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**PEDAGOGICAL CONTENT KNOWLEDGE AS A WAY FORWARD:
APPLIED RESEARCH IN CHEMISTRY EDUCATION**

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ABSTRACT: As a result of research into students' understandings, we have lists of student misconceptions, often accompanied by bland statements about preventative or curative actions. We have an enhanced knowledge of the conditions for effective learning, but little guidance as to how this knowledge might be applied to the teaching of particular topics. Research has not had the impact on science teaching that we might have hoped. Furthermore, science education research seems to be looking for direction. Much of chemical education research has used subject matter simply as a vehicle to develop domain-independent pedagogical theory. Commenting on the criteria used for evaluation of teaching, Shulman (1986) asked "Where did the subject matter go?" Perhaps a productive path for us to travel is what Shulman has labelled *pedagogical content knowledge* (PCK): knowledge about teaching and learning that takes into account the particular learning demands of the subject matter. Science teaching is afflicted with 'professional amnesia' in the sense that the understandings that drive the strategies of competent teachers are seldom recorded, so new teachers grow largely through experience. The chemical education enterprise is crying out for 'applied research' that probes and documents the topic-specific PCK of respected teachers. Some examples of research findings that support the claims are presented. [*Chem. Educ. Res. Pract.*: 2004, 5, 215-228]

KEY WORDS: *Pedagogical content knowledge, domain-specific, learning demands, subject matter importance, single-particle images, multiple-particle images.*

INTRODUCTION – A HISTORICAL OVERVIEW

The chemistry education enterprise has been engaged in two distinct phases over recent decades: a reflective phase followed by a research-based phase. In recent years we have been intensively engaged in *pure* chemical education research – advancing fundamental and generic pedagogical knowledge. The advances have not in general been translated to the classroom, and chemistry education seems unsure of its direction. Perhaps it is time to engage in a form of *applied* research, focused on the subject matter, which is of more direct use to the chemistry teacher.

Chemistry education since the beginning: What to teach?

Until a couple of decades ago, chemistry education thinkers were concerned primarily with the question "What should be included in the chemistry curriculum?" (For example, Battino, 1979; Campbell, 1979; Basolo, 1980; Bodner and Herron, 1980; Mellon and others, 1980; Davenport, 1985). The powerful influences were highly respected academic chemists

expressing opinion and judgement derived from reflection grounded in experience and wisdom. The way forward was seen to be dependent on selection of the ‘right’ content for the curriculum. Debates about what should be taught still go on (Hawkes, 2003, 2004; Lewis 2004), as they should.

Chemistry education post-1975: What is learned?

From about 1975 there has been a surge in research into the question “What is learned?” The focus shifted from the curriculum to the student, reflection gave way to experimental investigation, and those asking the questions were mostly ‘chemistry educators’ rather than chemists. In only a few instances were the researchers in Chemistry departments.

Probing students’ understandings became an industry. Amongst others, Nakhleh (1992) and Garnett et al. (1995) have published comprehensive reviews of the findings of this ‘misconceptions research’. These findings have led to questioning of the ‘transmission’ mode of teaching, and a period of reflection upon how people learn. ‘Constructivist’ theory (Bodner, 1986) and the ‘Information Processing model’ (Johnstone, 1997) have made important contributions in the regard. Bodner (1992) has warned “Changing the curriculum – the topics being taught – is not enough to bring about meaningful change in science education, we also need to rethink the way the curriculum is delivered.”

Chemistry education research now: Where are we at?

Now we have an encyclopaedic collection of student misconceptions. Sadly, the findings are usually accompanied by only bland, general statements about preventative or curative actions (such as “Find out what the students already know”). Another feature of today’s science education research is that the science subject matter of many research studies is not important in its own right, but is only a vehicle for developing educational theory. Many research papers are rejected by journals on the grounds that they contribute little to theories of pedagogy, even though they have significant things to say about the demands of learning particular concepts. Educational research has not had the impact on chemistry teaching that it should have had – presumably in part because the practice of teaching particular chemistry topics such as chemical equilibrium, electrochemistry, or thermochemistry is not well informed by the theoretically focussed literature.

Chemistry education research, as distinct from education research conducted on chemistry teaching, seems uncertain of its direction. To those involved in chemistry education, the main priority of research is to see immediate benefits transferred into the classroom and teaching lab. Before our teaching can advance, we need to be knowledgeable not only about the learning outcomes of our teaching, but of the conditions, including subject-specific factors, that have given rise to those outcomes. Then perhaps we can design our teaching accordingly.

FUTURE DIRECTIONS: A RETURN TO THE CONTENT?

Commenting on criteria used for evaluation of teaching, Shulman (1986, 1987) asked “Where did the subject matter go? What happened to the content?” He bemoaned that pedagogical knowledge had become dominant over subject matter knowledge. Of course we should attempt to advance educational theory, in the same way that any other discipline does ‘pure research’, but surely advances in theory of a discipline should be used to reflect upon and improve the practice of that discipline. Is the time ripe to think through what we now know about student learning, in conjunction with analysis of what it means to understand

particular concepts, to generate useful teaching strategies for each chemistry topic? And then to evaluate the effectiveness of these practices? This would constitute ‘applied research’ in the sense that it is designed to solve a problem, rather than to advance theoretical knowledge.

