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An Analogy For Discussing Progression in Learning Chemistry

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Abstract:

This paper is about one way of conceptualising learning in chemistry that may be useful for some teachers and their students. It is argued that there are particular problems associated with progression in understanding certain aspects of chemistry as students pass from GCSE/KS4, through A level, and beyond. These problems are intrinsically related to the abstract nature of the subject matter, and the wide range of conceptual models used by chemists. Metaphors and analogies can be very useful in understanding difficult ideas, and are often used in science and science education. A simple analogy that may help teachers and students conceptualise the learning process is discussed.

When it comes to atoms, language can be used only as in poetry,

(Neils Bohr)

Introduction: progression and learning about science.

Progression is a major issue for those concerned with science education . Teachers are urged to ensure that learning is meaningful to students - that it builds upon their existing knowledge - and this requires careful thought to the way in which the curriculum is structured, so that it may be presented in a suitable manner for it to be readily assimilated by those with the expected prerequisite knowledge.

Although I doubt if many readers would disagree with the previous paragraph, I wonder if there would be a strong consensus on what exactly progression in science education involves?

Does it mean using existing concepts to classify new phenomena?

Does it mean developing previously learnt models to make them more sophisticated?

Does it mean learning new fundamental principles that may unify several existing pieces of knowledge?

Does it mean applying existing principles to new 'territory' and thus extending the scope of understanding?

I expect that there are times in science education when progression could mean any of the above. Certainly as someone who has taught physics and chemistry topics to youngsters throughout the secondary age range I find all those suggestions familiar.

Does progression sometimes mean discarding simplistic notions learnt at an earlier stage and replacing them with more advanced ideas?

This is a more controversial suggestion, as it could be argued that we should never teach ideas that we are later going to want to 'unteach'. The vast literature into intuitive science knowledge suggests just how difficult it may be to ‘replace’ beliefs once they are established. Also what one teacher may see as an appropriate simplification, suitable for a specific learner at a particular time, may be seen by another teacher of the subject as simply ‘wrong’.

The value of having a metaphor

A recent study into higher level cognitive learning in science focussed in-depth on two science teachers . In this study great emphasis was placed on the importance of the teachers’ own metaphors in determining their teaching styles and behaviour - and consequently on the learning environment and opportunities for their pupils. The authors were concerned with the way the teachers conceptualised their teaching roles, but this is likely to be related to their personal theories of the learning process. Fox has discussed such personal theories, for example how teachers may see teaching as ‘transferring’ knowledge to the pupils. Other metaphors that may be used are of learning as ‘growing’ or ‘building’ or ‘travelling’ . Much current research in science education is undertaken in the constructivist paradigm, which is rooted in George Kelly’s metaphor of learners as scientists.

Do we need metaphors for conceptualising progression in chemistry?

It might seem that ideas about progression are quite straight-forward without needing to introduce any new metaphors. We attempt to extend, develop and sometimes replace students’ existing concepts. As a teacher of physics I would be reasonably satisfied with such a description of what I am trying to achieve in the classroom. As an A level teacher aiming to foster metacognitive skills I would be quite prepared to discuss the learning process in such terms with my physics students. However, in the past few years I have come to feel that for my A level chemistry teaching I need something different - both as a framework for my own thinking about my teaching, and as model for discussing learning with my chemistry students. The impetus for these reflections has its origins in on-going research into the development of students’ understanding of chemical bonding during an A level course.

Students who enrol on an A level course in chemistry would already have been introduced to some ideas about chemical bonding. During the course a student acquires more subtle and sophisticated concepts. Should the student progress to degree level work even more abstract ideas will be met. However these supplement, rather than replace, the more simplistic ideas learnt at

GCSE. Chemistry does not have the status of a complete and exact science, where all phenomena of interest may be analysed by a single fool-proof approach. Whilst in principle quantum mechanics may provide the basis for such a science, the problems of solving the equations for complex systems (i.e. anything complex enough to be of genuine interest in chemistry) mean that in practice such an approach has limited use. In addition most practising chemists do not have the mathematical intuition to understand the significance of the solutions of such equations unless they are translated into more familiar representations. Even Nobel laureates will use GCSE level chemistry concepts when they satisfactorily explain the phenomena under study. The difference between the 'expert' chemist and the relatively 'naive' student embarking on an A level course is that the novice does not have alternative strategies for when their GCSE level understandings do not help explain the chemical data.

One way of conceptualising progress in student understanding of chemical bonding is to use the analogy of a chemical toolbox. As the student makes progress in the subject she will acquire more tools, and learn both how and when to apply them. It will be noted that there has been a shift from talk of metaphors to an analogy. A metaphor has hidden meaning, whereas an analogy directly refers to one thing being like another. Metaphors may be very powerful, but unless the user is aware of their metaphorical nature they may direct thinking in ways the user does not realise . It is part of the thesis of this paper that the idea of a chemists' mental toolbox should be explicitly compared to a physical toolbox, so that the analogy is itself a metacognitive tool to help conceptualise learning.

