Frameworks for representing science teachers' pedagogical content knowledge

Pamela MULHALL, Amanda BERRY and John LOUGHRAN

Faculty of Education
Monash University
Victoria 3800
AUSTRALIA

E-mail: Pam.Mulhall@Education.monash.edu.au

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Abstract

Over the past five years we have been involved in a research project that has attempted to recognise and then represent the pedagogical content knowledge (PCK) of successful Australian science teachers. The aim has been to capture, document and share teachers' PCK about specific science topics in ways that may be accessible to teachers and researchers involved in science education. In this paper, we illustrate the two integrated ways we have represented science teachers' topic specific PCK and discuss the theoretical framework that has informed our choice of representation.

Introduction

One of the tasks of the science teacher is to help students to understand some of the content knowledge of science. In doing so, Shulman (1986; 1987) posited that teachers make use of pedagogical content knowledge (PCK), a special kind of knowledge that teachers have about how to teach particular content to particular students in ways that promote understanding.

While the concept of PCK is debated in the literature (e.g., Gess-Newsome & Lederman, 1999), there is general agreement that the development of PCK is embedded in classroom practice (Van Driel, Verloop, & De Vos, 1998), implying that novice teachers and experienced teachers who have not taught a particular topic before may have little or no PCK in that specific content area. On the other hand, "successful" teachers in a given content area, by which we mean those whose teaching in that particular content area promotes student learning, are likely to have well-developed PCK in that specific content area. Thus the question arises as to whether it is possible to enhance teachers' topic specific PCK in those content areas where their PCK is under-developed using, in some way, successful teachers' PCK and so "prevent every teacher from reinventing the wheel" (Van Driel et al., 1998, p. 677).

This question encapsulates one of the ultimate purposes for our research into topic specific PCK. Our research (Loughran, Mulhall, & Berry, In Press) seeks to redress a gap in the research literature, that of successful science teachers' topic specific PCK, and to represent this teacher knowledge using a format which may be useful in pre-service and in-service science teacher education. To date we have documented expert successful teachers' PCK in three different content areas of the secondary science curriculum: particle theory (Loughran, Berry, Mulhall, & Gunstone, 2002); chemical reactions (Loughran, Mulhall, & Berry, 2002); and, human circulatory system.

As with all research, the methodology chosen and the ways of representing the data are inextricably linked to each other and to the purposes and theoretical framing of the research. We have discussed elsewhere our development of a methodology (Loughran, Gunstone, Berry, Milroy, & Mulhall, 2000) and of ways of representing the data (Loughran, Milroy, Berry, Gunstone, & Mulhall, 2001), and, for reasons of brevity, do not elaborate on these here. Briefly though, (1) the data sources were classroom observations and individual and group interviews that involved experienced science teachers of Grades 7 to 12 who taught in Australian schools and were considered to be successful teachers by their peers, (2) we, the researchers, are all former experienced secondary science teachers now working as academics in science teacher education, and (3) the data representations were constructed from the data sources by us, the researchers, in a similar vein to that of Van Driel et al. (1998). The data represented in this paper relate to the teaching of

"Chemical Reactions". During individual and group interviews, teachers were asked what they considered to be the "Big science ideas/concepts" for teaching this topic: after these had been written at the top of columns in a table, teachers were asked questions relating to the teaching of each of these big ideas, their answers again being recorded in the table.

In this discussion, we focus on the links between the ways we have represented the data and one of the research purposes, to document topic specific pedagogical content knowledge in ways that enhance science teachers' professional practice. We conclude with a discussion of the benefits and limitations of these representations and how they might be used to help develop teachers' PCK.

Background

The concept of PCK conceived by Shulman (1986) embraces the idea that successful teachers have a special understanding of content knowledge and pedagogy which they draw on in teaching that content:

> [PCK includes] the most useful forms of representation of [topics], the most powerful analogies, illustrations, examples, explanations, and demonstrations - in a word, the ways of representing and formulating the subject that make it comprehensible to others. (p. 9)

Also encapsulated in the idea of PCK is the notion that successful teachers have a special knowledge about learners which informs their teaching of particular content:

> Pedagogical content knowledge also includes an understanding of what makes the learning of specific topics easy or difficult: the conceptions and preconceptions that students of different ages and backgrounds bring with them to the learning of those most frequently taught topics and lessons. (p. 9)

While Shulman's notion of PCK may seem to resolve the question of what it is that successful teachers know in order to teach in ways that achieve student understanding, the concept itself and its relationship to other fields of teacher knowledge is debated in the literature (e.g., Cochran, King, & De Ruiter, 1991; Ebert, 1993; Grossman, 1990; Lederman & Gess-Newsome, 1992). While the uncertainty of this relationship and the general "fuzziness" (Marks, 1990) around the concept of PCK itself have impacted on the method that we have used to explore teachers' PCK, our research has not focussed on these concerns. Rather, we, the researchers, are more interested in finding ways of helping pre- and in-service teachers to improve their practice. Thus, instead of exploring and evaluating PCK per se, we have used the notion of PCK as a means of thinking about and exploring the knowledge that successful teachers have about how to teach particular content topics to particular students in ways that promote understanding, the intention being to document this so that it might enhance the science teaching practice of others.