Perhaps a productive path for us to travel is what Shulman (1986) has labelled *pedagogical content knowledge* (PCK). While *content knowledge* refers to one’s understanding of the subject matter, and *pedagogical knowledge* refers to one’s understanding of teaching and learning processes independent of subject matter, *pedagogical content knowledge* refers to knowledge about the teaching and learning of particular subject matter that takes into account the particular learning demands inherent in the subject matter.

The rationale for doing this is aptly put by Geddis (1993):

The outstanding teacher is not simply a ‘teacher’, but rather a ‘history teacher’, a ‘chemistry teacher’, or an ‘English teacher’. While in some sense there are generic teaching skills, many of the pedagogical skills of the outstanding teacher are content-specific. Beginning teachers need to learn not just ‘how to teach’, but rather ‘how to teach electricity’, ‘how to teach world history’, or ‘how to teach fractions’. (p. 675)

We might add ‘how to teach stoichiometry’, or ‘how to teach chemical equilibrium’, or ‘how to teach stereochemistry’. Obviously the demands of learning about stoichiometry are different from the demands of learning about stereochemistry. A corollary is that the demands of teaching about stoichiometry are different from the demands of teaching about stereochemistry.

Each chemistry teacher has a unique knowledge of chemistry. We cannot hope to transmit to the students a duplicate of this knowledge. The teacher’s job is to re-package and re-present his/her knowledge in such a way that gives the students some hope of achieving the understandings that we hope for. The re-packaging task will depend upon the nature of the subject matter. And so we teachers have to come to know the subject matter, not only for itself, but also in terms of its teachability and learnability. This task has been conceptualised (Shulman, 1986) as ‘transformation of subject-matter knowledge into forms accessible to the students’. Geddis (1993) points out:

In order to be able to transform subject matter content knowledge into a form accessible to students, teachers need to know a multitude of particular things about the content that are relevant to its teachability. (p. 676)

Gess-Newsome and Lederman (1999) have compiled an informative monograph, from a somewhat theoretical perspective, on pedagogical content knowledge.

SOME EXAMPLES OF PEDAGOGICAL CONTENT KNOWLEDGE

There is a vast difference between knowing about a topic, and knowing about the particular teaching and learning demands of that particular topic. The following examples of PCK, some derived from research and some derived from experience, are intended to illustrate this difference.

Statements subject to shallow interpretation

The Law of Mass Action, or the Law of Equilibrium, is usually expressed in textbooks along the following lines:

If a system represented by the equation $aA + bB \rightleftharpoons cC + dD$ is at equilibrium at a specified temperature, then the ratio $\frac{[C]^c [D]^d}{[A]^a [B]^b}$ has a constant value. That is $\frac{[C]^c [D]^d}{[A]^a [B]^b} = K$.

It is my experience that many students interpret this with a rather limited meaning, expressed as follows using a real example:

In a vessel in which a reaction occurs that can be represented as $N_2O_4(g) \rightleftharpoons 2NO_2(g)$ concentrations change until, at equilibrium, there is a constant value of the quotient $\frac{[NO_2]^2}{[N_2O_4]}$.

This statement is correct, but it hardly represents the full meaning of the law. The focus of this interpretation is on one particular reaction mixture. In any one mixture it is also true that

$\frac{[NO_2]^4}{[N_2O_4]^{0.5}} = \text{a constant}$, and $[NO_2]^{11} [N_2O_4]^{56} = \text{a constant}$, and $[NO_2]^{-1} = \text{a constant}$

In fact, at equilibrium *any* function of $[NO_2]$ and/or $[N_2O_4]$ attains a constant value – simply because both $[NO_2]$ and $[N_2O_4]$ attain constant values.

It is PCK to recognise that the real significance of this law is that if we have numerous reaction vessels (A, B, C, ...) in which this reaction is at equilibrium at a specified temperature, they all have the same value of the quotient $\frac{[NO_2]^2}{[N_2O_4]}$

$$\text{ie, } \left(\frac{[NO_2]^2}{[N_2O_4]} \right)_A = \left(\frac{[NO_2]^2}{[N_2O_4]} \right)_B = \left(\frac{[NO_2]^2}{[N_2O_4]} \right)_C = \dots\dots\dots$$

This is not true for any other function of the concentrations.

I suspect that language is at the heart of the problem. In the Law of Mass Action, to chemists the word *system* refers to the process: i.e., all reaction mixtures containing NO_2 and N_2O_4 are the same system. To students, the word *system* probably refers to each separate reaction mixture. The chemist's meaning of *constant* is similar to 'same as' as used above. Perhaps the student interpretation of *constant* is more like its everyday meaning – i.e., unchanging. It is PCK to realise such language hazards, and to find ways to deal with them.

A profusion and a confusion of symbols and language

It is PCK to recognise that students may have trouble distinguishing the different meanings of the symbols O, O_2 , O^{2-} , and O_2^{2-} , as it is to recognise that if the formula $BaCl_2$ means twice as many Cl particles as Ba particles, then students might think that $BaCO_3$ mean three times as many CO particles as Ba particles.

