bonds were stronger than double bonds, and that sodium chloride - being soluble - "has a weak bond which the water is able to break".

Confusion between the macroscopic and microscopic

Chemistry students are expected to be able to analyse chemical systems at both the molar and molecular levels - often simultaneously - and perhaps teachers sometimes forget that this can be difficult for a novice. It was suggested above that some of the confusion between basic chemical terms arises from students failing to successfully make this distinction. If students commence an A level course while confused over such terms it can not be assumed that they will pick up the correct meanings in time without deliberate intervention. For example consider the case of an A level chemistry student who despite good G.C.S.E. grades, and generally very satisfactory performance on the course, was found to be confused over the meaning of basic terms such as element, compound and molecule. Her difficulties were diagnosed during the second year of the A level course which enabled remedial instruction to be given, however her misunderstanding of this fundamental terminology had not been spontaneously corrected by a full year of A level work.

A statement such as "an element [macroscopic entity] is a substance *made up from* one type of atom [microscopic entity] only" shows an appropriate relationship between these two levels, whereas "An element *is* the simplest and purest atom" and "graphite *is* an unstable atom" fail to make the distinction. A related error is to assign to atoms the properties of bulk material . In the present survey the following examples were found:

> One carbon atom breaks down due to heat …
>
> … the water molecules surround the Sodium atoms causing them to break down.
>
> When sugar is placed in hot water the sugar molecules break down or melt
>
> heat is one of the factors that causes particles to melt

Ideas about chemical processes

It is well known that energy is a difficult concept area for many students , so it is not unexpected that the role of energy in chemical processes is not well understood at the start of an A level course. The identification of bond formation with "a radioactive reaction", however, was of interest,

> If certain chemical bond together they will be unstable + cause a nuclear explosion.

The student who referred to energy "*created* by the chemical bonding" may not have meant the term literally, although several students felt that heat was required for bond formation - a misconception that could lead to difficulties during the A level course. Another thought the strength of a bond could depend upon the temperature at which reaction took place.

The role of oxygen in combustion was not universally understood,

> Graphite burns in the oxygen (at R.T) and oxygen is removed from the Graphite (Carbon). The result is Carbon dioxide.
>
> The oxygen *helps* the carbon to burn.

The latter response was not the only anthropomorphism in the survey: there were also the usual references to elements that "*try* to achieve a complete outer shell", and atoms that "*need*" more electrons or "*need* to get rid of an electron".

Several students thought that sodium and chlorine reacted because of the opposite charges of their (already formed) ions, for example,

Sodium	+	Chlorine	=	Sodium chloride
Na^{+}		Cl^{-}		NaCl

Sodium is a positive ion and Chlorine is a negative ion therefore they will both attract to each other and form a bond, to produce Sodium Chloride.

Misunderstandings about ionic bonding have been discussed before , and in the present survey "*molecules* of NaCl" were believed by several students to be the solvated species when salt dissolves. Other students believed that this (physical) process produced a chemical change,

NaCl dissolved →	H_2O	=	Na	+ Cl	+ H_2O
sodium chloride		water		sodium + chloride + water	

The Sodium forms a bonds with the OH^{-} ions and forms NaOH.
$NaCl + H_2O \rightarrow NaOH + Cl_2$.

One respondent also thought that "a chemical reaction happens when sugar hits the hot water", whilst another thought that "Sugar losses [*sic*] electrons to the H_2O". Another suggestion regarding electrons was that "The atoms of sodium and chlorine have electrons which move together to form sodium chloride."

Thoughts about classes of chemicals

Some of the students showed a tendency to explain chemical processes by simply classifying reactants. The following example of inductive logic is quite correct, but does suggest that the student perceives a 'problem' that would not be expected to exist for a G.C.S.E. science 'graduate',

> graphite belong in the carbon family. And when carbon is burned it a produces Carbon dioxide. I think that when graphite is burned it *also* produce Carbon dioxide.

One student suggested that as sugar was "Crystal" that "makes it Soluble is water" - the use of upper case letters seems to add weigh to this 'argument'. Two other suggestions for why salt dissolve were even more dubious: that "Water is a Solution" and that "Sodium chloride is soluble in water because salts contain Hydrogen + Oxygen" (note the capital letters again.) The reaction of sodium with chlorine was also explained in terms of inappropriate categories:

> Sodium reacts in chlorine to become sodium chloride, because chlorine is an oxide, so when they react it changes to sodium chloride. The sodium + chlorine becomes salt when they react because of the oxide.
>
> As Sodium is a reactive meterial[sic] and chlorine is a acid. When Sodium is placed in Chlorine, Sodium react badly making a flame and maybe a noise. I think why this reaction happen is because as Sodium reactive metal meaning that it atomic configuration is unstable make the metal danger And as Chlorine is a dangerous acid. When sodium is placed in Chlorine, the sodium start dissolving in the acid due to all the particle rushing around quickly pushing together with Chlorine atom. Producing Sodium chloride.