Of course whether the documentation of teachers' PCK is useful to other teachers depends to some extent on the degree to which a teacher's PCK is idiosyncratic. Van Driel et al. (1998) conclude from their investigation of the literature that research on science teachers' PCK should enable useful generalisations to be made. Our position is that it is reasonable to assume that there will be similarities between teachers in Australian schools who have similar backgrounds in teaching and learning science. Thus our research method generates knowledge about PCK which is generalised across small numbers of teachers, leading us to believe that it potentially applies to others.

Interestingly, there are few examples in the literature of topic specific PCK in science. The approach of most researchers in this area has been to compare and contrast particular aspects of PCK of individual teachers (e.g., Magnusson & Krajcik, 1993, heat energy and temperature) and of groups of teachers (e.g., Clermont, Borko, & Krajcik, 1994, density and air pressure); to use case studies of novice and/or practising teachers to explore aspects of their topic specific PCK (e.g., Geddis, Onslow, Beynon, & Oesch, 1993, isotopes); and to explore the effect on science teachers' topic specific PCK of programs that relied on the researchers' own PCK in that particular content area (e.g., Parker & Heywood, 2000, forces in floating and sinking; Van Driel et al., 1998, chemical equilibrium). Given our perspective of wanting to make generalisations about the topic specific PCK of successful teachers, we note that researchers have not provided detailed overviews of teachers' topic specific PCK and have neither explored that of successful teachers nor attempted to synthesise the data from their research. An interesting exception to the latter is Van Driel et al. (1998) whose description of what teachers do to help students understand the dynamic nature of chemical equilibrium was constructed by synthesising the researchers' results.

Because the literature lacks detailed examples, we have developed our own approach to representing teachers' topic specific PCK, which we now discuss.

Our frameworks for representing teachers' PCK

The forms of representations of teachers' PCK that we have developed stem from our belief that such representations should be consistent with current views about: (1) effective science learning and teaching; (2) the complexity of teacher thinking; and, (3) ways of promoting understanding of teachers' experiences of teaching. We elaborate each of these issues below.

Current views about learning and teaching science

A recurring theme in research into students' learning about science over the past twenty years has been the prevalence of students' alternative conceptions about science ideas (e.g., Pfundt & Duit, 1994). This research is linked to a view of learning which draws on personal and social constructivist ideas: the student's learning is influenced by their own personal cognitive framework which they have developed as a consequence of their prior experiences and by the ideas of the culture in which they live (Driver, Asoko, Leach, Mortimer, & Scott, 1994). From this perspective, the role of the teacher is that of mediator of learning, rather than transmitter of knowledge (Tobin, Tippins, & Gallard, 1994). To be effective, the teacher must be knowledgeable about common student misconceptions, constantly monitor students' understanding, design/introduce experiences at appropriate points which will promote learning, act as the cognitive coach who introduces new concepts, and provide opportunities that help students become proficient users of these concepts. Discussion between students and between teacher and student/s about science ideas and the ways these differ from everyday understandings are central to many of the teaching activities (Driver et al., 1994; Hollon, Roth, & Anderson, 1991; Leach & Scott, 1999; Tobin et al., 1994). Importantly, teaching for understanding takes much longer than is allowed for in conventional approaches: as a consequence the breadth of content that can be covered is less than what has been traditionally expected (Hollon et al., 1991, p. 149).

While some consider that a transmissive model underlies much of the research on PCK (Calderhead, 1996), we have used a constructivist perspective to interpret and represent teachers' PCK. Our representations foreground those aspects of teachers' knowledge which help them to formulate teaching approaches that promote student learning.

Views of teacher thinking

As many have noted, teaching is a complex activity involving much more than a series of actions by the teacher (Clark & Peterson, 1986). Notions of "teacher thinking" focus on the complexity of thought that informs the teacher's actions and decision making in a particular teaching situation (Husu, 1995). Importantly, we would argue, whether or not a particular action by a teacher is illustrative of that teacher's PCK depends upon the teacher's reasons for that action. Thus our representations of topic specific PCK attempt to make explicit a successful teacher's reasoned decision making in the context of teaching that particular science content because it provides evidence that the teacher is using pedagogical content knowledge.