It is PCK if one realises the potential for confusion when students are required to use a variety of arrow symbols, each with quite different meanings - such as those that represent chemical transformation, reaction mechanism electron-pushing, chemical equilibrium, and resonance. And it is PCK to be aware of the language demands on students demonstrated by Bent (1984) in his list of the following more-or-less equivalent statements concerning displacement of copper from aqueous solution by zinc:

Zinc reduces copper(II) ion
Copper(II) ion oxidises zinc
Zinc displaces copper from solution
Copper won't displace zinc from solution
Zinc is a better reducing agent than copper
Cu²⁺ ion is a better oxidising agent than Zn²⁺ ion
Zinc is a better electron donor than copper
Cu²⁺ ion is a better electron acceptor than Zn²⁺ ion
Copper is more easily displaced than zinc
Copper is more noble than zinc.

It is PCK to realise that the term *dispersion force* (which acts to hold particles together) may provide some confusion for students because in everyday useage the term *dispersion* means to spread out. This is one of a myriad of examples of mismatch between everyday and scientific meanings of words. Others include *attractive forces*, *spontaneous reaction*, *weak acid*, *preparation of a gas*, *saturated solutions*, *volatile liquids*, and *properties of substances*.

The difficulties of language are highlighted by the following definitions taken from the IUPAC *Compendium of Chemical Terminology* (The 'Gold Book')

Base: A chemical species or molecular entity having an available pair of electrons capable of forming a covalent bond with a hydron (proton) (see *Bronsted base*) or with the vacant orbital of some other species (see *Lewis base*).

Polarity: When applied to solvents, this rather ill-defined term covers their overall solvation capability for solutes, which in turn depends on the action of all possible, nonspecific and specific, intermolecular interactions between solute ions or molecules and solvent molecules, excluding such interactions leading to definite chemical alterations of the ions or molecules of the solute.

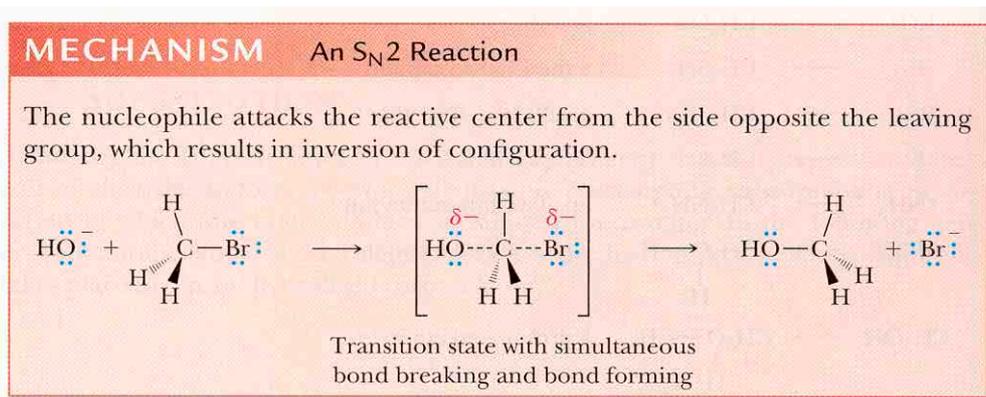
While these statements might define the concepts well for professional chemists, because of the level of language and the interdependence amongst concepts for meaning, they are not very useful for many people outside of that audience – and certainly not for secondary school students, or even relatively unqualified teachers.

Of course the problems of language in communication of science ideas has been the subject of many papers (for example; Cassells and Johnstone, 1983; Herron, 1996; Marais and Jordaan, 2000; Schmidt, 2000; Sutton, 1998).

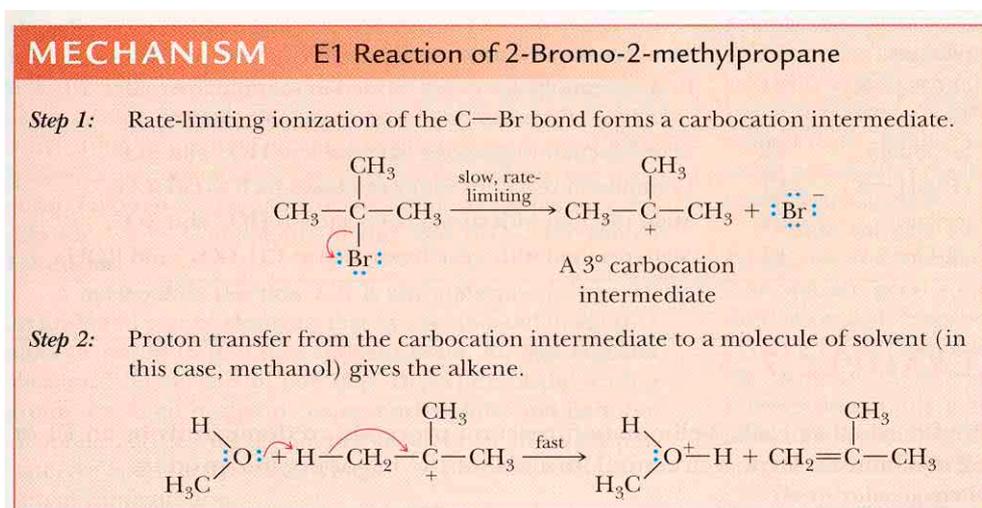
Instructional strategies that provide unintended cues