The GCSE 'graduate' has a 'toolbox' containing some useful chemical 'tools' to tackle a range of chemical 'jobs'. As students pass through an A level course they will continue to use these tools, but they will also meet many 'jobs' where their 'toolbox' does not provide them with a suitable instrument. The task of the teacher is to provide additional tools, and training in how and when the different tools should be used: a role which fits quite well with the idea of cognitive apprenticeship that has been discussed as a model for learning in science . Some students will be more successful in acquiring the tools than others - success being measured not only in ownership of the tool (i.e. describing the rules of valence shell electron pair repulsion theory) but also in its appropriate use (i.e. explaining and predicting the shapes of simple molecules, but not trying to use it to explain patterns in ionisation energies - a job which requires a different tool.) The practising chemist has a more extensive toolbox than the GCSE candidate, but still uses some of those same basic instruments. Different practising chemists carry with them, and use, different toolkits - they will have acquired different tools over their careers, and even perhaps discarded some that are not appropriate for the jobs they undertake.

I believe this analogy is a very powerful one, as it avoids the incorrect idea that more sophisticated understanding 'replaces' more basic ideas: in chemistry this is not always true - the more sophisticated ideas often supplement and complement the more basic ones. The owner of a new screwdriver does not discard her hammer, she just no longer uses it to try and undo screws!

The tools I am discussing are mental tools: rules, laws, heuristics, models, representations etc., they are tools from Popper's 'World 3' ("objective thought, especially products of the human mind") , but so are the chemical jobs to be undertaken - explaining and predicting the properties and processes of nature: why are different substances solid, liquid or gas at room temperature?, why does iron - but not sulphur - conduct electricity?, why does ethene - but not benzene - undergo addition reactions?, why is ice at O˚C less dense than water at the same temperature?, why is sodium soft and sodium chloride hard? The materials exist out there in 'World 1' (the "physical world"): but our categories, and our explanations are mental constructions. As with other kinds of tools, these mental tools are not usually fully acquired at first acquaintance: the apprentice may first see the craftsman with a chisel, then borrow one, and then buy a cheap one, and later replace this with more professional equipment - and his skill in applying the instrument to his materials will be developed with practice.

Well Miss, which is it?

Curriculum planners have been warned that according to Piagetian stage theory many young people studying science have not reached the level of formal operations that would seem to be required for some aspects of standard secondary science courses . Some researchers working within the stage theory paradigm have suggested that some aspects of mature adult thought actually relate to a fifth level of 'post-formal operations'. Karlin for example summarises such a stage in terms of its over-riding conceptualisation (synthesis, c.f. analysis for formal operations); the tiers of thought involved (relativism and dialectical syntheses, rather than hypothetico-deductive and empirical verification); and the corresponding world view (contextualism and organicism, rather than formism and mechanism) . It might be thought that such cognitive development would take the learner beyond the types of thinking skills required in school science - even at A level. However when it is pointed out that the characteristics of this proposed post-formal level of thinking include accepting the relative nature of knowledge and accepting contradiction as part of reality some aspects of twentieth century physics may come to mind. If one accepts the validity of the fifth stage, and the findings about the frequency of attainment of Piagetian stages at different ages - for example only 50% of the adult population attain formal operations - then one should have reservations about teaching concepts in school science that seem to have inherent contradictions (or have a manifold nature depending on the contexts in which they are met) when it seems likely that few learners will be able to operate in the appropriate mental mode. That is unless it is possible to allow the ideas to be conceptualised in some more concrete form. It is suggested that the models and rules and categories and principles and heuristics and generalisations and approximations and conjectures and hypotheses and theories that make up much of our science are presented as such: i.e. as available tools in our mental toolbox, rather than as factual scientific knowledge that students expect to be absolute - but in practice seem to be relative and contradictory.

Perhaps it might be argued that school science is such that this problem would not arise: after all wave-particle duality is just a small aspect of A level physics, and there is little else to cause this type of confusion? Let us briefly consider some questions from chemistry:

What type of bond is found in the tetrachloromethane molecule?