Teachers' experiences of teaching

Representations of teachers' practice that are intended to capture and portray the nature of experience increasingly draw on narrative forms (Connelly & Clandinin, 1990, 2000). Narrative in research on teaching has the capacity to render the teaching experience in rich detail, including its particularities, complexities and indeterminacy, and to open up this experience for others' understanding. As Fenstermacher (1997) observes,

> Through narrative we begin to understand the actor's reasons for the action, and are thereby encouraged to make sense of these actions through the eyes of the actor. This understanding constitutes an enormous contribution to learning about and getting better at teaching. (p. 123)

Conle (2003) concludes that narrative can also help the reader to view and interpret phenomena differently; develop the reader's tacit, practical knowledge; and lead to personal and professional changes in the reader, and to their "[v]isions of what can be" (p. 11).

We have used narrative as one mode of representing teachers' PCK in this research. Because narrative constructions have the capacity to represent the holistic nature of teachers' knowledge and experience, we can explore the interacting elements of context, teachers' and students' past experiences and their future plans and actions. This is in contrast to traditional "scientific" modes that aim to isolate elements of experience for separate examination.

Our representations of science teachers' topic specific PCK

To represent successful science teachers' PCK about a particular science topic, we have developed two different but complementary formats. These are the CoRe (Content Representation, shown in Appendix A) which is an overview of the particular content taught when teaching a topic, and PaP-eRs (Pedagogical and Professional-experience Repertoires, an example being that in Appendix B), accounts of practice intended to illuminate aspects of the CoRe in a particular classroom context. The examples shown in these appendices relate to the teaching of the topic, 'Chemical Reactions', to a mixed ability Grade 10 class. It is important to realise that the PaP-eR shown in Appendix B is but one of a number we have developed that are linked to the 'Chemical Reactions' CoRe, each focussing on a different aspect of a successful teacher's PCK in this area.

As noted previously, our approach to data gathering is discussed elsewhere (Loughran et al., 2000, 2001) and it is not within the scope of this paper to detail the ways in which data about science teachers' knowledge of practice was obtained. Suffice to say our representations are a synthesis of our research data (individual and group interviews with experienced, successful science teachers and observations of their science teaching).

About CoRes

A CoRe (Content Representation) provides an overview of how teachers approach the teaching of the whole of a topic and the reasons for that approach - what content is taught and how and why - in the form of propositions. Importantly, a CoRe refers to the teaching of a particular topic to a *particular* group of students (e.g., mixed ability, Grade 10 general science class).

The CoRe for 'Chemical Reactions' shown in Appendix A refers to the teaching of a typical class at the Grade 10 level. The CoRe was developed by asking teachers to list at the top of each column what they considered to be the "big ideas" for teaching 'Chemical Reactions' to that grade level. Teachers then provided the information shown in the column underneath each big idea as they were asked about the different aspects of their knowledge and practice shown in the left-hand column. The CoRe is a generalisation of teachers' responses. Taken as a whole, the CoRe represents pedagogical content knowledge because of the reasons it provides which link the how, why and what of the content to be taught with the students who are to learn that content. We elaborate on this below.

As we mentioned earlier, our framing of teachers' PCK has been influenced by constructivist perspectives of learning, for which the implications are that teaching for understanding entails teachers developing knowledge about science and learners that enable them to make: (1) curricular decisions; and, (2) instructional decisions (Hollon et al., 1991, p. 149). We use these two groupings to discuss below the kind of information highlighted in each row of the CoRe.

Using knowledge about science and learners to make curricular decisions

Grade level It is important to emphasise that a CoRe refers to a particular type of class, which for the case shown in Appendix A is a Grade 10, mixed ability general science class.

Big science ideas/concepts "Big ideas" is a term often used in science to describe an idea that has had a profound impact on the ways scientists understand and conceptualise the world. Our use of the term is not synonymous with this: we mean the science ideas that the teacher sees as being at the heart of understanding the topic for the particular class under consideration (Smith III & Girod, 2003). (Nevertheless, a big science teaching idea may also be the same as a big science idea.)

What you intend the students to learn about this idea Being specific about what a particular group of students should be able to learn is an important aspect of well developed PCK. In contrast, teachers inexperienced at teaching a topic are often unsure what the students are capable of achieving.

Why it is important for the student to know this In making decisions about what to teach, successful teachers draw on their knowledge of what science content is relevant to students' everyday lives and how the content links with other areas that students study. Related to the latter is "curricular saliency" - how important a particular science idea or topic is to the overall science curriculum (Geddis et al., 1993).

What else you might know about this idea (that you don't intend students to know yet) When selecting what to teach, teachers often make difficult decisions about which content should be omitted (Hollon et al., 1991). Indeed, as noted earlier, constructivist perspectives of learning recognise that teaching for understanding takes time, which places limits on the range of what can be taught.

Using knowledge about science and learners to make instructional decisions

Difficulties/ limitations connected with teaching this idea Shulman (1986) considered that teachers' insights into the potential difficulties when teaching a particular topic to the class in question were an important aspect of teachers' PCK.