When we discuss nucleophilic substitution and elimination reactions, in textbooks or in lectures, we almost always use a different way of representing the substrate molecule in substitution reactions than we do in elimination reactions. For substitution reactions we usually use a three-dimensional representation showing the tetrahedral orientation of substituents about the carbon atom at which substitution occurs – as in the following diagram from Brown (2000):*

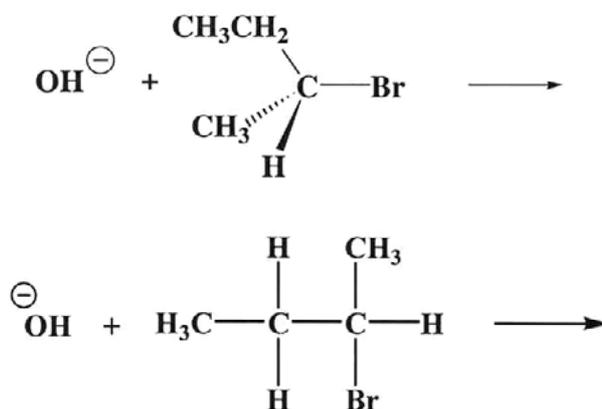
* Material from Brown (2000) on next page is used by permission of John Wiley and Sons Inc.



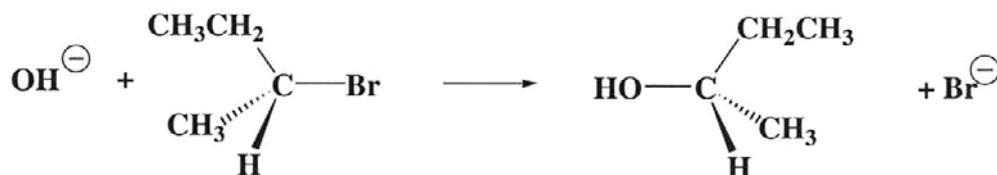
For elimination reactions, we most often use a planar arrangement that focuses on the bond where elimination will occur. Again using Brown (2000) to illustrate:



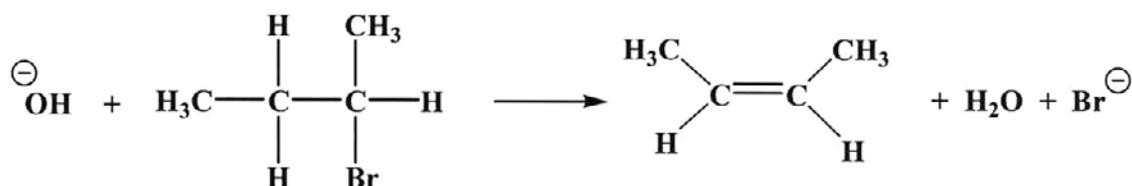
These practices are for sound pedagogical reasons, but Ladhams Zieba (2004) has found that the form of representation can provide misleading cues to students. She asked first-year undergraduate students to predict the reaction products, given the following different representations of the same starting materials:



Of those students given the first task, almost all predicted a substitution reaction:



Almost all students given the second task predicted that elimination would occur:

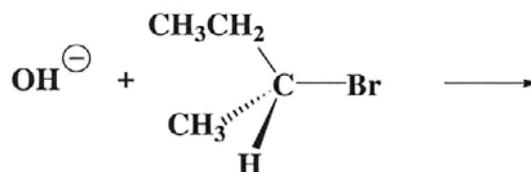


Since both substrate representations are of the same molecule, it seems that the students had been unintentionally cued into different answers by the instructional process. It is PCK to realise this, and to adopt appropriate teaching strategies.

Distinguishing models from ‘reality’

Kleinman et. al. (1987) describe how students were asked if molecules of bromobenzene have a plane of symmetry. On inspection of a structural representation of bromobenzene, one student declared that they do not because ‘B’ and ‘r’ are different. Just as the words *car*, *football* and *traffic light* should evoke images of a reality rather than of the words themselves, so students need to be able to see beyond drawings of structures of molecules to the ‘reality’ that they represent. This was obviously not the case for this student.