Ideas relating to valency

It has already been reported above that some students confused the valency of sodium and chlorine with formal charges on the atoms. One student made a similar error in considering the combustion of carbon,

> Carbon is a positive ion and oxygen is a negative ion. Therefore they will attract each other.
>
> C^+ + O_2^- = CO_2
>
> carbon ion oxygen ion = carbon dioxide

Carbon was also described as having a positive valency of one, and twice each as having "two electrons free in the outer shell" and "two electrons missing", although it might be assumed that the carbon atom would be one of the more familiar atomic structures from G.C.S.E. work.

Student ideas about 'chemicals' and natural states

The chemist does not consider 'chemicals' as a special class of materials, outside of everyday life. In a similar way the distinction between natural and synthetic materials is not considered to have particular significance for the chemical behaviour of those materials. However research suggests that the difference may be meaningful to novices . In the present survey several references were made to 'chemicals' being formed, or needed for particular processes. There were also a number of references to the distinction between the natural and the artificial, such as

> An element is a substance that is found *naturally* and is not a combination of two things, nor is it *synthetic*.

and for reactions,

> Chemical reactions occur *naturally*. They *also* occur when chemists make them in a variety of different ways e.g. by applying heat, pressure to substances to make them react.

Further research is needed to find out whether perceiving such a distinction as significant is likely to interfere with progress in learning chemistry.

Section 3: Acting on the data collected

In the previous section some of the comments of students in one class commencing A level Chemistry were reported. Many of the misconceptions reported here reflect the findings of the Learning in Science project (based at Waikato University, New Zealand), the Children's Learning in Science project (based at Leeds University) and other published research . It might however be considered surprising to find such a range of basic misconceptions and muddled thinking among a group of the more successful and motivated students who enrol on an A level course. The *specific* ideas revealed are a product of the *particular* students in the group and the probes used, but it is suggested that a similar set of responses would be elicited from other groups. It is seen to be illuminating for a teacher to carry out such an investigation at the start of an A level course. There would be little point, however, if there was no intention to act on the findings of such an enquiry. Misconceptions do not automatically become corrected through exposure to the correct use of terms and concepts during normal teaching. For example the class discussed in section 2 also included two students retaking the first year of an A level course, and they also undertook the tasks set. The following statements are taken from their work, (after a full year of A level chemistry)

> Compound is one or more elements *mixed* together.
>
> Metallic Molecules are shiney.
>
> Anything that burns gives of CO_2…
>
> …Sodium and Chlorine have opposite charges, and their ions also…
>
> in hot water, the Sugar will *melt* fairly easily

One important response would be to provide the class with early feedback about any serious misconceptions - although it is of course important to do so in a sensitive manner, so as not to damage the enthusiasm and confidence of the students. However research suggests that some alternative conceptions may be very stable, and a one-off remedial input is unlikely to be sufficient to permanently overcome all the misconceptions revealed. Rather a 'drip-feed' approach may be more effective, with the teacher taking appropriate opportunities to rehearse those basic definitions and principles of the subject found to cause problems.

Educational research and theory presents a range of ideas to help teachers to facilitate effective learning, and as the literature is extensive only the briefest outline is appropriate here. A selection of useful reading is cited in the notes at the end of this article.

Conceptual analysis

Teachers may analyse major topic areas to ensure that as far as possible there is a logical order of presentation of material . In particular it should be borne in mind that most learners assimilate complex new ideas slowly (over the weeks if not months after the initial presentation), and therefore wherever possible attempts should be made to use 'advance organisers' which should be "formulated in terms of language and concepts already familiar to the learner".

Challenging alternative conceptions

Simply stating that an idea is wrong is not likely to be sufficient for a learner to be able to change her way of thinking, particularly when the idea is deeply held and enables her to interpret new information so that it seems to make sense. It has been suggested that it is necessary to challenge the alternative conception by demonstrating its inadequacy, perhaps by presenting an experiment with an outcome contrary to that predicted, or by arguing through the idea to show some self-contradiction or obviously incorrect conclusion.

Analogies

Meaningful learning requires presented material to make sense to the learner, in terms of existing knowledge. One way to make the novel more familiar to through the use of analogies, metaphors and models. These devices may act as cognitive bridges between existing ideas and new knowledge.