Knowledge about students' thinking that influences your teaching of this idea This part of the CoRe makes explicit the influence on their decision-making of teachers' experience in teaching this topic. When planning lessons, teachers draw on their knowledge about commonly held ideas about the topic that students bring to class (the importance of which is highlighted by the "alternative conceptions" literature mentioned earlier) and also the usual responses (including level of interest) of students to specific teaching and learning situations.

Other factors that influence your teaching of this idea Contextual knowledge about students and general pedagogical knowledge that influences the teaching approach are indicated in this part of the CoRe.

Teaching procedures (and particular reasons for using these to engage with this idea) The term "procedures" is used in the sense of that in the PEEL project (Baird & Northfield, 1992): it acknowledges that from a constructivist perspective, student change in terms of learning is gradual and involves the student's active engagement with the science ideas under consideration. Teaching procedures cannot guarantee learning: rather their purpose from a constructivist perspective is to influence student thinking in ways that promote better understanding of science ideas (Leach & Scott, 1999).

Specific ways of ascertaining students understanding or confusion around this idea Teachers need to constantly monitor the progress of students' understanding so that they can determine the effectiveness of their teaching of the topic and plan future lessons. While summative assessment is usually explicit, teachers' formative assessment is often unacknowledged and implicit, and probably more specific to the topic being studied.

We note that some parts of the CoRe have more detail than others, in part a consequence of the difficulty of exploring teachers' PCK (Loughran et al., 2000, 2001; Mulhall, Milroy, Berry, Gunstone, & Loughran, 2000). However, the form of representation of a CoRe allows additions and changes to be made as further insights from expert, successful teachers are gained. This does not imply that there is only one CoRe for each topic. Indeed we have found more than one CoRe seems to be applicable to 'Chemical Reactions' (Loughran, Mulhall, & Berry, 2002). This is not surprising in view of the developing research literature on the role of beliefs and contextual factors in teachers' understandings and practice (e.g., Tobin et al., 1994; Tobin, 1998).

The CoRe enables an overview of teachers' PCK for a topic to be made, and provides some insights into the decisions that teachers make when teaching a particular topic, including the linkages between the content, the students and teachers' practice. However, because the information is represented in the form of propositions, it is limited in terms of providing insight into teachers' experiences of practice. It was for this reason that we developed PaP-eRs (Pedagogical and Professional-experience Repertoires), which we now discuss.

About PaP-eRs

In our research, PaP-eRs are narrative accounts of a teacher's PCK for a particular piece of science content. Each PaP-eR "unpacks" the teacher's thinking around an element of PCK for that content, and is based on classroom observations and comments made by teachers during the interviews from which the CoRes were developed. PaP-eRs are intended to represent the teacher's *reasoning*, that is, the thinking and actions of a successful science teacher in teaching a specific aspect of science content. The function of the narrative is to elaborate and give insight into the interacting elements of the teacher's PCK in ways that are meaningful and accessible to the reader, and that may serve to foster reflection in the reader about the PCK under consideration, and to open the teacher reader to possibilities for change in his/her own practice.

The example of a PaP-eR from the topic area of 'Chemical Reactions' shown in Appendix B has been annotated using "call out" boxes to highlight the interpretive frames we have used in its construction. (The shaded call-out boxes do not form part of the PaP-eR.) The "voice" of this PaP-eR is that of a teacher reflecting on her/his understanding about the problematic nature of the concept of substance, an understanding developed through experience of practice. The "voice" of the call-out boxes is that of the researchers elaborating what they intended to illustrate in the different parts of the PaP-eR. It is important to realise that this PaP-eR is but one of a number that are linked to the 'Chemical Reactions' CoRe, each focussing on different aspects of a successful teacher's PCK.

PaP-eRs offer one way of capturing the holistic nature and complexity of PCK, more than is possible in the CoRe. PaP-eRs have the capacity to represent a "narrative whole", and function to explain in a text what one knows in action as a teacher. Many of the PaP-eRs involve teachers coming to see experience differently, or "reframing" (Barnes, 1992) over a "widened range of attention" (Dewey, 1933) what goes on in the learning of particular science concepts. In so doing, the reader is afforded insights into teachers' development of pedagogical content knowledge of that science topic.

Conclusion

The CoRes and PaP-eRs are complementary representations of successful teachers' PCK about the teaching of a particular topic to a particular group of students. A CoRe provides an overview of teachers' pedagogical content knowledge related to the teaching of a topic in the form of propositions. A PaP-eR is a narrative account that offers insight into the interacting elements of a teacher's thinking about a small "piece" of this PCK. Both representations of PCK are constructed from our research amongst a small group of teachers and, consistent with representations used by other researchers of PCK (Van Driel et al., 1998), they should not be interpreted as depicting the PCK of each teacher in the study. Rather, these representations are generalisations of teachers' pedagogical content knowledge about teaching particular science content to a particular group of students, and as such are potentially valuable contributions to the knowledge base of teaching.