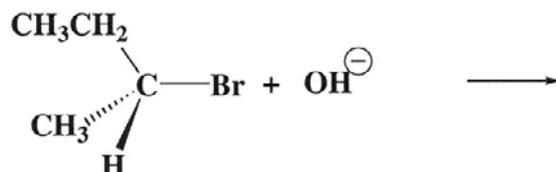
It is PCK to realise that sometimes students make mental operations on the drawing on the page or whiteboard, rather than on the reality that it represents. Ladhams Zieba (2004) has demonstrated this. She asked 18 second-year university students to draw the product species most likely to be produced from the substitution reaction of 2-bromobutane represented as follows:



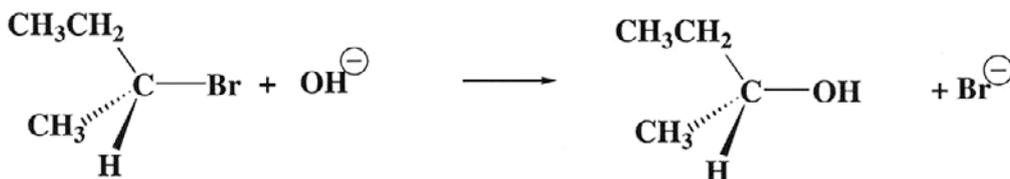
Ten of them drew the inverted substitution product that you might expect from ‘backside attack’ in an SN₂ reaction:



The other eight students drew a variety of responses. Seventeen other students were given the same task, now represented by an equation in which the positions of the formulas of the two reactant species are reversed:



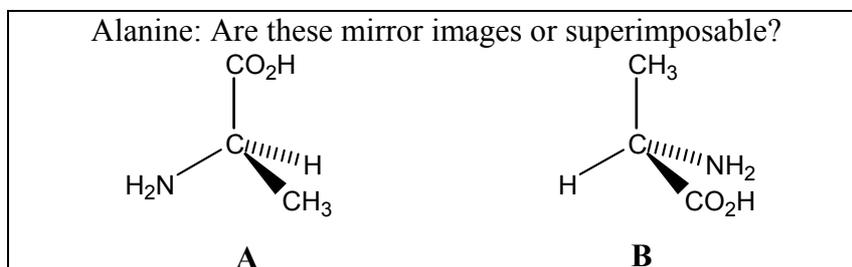
Eight of the students drew a substitution product without inversion, as though the hydroxide and bromide had simply switched places:



Only one of the others suggested inversion of the substituted butane. Obviously, these students are operating on the written representations, rather than on reaction mixture that the representations are modelling, with its multitude of possible collisional orientations and energies.

Mental operations on 3-D images: abilities and visualisation strategies

Head and Bucat (2002) have reported that undergraduate students and academic staff not only differ widely in their abilities to discriminate whether relatively simple representations of molecular structures are identical or enantiomeric, but they each consistently employ idiosyncratic decision-making strategies. This was demonstrated by interviewing students in relation to the following self-explanatory task.



Over a number of such tasks, each person consistently used one of the following general strategies:

1. One image (say A) is mentally manipulated in order to compare it with a stationary image of the other.

2. The structures are compared with each other by mental manipulation of both images.
3. The mirror image of one structure (say A) is created and this is compared with the image of B by mental manipulation. Once the relationship between B and the mirror image of A has been decided, the relationship between structures A and B is deduced
4. The mirror image of one structure (say A) is created and then the image of B is mentally manipulated to decide whether it is superimposable upon A or upon the mirror image of A.

And within these consistent general approaches, each person demonstrated consistent idiosyncratic methods of mental manipulation. These included mentally placing the same substituent at the top of each structure, exchanging pairs of substituents, rotating structures about a bond pointing in a particular direction, rotating about the C-H bond, and arranging the images so that the same two bonds were both in the plane of the paper.

There is some PCK here for all of those of us who have been guilty of being impatient with students who could not ‘see it’ in our own idiosyncratic ways.

Single-particle vs. multiple-particle sub-microscopic visualisation

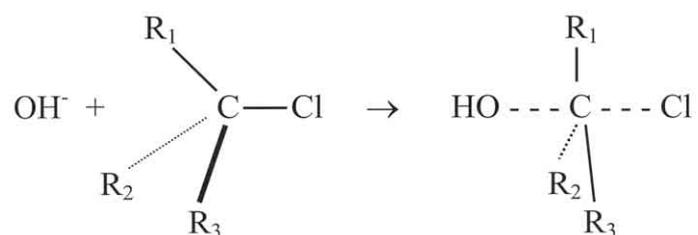
Nowadays it is common PCK for teachers, textbook writers and instructional designers to recognise that understanding chemistry involves switching between consideration of bulk, observable properties of substances and sub-microscopic images of particles of those substances - as pointed out by Johnstone (1982).

But things are even more complex than this. Sometimes at the molecular level we need to engage an image of one particle for a particular purpose. We do this when we want to indicate, for example, connectivity, bond angles, cis-trans isomerism, stereochemistry, or the polar nature of a molecule.

On the other hand, for some purposes we need to use pictures with many atoms, ions or molecules to develop sensible understanding of phenomena. For example, it is impossible to represent diffusion of gases, solubility of a solid in a liquid, or optical activity by other than many-particle pictures. Recognition of this is in itself PCK.

Why is this important? Sometimes students may use the inappropriate image. For example, Ben-Zvi *et al* (1987) have shown that some school students in Israel have responded to a question asking whether it is possible for N₂O₅ to be formed by reaction between N₂(g) and O₂(g) by saying “No. Where from did we get three additional oxygen atoms?” Obviously the symbolism N₂(g) and O₂(g) did not cause these students to engage a many-particle picture. Ben Zvi *et al* have speculated that a contributing cause might be our tendency to use for instructional purposes single-particle pictures of many-particle events.