At GCSE this question may be readily answered as carbon and chlorine are both non-metals, so the bond will be covalent. At A level a student will learn about electronegativity, and understand that the bond is polar. This does not mean that the category of covalent bond is no longer used: the bond in the hydrogen molecule is still classed as covalent. Nor does it mean that the demarcation of the 'covalent bond' concept has changed: the bond in tetrachloromethane has not been re-assigned to the category of polar bonds from that of covalent bonds. Whether the bond in this molecule is described as covalent or polar depends on the context of the discussion. Likewise the categories of metal and non-metal do not cease to be useful when the concept of electronegativity is available. Aluminium was a metal at GCSE level and that may be used to explain why it tends to form cations rather than anions; it remains a metal at A level - but a more powerful tool is need to explain its amphoteric chemistry. This can be difficult for students to appreciate, but if concepts such as 'covalent bond', and 'polar bond', 'metal' and 'electronegativity' are seen as mental tools this may help them accept such plurality. Difficult concepts such as resonance may be approached in the same way.

Why does water have an anomalously high boiling temperature?

In general boiling temperature is related to molecular mass, as the larger a molecule the greater the intermolecular forces. Yet some materials - such as water - have much higher boiling temperatures than their molecular mass would suggest. The reason is that water has hydrogen bonding between molecules. Why does this make a difference? One way of understanding this is to move outside of the relationship between molecular mass and the extent of induced dipole - induced dipole forces. The hydrogen bonds are an additional force holding molecules together, so more energy (and therefore a higher boiling temperature) is needed to separate molecules. Alternatively, remaining within the framework of boiling temperature depending on molecular mass, the hydrogen bonds hold together several H2O units, leading to a larger effective molecular mass. Which explanation is correct?

How should a polar bond be represented?

Should Lewis type diagrams be used with the electron pair shown closer to the more electronegative atom? Or should electron density be shown as contours or a 'distorted' electron cloud? Or perhaps ∂+ and ∂- symbols will be appropriate? Or an arrow on the bond to show the inductive effect? Or a resonance between two canonical forms: one covalent and one ionic. How easy is it for the sixteen year old 'apprentice' to appreciate that any of these representations could be used?

Sometimes there are several tools suitable for undertaking the same job (adhesives, nails, screws, rivets and bolts for example) and the choice is a question of personal preference and competence, or time constraints or aesthetics. A historical example may be of value: Heisenberg and Schrödinger both developed quantum mechanical methods. Some scientists of the time thought they needed to decide which formalism was the correct one to use: matrices or the wave-equation? Now we see both methods as being useful tools: the one that is chosen depends on the problem and the cognitive style of the person undertaking the calculation.

What kind of toolbox?

The tools I refer to as analogous to chemical concepts in this article are of the type I keep in my own toolbox: screwdrivers, chisels, hammers. I am a householder and need to have such a toolbox. Perhaps not all students would find such an analogy suitable? Analogies are meant to bridge between the familiar and the unfamiliar - they have little value when the analogue itself has to be explained! Sadly even today it is possible that a toolbox of this type may be more familiar to male students than females - and it is important that we make efforts to ensure our approach to teaching the physical sciences is 'girl-friendly' . Related ideas might be to consider kitchen tools (at the risk of moving from a traditionally male area to a traditionally female one); the pencil-box with its collections of pens, pencils, protractor and so forth; artists materials/media (oils for one job, pastels for another); or selecting laboratory equipment for a practical 'job': the same liquid might be placed in a measuring cylinder, a beaker or a boiling tube for example, depending on the 'job' the liquid will be used for.

Thinking about learning chemistry in terms of tools

The adoption of an analogy is only constructive if it suggests a new way of thinking. The toolbox analogy suggests the following comparisons:-

The skilled craftsperson has a range of techniques that she is able to chose from for specific jobs. Competence does not just imply ownership of tools, but selecting the right tool for each job.

The acquisition of a basic tool kit puts the craftsperson in a position to build new tools, either customised - more specialised - tools for specific jobs, or more powerful versions of existing tools, or new tools combining the properties of several existing ones.

Competence involves practice in using tools, preferably in a range of circumstances, over a period of time.

Tools may be used crudely, or with increasing finesse.

Tools may be applied appropriately, or inappropriately - a chisel should not be used as a screwdriver!

There is often more than one way to effectively undertake a job.

Like all analogies, the toolbox analogy has its limitations, and if used to help develop metacognition in students it is important to explore the limitations as well as the strengths. However I do believe it could provide useful insights for teaching about chemical bonding, for learning about chemical bonding, and for researching into learning about chemical bonding.

As a final thought - an 'objective' question:

Why is the first ionisation enthalpy of chlorine greater than that of sodium?

A) because more energy is required to remove the electron from the chlorine atom;

B) because the highest occupied orbital in chlorine is at a lower energy level than the highest occupied orbital in sodium;

C) because chlorine is more electronegative than sodium;

D) because sodium is a metal and has a greater tendency to form a cation than non-metallic chlorine;

E) because greater force has to be applied to remove the chlorine electron as chlorine has a greater core charge than sodium, and its valence electrons are nearer the nucleus.

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