Both forms of representation of teachers' PCK are limited in that they do not enable us to "see" the teaching in action, or tell us how teachers' beliefs about the nature of the knowledge represented influence their practice. Nevertheless CoRes and PaP-eRs allow insights into the ways that successful teachers think about science content in the context of teaching. Importantly, both CoRes and PaP-eRs provide reasons which support our assertion that the teachers' knowledge that is represented is pedagogical content knowledge (Fenstermacher, 1994). A long term goal is to establish the "ecological validity" (Kagan, 1990) of this work, i.e., that teachers who have this knowledge do in fact teach in ways that lead to student understanding.

It is well accepted that much teacher knowledge is implicit, with teachers rarely having the opportunity to reflect on what they do in the classroom and why. Further, curriculum and other documents tend to represent the teaching of a topic in an undifferentiated form as certain content to be learned and understood, and activities that might engage students. Not surprisingly, teachers' framework for thinking about and discussing with colleagues the teaching of a topic is often limited to "what works". The framing of the CoRes has the potential to help problematise the content and teaching approaches in teachers' minds, and to provoke their thinking about what is important in the teaching of a topic and why. It may also help teachers to identify what they need to know and think about when teaching a new topic (e.g., "What are the big ideas for teaching this topic to this particular group of students?" "What should I expect, and equally, not expect, these students to learn?" "What teaching procedures will help this group of students to understand a particular big idea?" etc) and to become aware of the PCK they already have. PaPeRs may also help in some of these ways, as well as making explicit the ongoing reflection and problem solving that is part of teachers' sense making of what happens in the classroom. Thus, the purpose of both CoRes and PaP-eRs is to not only represent teachers' topic specific PCK, but also to act as triggers that may help other teachers (both pre- and in-service) widen their range of attention about practice, leading to a reframing of their experience and a development of their PCK. As Bullough (2001) notes,

> Teachers need help to think more complexly about their practice and the reasons behind their actions in the light of how particular pupils learn and in relationship to specific formal academic knowledge. (p. 665)

CoRes and PaP-eRs make explicit this complexity in teachers' thinking and are intended to promote an awareness of this, and a capacity for this, in teacher readers. At this point in our research, we are unsure whether CoRes and PaP-eRs achieve this aim. It is possible that our work may be more helpful for practising teachers who have some experience because, as Calderhead (1996) notes, experienced teachers are "able to make a deeper interpretation of events, interpreting significant contextual cues" (p. 717). For pre-service and beginning teachers, on the other hand, it is possible that our representations of PCK may not "resonate with the context within which they will eventually teach" (Bullough, 2001, p. 664). Thus another long-term goal of our project is to explore the accessibility and usefulness of these representations of PCK for teachers and researchers, including the extent to which they are helpful in developing teachers' PCK.

Finally, we are in agreement with the assertion by Bullough (2001) that exploring critical aspects of PCK and how these aspects should be divided between pre- and in-service teacher education requires answers that involve what Bagley calls "a unique quality of scholarship" (Bagley cited in Bullough, 2001, p.665).

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APPENDIX A

CoRe for Chemical Reactions (Grade Level: 10 mixed ability)

	BIG SCIENCE IDEAS/CONCEPTS				
	A. In a chemical reaction (one or more) new substances are produced.	**B. Chemical substances can be represented by formulae.**	**C. Equations describe the reactants and products in a chemical reaction.**	**D. There are patterns to many chemical reactions.**	**E. Organic chemicals contain carbon.**
What you intend the students to learn about this idea.	◦ A chemical reaction involves an input (reactants) and an output (products - which have different chemical properties). ◦ Chemical reactions are all around us.	The formula of a substance reflects what it 'looks like' at the atomic level. A particular chemical always has the same formula regardless of where it comes from. The way of writing formulae is universal amongst chemists. 'Rules of the game' Some elements are represented as if they are single atoms (eg metals such as zinc, which is Zn) and others are represented as molecules (eg oxygen, which is O2).	Equations are a form of chemical communication - for a particular reaction, the same equation applies in all parts of the world. The learning of more able students may be extended to include: ◦ The equation represents the proportion of reactants needed and of the products produced. ◦ When writing equations: 1 It is necessary to use correct formulae for reactants and products. 2 Equations need to be	◦ Classifying reactions enables one to predict products. ◦ As with much of chemistry, this predictability is not perfect: although you can write an equation, the reaction does not always happen at all, or happen according to prediction. An understanding of (and ability to correctly use) useful terms like acid, base, salt, combustion, precipitation etc is important. Students should	Organic chemicals contain carbon. Carbon atoms can form 4 bonds with other atoms. This means that they can form an infinite array of compounds. Many of these compounds contain long chains of carbon atoms to which hydrogen and other atoms are linked. Most of the chemicals in the world around us (and inside us) are organic. Organic chemicals can react to make molecules which we can use (eg glucose, carbon dioxide - the latter is not always