We can anticipate a sense-making problem when textbooks say that the rate of an S_N2 substitution reaction depends on the concentration of both the substrate and the nucleophile, and then use a single-particle representation:



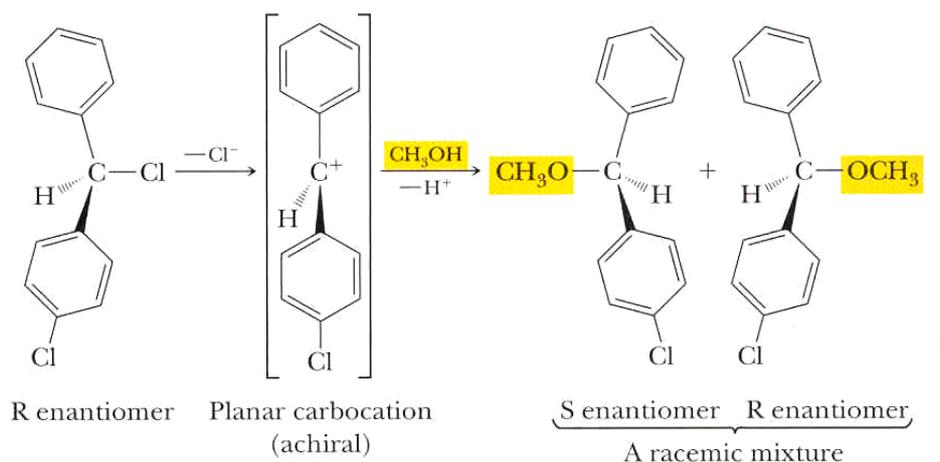
In this situation, many university students think that what is meant by the *rate of the reaction* is how fast the portrayed event proceeds. But how fast this single event proceeds is *not* what is meant, and indeed there is no sense to be made from the statement that the speed of the event is dependent on the concentrations of the reactants. Of course, the *rate of reaction* refers to how many such reaction events occur per second.

The problem might be exacerbated by language that implies a single-particle event - such as the following textbook extract:

The nucleophile OH^- uses its lone-pair electrons to attack the alkyl halide carbon 180° away from the departing halogen atom. This leads to a transition state with a partially formed C-OH bond and a partially broken C-Br bond.

The teacher whose PCK recognises the above considerations will use graphics (and language) indicating many reaction events occurring over time in a reaction mixture. Fortunately, computer graphics are now capable of powerful many-particle representations that portray the dynamic and probabilistic nature of reaction kinetics.

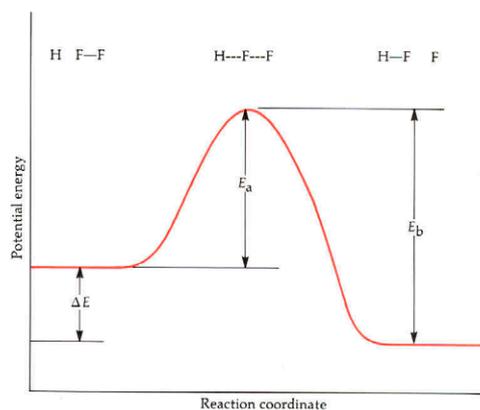
And another example. It is common to depict reaction mechanisms in organic chemistry through representations that show one molecule of each reactant. For example, the following textbook excerpt (Brown, 2000) represents an $\text{S}_{\text{N}}1$ substitution reaction leading to a racemic mixture of products.*



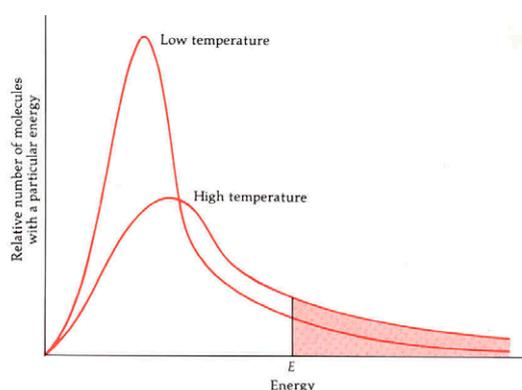
Ladhams Zieba (2004) has found that university students can be confused by this portrayal. How can we get two molecules of product from only one molecule of substrate compound? The teacher with PCK in this area, will take the trouble to represent this situation with a graphic showing many reacting particles, half of which give rise to one enantiomer, and half to the other.

To yet another example of PCK, it is perhaps significant that of the two diagrams usually used to account for temperature dependence of reaction rates, one refers to single particle events, and the other refers to many-particle situations. The activation energy profile diagram is a portrayal of a single reaction event:

* This material is used by permission of John Wiley and Sons Inc.



The Boltzmann distribution diagram, however, refers to the average energies of many particles:



I suspect that reconciliation of these two diagrams is not as easy for some students as we teachers perhaps assume. Some research on the issue would be useful.

Learnability vs. Correctness

A teacher with well-developed PCK would have an acute awareness of the tension that may exist between attempts to simplify the subject matter for immediate “learnability” and either correctness (the ‘truth’) or long-term teaching goals. Hawkes (1995; 1996, 1997, 1998, 1999) has published regularly in the *Journal of Chemical Education* on this issue.