> It is necessary to construct or identify a framework in which to locate the new idea. Metaphors and analogies enable the student to borrow frameworks from other contexts

In an analogy an attempt is made to point out how certain aspects of the material to be learnt are similar in some way to something familiar. It is important for the teacher to be explicit about which aspects of the comparison are intended to make up the analogy, else the learner may well transpose additional irrelevant characteristics to the material to be learnt. It is also important that the analogue is indeed familiar to the learner. For example one comparison that is sometimes made is between the atom and a solar system. There are many senses in which these two system differ, but the aspect of a planet being held in orbit by mutual gravitational attraction to a central sun is analogous to a simple model of an electron orbiting the atomic nucleus due to mutual electrostatic attraction. However the present author has found some of his students believe that planets actually repel the sun, a misconception that could easily be transferred by analogy to the atomic system. Models are widely used in science education. It has been suggested that models may be considered as "formalized or institutionalized analogies" , and an A.S.E. publication recently reviewed the use of models in science teaching . A metaphor makes an implicit comparison, and although it has been suggested that the human conceptual system makes great use of metaphors in learning , there is always the danger of the intended comparison being misconstrued, so that it is suggested that metaphors used in teaching should be converted into analogies by making the points of comparison explicit. Glynn summarises a strategy for the effective use of analogies in teaching:

1. Introduce target (i.e. novel material to be learnt);

2. Cue retrieval of analog;

3. Identify relevant features of target and analog;

4. Map similarities;

5. Draw conclusions about target;

6. Indicate where analogy breaks down.

Metacognition

Finally it may be pointed out that part of the A level teacher's role is to develop learners from being largely reliant on directed study, to becoming somewhat responsible for their own learning. This may be particularly important for those students who intend to move on to Higher Education, but the skills of being an effective independent learner are valuable for all citizens in a democratic society. No matter how skilled the teacher is *as* a teacher, the teaching-learning process is equally dependent on how skilled the learners are *as* learners. Education has been described as process of building common knowledge - shared understandings - between teachers and learners, and as such it relies on effective communication . Consequently as well as focussing on the transmission (the teacher carefully analysing concepts and selecting bridging analogies), it is just as important to ensure efficient reception - that the learner has the skills to make good use of the teaching provided. A class of students who are aware of their own preferred learning styles, capable of evaluating their own learning, and have a range of study techniques available may be more rewarding to teach than a group with less self-confidence as learners, and who demand an endless stream of dictated notes. The self-critical, self-aware learner is likely to be the more effective learner. Part of this awareness extends to the perception of the material to be learnt not as absolute knowledge (unquestioned and eternal), but as a human product - the attempt of scientists to model the patterns and regularities of nature as revealed through imperfect experiments and observations. This allows the student to have confidence to realise that often it is the general meaning of an idea that is important, rather than a particular form of words. It also helps the student deal with those areas of knowledge where scientists have not yet been able to provide a single simple model or theory that will always match empirical evidence. It has been suggested that students may better cope with the range of complementary (and sometimes contradictory) conceptual models used in a subject such as chemistry if they learn to see the various models as a kit of conceptual tools from which they can select according to the task 'at hand' . Metacognition in learning science has been explored by a number of workers, notably Novak who has discussed the value of teaching students techniques such as concept mapping.

Concluding comments

This paper reports some results from a small scale attempt to survey misconceptions about fundamental chemical ideas in a single class commencing A level. Had different tasks been set it is likely a different range of erroneous and alternative ideas would have been uncovered. There is no suggestion that the fifteen new A level chemists discussed here are strictly representative of the wider population of young people commencing A level and equivalent courses. What *is* suggested is that *any* new class will include students who hold to a variety of ideas that are at odds with the basic 'prerequisite' chemical knowledge assumed for the course. Such alternative conceptions may act as a block to effective communication between the teacher and the students, and consequently a barrier to progression in learning. Constructivist approaches to science education suggest that erroneous ideas need to be addressed before effective learning can take place, and that this can only happen if they are first made explicit to both learner and teacher. If this does not happen then the students are likely to reinterpret new information in the light of their existing conceptions rather than change those conceptions.

Once misconceptions are diagnosed the teacher needs to teach accordingly. It has been suggested that this may involve some demonstration of the inadequacy of the students' existing ideas. It has been pointed out that effective learning needs to be incremental, building on existing knowledge in manageable steps; perhaps using analogies as bridges and models as scaffolding. It is also suggested that the construction of 'common knowledge' will proceed more readily when the responsibility for learning is shared between teacher and students. However the main purpose of this paper was to illustrate just how insecure students' foundations for advanced level study may be. The main advice offered is that when considering learners' background knowledge the old teaching adage still applies: *take nothing for granted.*