		Compounds are represented by the molecules they contain (eg water, which is H2O) or by the combination of charged atoms ('ions') they contain (eg salt, which is Na+Cl-). All substances are made up of zillions of atoms. When you breathe in oxygen, you are breathing in zillions of 02 molecules.	balanced because mass is conserved.	understand the 'well behaved' reaction types, eg acid-base, acid-carbonate, acid-metal, precipitation, combustion, synthesis/ decomposition.	considered 'organic').
Why it is important for students to know this.	It enables an understanding of real life situations (eg as reported in newspapers) and personal experiences: eg environmental issues such as pollution, corrosion, analysis of bottled water, cooking a cake, lighting a match, effervescent powder, BBQ It helps develop an understanding of	Formulae are part of the language of chemistry. The ability to communicate the structure of a substance through writing its formula is a vital precursor for further studies. To understand chemical reactions in Year 11 students need to understand the order of magnitude of numbers of particles involved.	Equations form the language used to explain chemical reactions.	Categorising reaction types provides students with reasonable predicting measures about products. If an experiment does not proceed as anticipated, students need to appreciate that they should consider the possibility that there is something that they haven't taken into account (rather than assume something is wrong with their observations).	There are lots of organic chemicals all around us.

	consumer chemistry, eg ammonia in floor cleaners.				
What else you might know about this idea (that you don't intend students to know yet).	Not all reactions are complete (eg some biological reactions & some industrial processes) - this is not addressed unless it is raised by a student. The chemical equilibrium constant is a guide to the extent to which a reaction proceeds. Chemical reactions involve the breaking of existing chemical bonds and the formation of new ones.	States of matter are usually indicated. Complex formulae are left out as they are too confusing for students (eg toluene).	Chemical equations involving half reactions, redox reactions and ionic transfer are complex and can be too confusing at this level.	Although most reactions **are** predictable, there are rare exceptions, some of which are the consequence of important rules met in Senior Chemistry (eg why Zn reacts with dilute acid, but Cu does not — a Redox reaction). While combustion at this level refers to combining with oxygen, in fact something can be burned in anything which can oxidise it, eg chlorine, fluorine.	There are more organic chemicals than all the others put together. At this level we hardly scratch the surface beyond seeing that organic chemicals react too.
Difficulties / limitations connected with teaching this idea.	The explanations of what is occurring are quite abstract. This is compounded by the fact that the scale is so small in comparison to the macroscopic level at which the students are working. Thus it is difficult for students to make links between the macro- and micro-scopic	If students cannot write the formulae of substances then further work (eg on equations) is difficult. One can provide a technique for struggling students of swapping valencies and writing them as subscripts:	Too much emphasis on the microscopic behaviour can detract from development of knowledge and understanding of the macroscopic behaviour of substances.	This topic is so broad, one can only deal with a few types, on the basis of safety and those which are available in the school lab. It is difficult to generate many examples that are related to students' everyday experiences because what happens in the lab is oversimplified	It is always difficult to know whether or not one should teach functional groups, which are the basis of lots of organic reactions. It is difficult to provide suitable experimental work because most organic chemicals are either flammable, toxic or both!

	levels of behaviour of chemicals.	eg Pb^{4+} PO_4^{3-} $Pb_3(PO_4)_4$ This works without understanding but can lead to problems (eg Mg_2O_2).		and specialised. Students have to accept 'in good faith' the teacher's explanation of the details of a reaction. Teachers' concern for management and safety often creates a dilemma for the construction of good learning episodes.	Bonding is central to developing an understanding of organic compounds but is a difficult concept for students to grasp at this stage.
Knowledge about students' thinking that influences your teaching of this idea.	Teachers can get a 'feeling' of general interest level of the class by the links the students are making to other ideas and experiences.	Formulae are often taught in Year 9 but always require revising. This also applies to ionic and covalent compounds. To work out the starting point for teaching, find students' ability level by getting them to write formulae/ equations as this helps to understand how they're thinking about it. Students tend to think that a formula only represents one 'lot' of that substance, eg H_2O means just two H and one O.	Students usually demonstrate a superficial acceptance of Conservation of Mass. It is a difficult concept for them to grasp so exploring their thinking beyond superficial responses matters. At this stage of their development, students are often particularly interested in environmental issues, many of which can be linked to ideas about chemical reactions.	It is often hard to convince students of the value of their observations and of experiments that don't 'work' according to the rule, and that one can learn a lot about chemistry from one's observations. They often think that an experiment is wrong if it doesn't get the results expected and therefore do not interrogate the ideas or their approach to the experiment seriously enough.	