RECOMMENDATIONS

To find out about student difficulties through research (or experience) is only one aspect of PCK. A much richer form of PCK is that which evolves from consideration of how to deal with those difficulties in the classroom, to try out ideas and to evaluate them in practice. Currently in the teaching profession the accumulated PCK of each of its participants grows with experience, peaks at retirement, and then disappears - often with hardly a contribution to the collective wisdom of the profession. This is a form of ‘professional amnesia’. What other profession would accept this state of affairs? While in other professions, successive standard-bearers “stand on the shoulders of giants who came before them”, the teaching profession seems to be engaged in many-fold “re-inventions of the wheel”. I recommend two courses of action:

1. For each topic, teachers, chemists and chemistry education researchers should work together, integrating pedagogy, chemistry and research findings, to systematically create and document a pool of PCK. The collection might constitute a research-based resource pool of notes, ideas and strategies relevant to the teaching and learning of the subject matter, to which all chemistry teachers have access. There are already a myriad of teaching tips and discussions to be found about the teaching of particular topics in the science education literature. But there is not a systematic collection of these based upon research and analysis of particular aspects of the subject matter, accompanied by evaluations in the classroom.
2. Architects, chess players and lawyers can learn from documented case studies that exhibit the philosophies and skills of masters in their field, indicating their 'game plans', their strategies, tactics, and responses to particular problems and situations. Wouldn't chemistry teaching benefit from research which provided detailed case studies of master teachers teaching about chemical equilibrium, for example? This 'applied research' would not only describe the master teacher's actions, but also probe his/her thought processes at critical points during a course, and track the changing understandings and perceptions of the students.

There are previous reports of observations of teachers' use of content knowledge in the classroom (Garnett, 1987; Munby & Russell, 1992; Wilson, Shulman, & Richert, 1987), but in these the subject matter has been merely the vehicle for making interpretations about the generic nature of teacher knowledge. We need studies which, in the light of these generic characterisations, observe, interpret and evaluate the PCK used by particular teachers in instruction of a particular topic, *to illuminate the teaching of that topic, rather than to illuminate teaching in some generic sense.*

There already have been attempts to describe pedagogical content knowledge pertaining to particular chemistry topics. Examples include those by Geddis et al. (1993), Magnusson and Krajcik (1993), and De Jong et al. (1995) which refer to the content-related demands of teaching about the topics of isotopes, thermodynamics and oxidation-reduction chemistry respectively. Hopefully these represent the beginning of an accumulation of such analyses, which would be extremely useful for both the pre-service education and the professional development of chemistry teachers. And they might even be useful resources for chemistry students - especially those at the tertiary level.

I believe that the "pedagogical-content knowledgeable" teacher is well-placed to make sound choices between alternative courses of action, based on content-specific reasoning, in order to maximise richness of learning. Of course one needs to recognise that classroom decisions cannot be made entirely on content-specific grounds. Any teacher will, with some degree of consciousness, take into account his/her educational philosophy, his/her personality, system constraints, colleague support, colleague constraints, and understanding of the culture, aspirations and the abilities of the students. In other words, it would be folly to claim that we can produce a recipe for best teaching of any particular topic for all teachers, all students, all systems, all cultures.

Finally, I make the claim that developing pedagogical content knowledge about topic X constitutes the creation of new knowledge different from, but equally as worthy as, research knowledge about topic X itself. Recognition of this might enhance the status of good chemistry teachers.

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REFERENCES

- Basolo, F. (1980). Can descriptive inorganic chemistry be taught in general chemistry classes? *Journal of Chemical Education*, 57, 45-46.
- Battino, R. (1979). Why thermodynamics should not be taught to freshmen or who owns the problem? *Journal of Chemical Education*, 56, 520-522.
- Bent, H.A. (1984). Uses (and abuses) of models in teaching chemistry. *Journal of Chemical Education*, 61, 774-777.
- Ben-Zvi, R., Eylon, B.-S., & Silberstein, J. (1987). Students' visualisation of a chemical reaction. *Education in Chemistry*, 24, 117-120, 109.
- Bodner, G.M. (1986). Constructivism: A theory of knowledge. *Journal of Chemical Education*, 63, 873-878.
- Bodner, G.M. (1992). Why changing the curriculum may not be enough. *Journal of Chemical Education*, 69, 186-190.
- Bodner, G.M. & Herron J.D. (1980). Impressions of the McMaster Conference on new directions in the chemistry curriculum. *Journal of Chemical Education*, 57, 349-350.
- Brown, W.H. (2000). *Introduction to organic chemistry*, 2nd edn. Saunders.
- Campbell, J.A. (1979). What thermodynamics should be taught to freshmen, or what is the goal? *Journal of Chemical Education*, 56, 520-522.
- Cassels, J.R.T. and Johnstone, A.H. (1983). The meaning of words and the teaching of chemistry. *Education in Chemistry*, 20, 10-11.
- Davenport, D. (1985) Why teach the gas laws? *Journal of Chemical Education*, 62, 505-506.
- De Jong, O., Acampo, J., & Verdonk, A. (1995). Problems in teaching the topic of redox reactions: Actions and conceptions of chemistry teachers. *Journal of Research in Science Teaching*, 32, 1097-1110.
- Garnett, P.J. (1987). Teaching for understanding: Exemplary practice in high school chemistry. In K. Tobin & B.J. Fraser (eds.), *Exemplary practice in science and mathematics education*, pp. 45-58. Perth: Science and Mathematics Education Centre, Curtin University.
- Garnett, P.J., Garnett, P.J., & Hackling, M.W. (1995). Students' alternative conceptions in chemistry: A review of research and implications for teaching and learning. *Studies in Science Education*, 25, 69-95.
- Geddis, A.N. (1993). Transforming subject-matter knowledge: The role of pedagogical content knowledge in learning to reflect on teaching. *International Journal of Science Education*, 15, 673-683.
- Geddis, A.N., Onslow, B., Beynon, C., & Oesch, J. (1993). Transforming content knowledge: Learning to teach about isotopes. *Science Education*, 77, 575-591.
- Gess-Newsome, J. & Lederman, N.G. (1999). *Examining Pedagogical Content Knowledge*. Kluwer.

- Hawkes, S.J. (1995). pK_w is almost never 14.0: Contribution from the Task Force on the general chemistry curriculum. *Journal of Chemical Education*, 72, 799-802.
- Hawkes, S.J. (1996). Salts are mostly NOT ionized. *Journal of Chemical Education*, 73, 421-423.
- Hawkes, S.J. (1997). Graham's Law and perpetuation of error. *Journal of Chemical Education*, 74, 1069.
- Hawkes, S.J. (1998) Solubility and the perpetuation of error. *Journal of Chemical Education*, 75, 138.
- Hawkes, S.J. (1999). Complex calculations are worse than useless. *Journal of Chemical Education*, 76, 1099.
- Hawkes, S.J. (2003) Why do we teach equilibrium calculations? *Journal of Chemical Education*, 80, 1381.
- Hawkes, S.J. (2004) Reaction to "Why do we teach equilibrium calculations" *Journal of Chemical Education*, 81, 1265.
- Head, J. & Bucat, R. (2002). Visualisation and mental manipulation of molecular structures. *Australian Journal of Education in Chemistry*, 59, 25-29.
- Herron, D.J. (1996). The role of language in teaching chemistry. In D.J. Herron, *The chemistry classroom*, pp. 161-182. American Society of Chemistry.
- IUPAC *Compendium of chemical technology*. Online version.
<http://www.iupac.org/publications/compendium/index.html>
- Kleinman, R.W., Griffin, H.C., & Konigsberg Kerner, N. (1987) Images in chemistry. *Journal of Chemical Education*, 64, 766-770.
- Johnstone, A.H. (1982). Macro- and microchemistry. *School Science Review*, 64, 377-379.
- Johnstone, A.H. (1997). Chemistry teaching - Science or alchemy? *Journal of Chemical Education*, 74, 262-268.
- Ladhams Zeiba, M. (2004). *An investigation of teaching and learning processes in the study of reaction mechanisms in organic chemistry*. Submitted PhD thesis, University of Western Australia.
- Lewis, D.L. (2004). Reaction to "Why do we teach equilibrium calculations". *Journal of Chemical Education*, 81, 1265.
- Magnusson, S. & Krajcik, J.S. (1993). Teacher knowledge and representation of content in instruction about heat energy and temperature. Paper presented at the *Annual Meeting of the National Association for Research in Science Teaching*. Atlanta.
- Marais, P. & Jordaan, F. (2000) Are we taking symbolic language for granted? *Journal of Chemical Education*, 77, 1355-1357.
- Mellon, E.K. et al. (1980). SYMPOSIUM: Introduction to symposium on inorganic chemistry in the curriculum: What should be left in and what should be left out. *Journal of Chemical Education*, 57, 61-??.
- Munby, H. & Russell, T. (1992). Transforming chemistry research into chemistry teaching: The complexities of adopting new frames for experience. In T. Russell & H. Munby (eds.), *Teachers and teaching: From classroom to reflection*, pp. 90-108. London, New York, Philadelphia: The Falmer Press.
- Nakhleh, M.B. (1992). Why some students don't learn chemistry: Chemical misconceptions. *Journal of Chemical Education*, 69, 191-196.
- Schmidt, H.-J. (2000). In the maze of chemical nomenclature - How students name oxo salts. *International Journal of Science Education*, 22, 253-264.
- Shulman, L.S. (1986). Those who understand: Knowledge growth in teaching. *Educational Researcher*, 15, 4-14.
- Shulman, L.S. (1987). Knowledge and teaching: Foundations of the new reform. *Harvard Educational Review*, 57, 1-22.
- Sutton, C. (1998). New perspectives on language in science. In B.J. Fraser and K.G. Tobin (eds.), *International Handbook of Science Education*, pp. 27-38. Kluwer.
- Wilson, S.M., Shulman, L.S., & Richert, A.E. (1987). 150 Different ways of knowing: Representations of knowledge in teaching. In J. Calderhead (ed.), *Exploring teacher' thinking*, pp. 104-124. London: Cassell.