Other factors that influence your teaching of this idea.	The idea of chemical reactions is introduced in early secondary years so this would be revisiting the concept. In particular students have already seen some chemical reactions and are familiar with tests for carbon dioxide, hydrogen and oxygen. If students don't make links that you want them to then you need to help them by asking 'leading' questions (eg to help them see patterns in acid/base reactions). Because of safety considerations it is difficult to provide meaningful opportunities for practical work which engage the students in designing their own experiments.	Students often enjoy working out formulae using a given table of valencies. Expecting students to remember valencies can lead to rote learning rather than understanding.	More able students often enjoy balancing equations. Discussion of the importance of predicting correct proportions to minimise costs and unwanted environmental effects in industrial processes can be useful in generating 'a need to know' amongst students.	Students are probably familiar with terms like acid, base, salt, combustion (or 'burning') Students enjoy practical work and like 'playing' with chemicals and apparatus. Practical work is also appealing because it is a sensory experience. Students are not expected to remember reaction types at this level as this would lead to cognitive overload. However given the categories of reaction types they should be able to make reasonable predictions about possible products. Reaction types covered (see first box in this column) are interesting for students but not too dangerous.	Organic chemistry is more important and relevant for students than inorganic (eg hard to justify importance of learning about ZnCl2 for most students) but is much more complicated and dangerous.
Teaching procedures	Practical work can be presented in the form of a problem to be solved (eg	Chalk and talk (often effective for those who grasp ideas easily).	Practical work involving a range of different reactions where students	◦ Forensic science Identification of unknown ionic	Students make models of molecules of some familiar chemicals (eg

(and particular reasons for using these to engage with this idea).	in a forensic science context, students have to identify the nature of some mystery powders). This helps develop 'a need to know' using a real world context and helps develop knowledge about the properties and behavior of substances. It also provides an opportunity for students to practice writing formulae and equations. Most students enjoy the activity and are able to achieve a reasonable level of success in it.	Making models Make models of molecules and ionic substances using 'Playdoh' provides a sensory and visual aid to understanding formulae. 'Dirty tricks' To help promote understanding about how formulae are written, ask which is right: 1. NaOH or Na(OH) [teacher may need to point out that brackets are not needed here] 2. CaNO32 or Ca(NO3)2 [students often realise there is something wrong with the first of these]. Linking To explain why we write Ca(OH)2, it may be useful to make links to maths - where a mathematician might write 2(x+1) the chemist would write (x+1)2.	identify as many products as possible. Results are discussed as whole class leading to writing equations as words, then symbols. Algorithmic skills can be developed in more able classes by presenting students with a page of equations of steadily increasing difficulty. The challenge is to see how many they can correctly balance.	compounds through practical work (using flame/ precipitation/etc tests previously derived by testing known substances) and using semi-micro test tubes (for safety). - gives students control - provides a real-world application - a motivation - helps students to remember reactions and understand equations. ◦ POE (Predict-Observe-Explain) To emphasize predictability is not a guarantee of what happens, and that observation is the key to chemistry, this POE is useful: get students to predict what happens when add CaCO3 (as marble chips)+ H2SO4 and then perform experiment. There	petrol, nail polish remover) with Molymod™ kits (which are so designed that they closely replicate the exact shape of the actual molecule). It is useful to have as many actual samples of these chemicals in the lab to help emphasise that the models are of real molecules in real things. This also provides the opportunity for students to become familiar with some of the physical properties of these chemicals (eg smell, appearance etc). Soap making

				appears to be no reaction (actually it bubbles a little bit and then stops because the $CaSO_4$ formed is insoluble, forms a coating over the unreacted $CaCO_3$ and stops the reaction). Ask students to explain their observations.	
Specific ways of ascertaining students' understanding or confusion around this idea.		'Dirty tricks' The teacher deliberately makes mistakes and waits for students to notice (eg write CaOH2 instead of Ca(OH)2	Write the formulae first, then get students to balance the equation - this shows whether or not conservation of mass is obvious to students. POE (Predict-Observe-Explain) Get students to weigh a piece of Mg, then predict weight of product after it burns, measure this weight (ie observe) and explain the result. This POE offers evidence that the burning of Mg involves an 'adding on' to the Mg. It also helps to make an abstract equation real.	See POE in box above	

APPENDIX B

A PaP-eR on Chemical Reactions

Understanding What Substances Are

NB Shaded 'call out' boxes have been added to highlight researchers' interpretive frames but do not form part of the PaP-eR.

This PaP-eR discusses the importance of students developing an understanding of the idea of substance and how substances differ, as a precursor to recognising and understanding chemical reactions.

→ *A succinct description of the science pedagogical content knowledge that will be elaborated in this narrative*

Chemical reactions tend to be presented to students as processes in which new substances are formed. I used to consider this idea to be unproblematic for students and tended to focus instead on developing student understanding of scientific explanations for the behaviour of a reaction at the atomic level. After I had been teaching awhile, I became aware that students often aren't sure what a 'substance' is and find it hard to decide if a chemical reaction has occurred: when they 'see' a chemical reaction taking place, they do not automatically 'see' that new substances are formed because they do not think this way about matter.

→ *Narrative voice is that of a thoughtful teacher reflecting on past experience.*

→ *Teacher recognizes this is a complex concept. Teacher's knowledge develops in action.*

→ *Teacher questions what is usually seen to be 'unproblematic', i.e. students' understanding of what is a substance.*

Over the years I have often heard this kind of conversation between students in prac groups as they are doing an experiment:

→ *Teacher knowledge derived from experience of practice; noticing a pattern in the way students respond.*

Pat (recording the group's notes about the prac): What happened?
Kim: It went fizzy.
Pat: Did you see any new substances?
Kim: Nope.

Sam: What shall I write down was formed?
Chris: A blue colour

PaP-eRs are located in a particular classroom context. Each class is different and the teacher's responses to that class will be based on specific knowledge of the particular group as well as general knowledge about teaching this content at this year level.

While students such as these 'see' bubbling, they don't make the connection that a new substance - gas - is formed. They may 'see' a colour change but not that a different substance - powder - is now floating around in the test tube. So I spend a lot of time trying to develop student awareness of substances. I do this by trying to develop student awareness of the ways in which 'stuff' differs. In chemistry terms that means considering the physical and chemical properties of a piece of 'stuff' but early on I don't worry about this distinction.

Teacher makes decisions (based on awareness of students, content, curriculum, pedagogy).

Teacher's knowledge about properties of substances (content knowledge) and knowledge about how students learn (pedagogical knowledge) together inform the decision that is made (PCK).

Teacher recognizes that student learning develops slowly and through a variety of approaches.

We do a lot of activities where basically the task is for students to try to describe as accurately as possible a number of different substances. I pick out a few substances that have a similar property (for example colour) and ask how we know they are different. Sometimes it's hard to be sure (unless we perform a chemical analysis - but that is a long way down the track for these students) but the important thing is to start students thinking about the differences between things and what makes a substance different from the rest. It's really important to have some pure powders among the examples

Teacher recognises the importance of providing a range of opportunities for students to grapple with one of the big ideas of science.

students have to consider and some whole pieces of the substances that these powders come from, such as a piece of iron and fine iron filings: this helps them to realise that powders are the same 'stuff' or 'substance' as the thing they came from, and that size is not a good way of distinguishing substances.

When I think they have the idea, I push them further to start considering situations where a new substance may have been produced. Of course this is getting into chemical reactions, but I don't use that term yet. I am still focussing on the idea of substance and whether students can distinguish between different substances. I give students this handout to discuss in small groups.

→ *Teacher is constantly monitoring student learning. This informs what will be done next.*

IS A NEW SUBSTANCE BEING FORMED HERE?	
The event	Group decision (with reason)
The foul smell of food gone bad	
The rusting of a nail	
Cheese being grated	
Baking a cake	
A tree growing from a seed	

→ *Teacher's understanding of the content informs his/her choice about which everyday examples are useful to include for students' learning.*

As the discussions progress, I wander around and listen. Conversations like the following tell me they are getting the idea.

> Gina: Well grated cheese looks the same as the block of cheese it came from.
> Teresa: Tastes the same too - yum!
> Tom: Yes, it's just smaller bits of the big cheese but still the same stuff.

→ *Teacher's understanding of content and pedagogical approach (listening, not intervening) helps develop teacher's awareness of students' understanding. Teacher is listening for and at the same time, listening to.*

Hugh: Of course a cake is a new substance!
Con: Yeah, looks and feels totally different to the eggs, butter, flour and sugar.
Tim: In fact you can't even see them anymore.

If I hear an observation like Tim's, I store it in the back of my mind for the next lesson when I want to develop the idea that when new substances are formed, the original ones disappear. For the moment though I am pleased that the students can recognise when new substances are formed. (The tree growing from a seed is a tricky one - the leaves look new but what about the bark? There are often arguments between the students about this - what's important here is not the actual decision that students make but their reasoning and I like to emphasise that it's situations like this, where scientists are not sure of the answer, that often lead scientists to doing further experiments.)

Teacher is sensitive to what is occurring 'within the moment' and considers its influence on future learning decisions.

Sense of teacher's reasoning why learning experience is constructed in this way.

Ultimately I want students to see things they have seen before, both in the world around them and in the lab, in a new way so that the conversations in the lab I mentioned at the start run like this:

Pat (recording the group's notes about the prac): What happened?
Kim: It went fizzy.
Pat: So a gas was produced?
Kim: Yes.

Sam: What shall I write down was formed?
Chris: A blue substance.

Teacher's purpose for his/her teaching linked to big science idea which he/she sees as problematic in terms of student learning.

Teacher awareness of his/her role in providing opportunities for learning.

Exchanges like this between students tell me that they are starting look at the world through the lens of 'substance' rather than just properties (eg colour) and behaviour (eg bubbling). Soon they will be ready for the concept 'chemical reaction'.