Pedagogical content knowledge in science education: perspectives and potential for progress

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Introduction

Pedagogical content knowledge (PCK) in science education has received extensive research attention since inception in the mid-1980s, but remains un-noticed by many science teachers. In contrast, research on students' learning and in particular their misconceptions about science topics has been publicised widely. Most science teachers have heard of misconceptions, but almost none know about PCK: the author used the term with a group of experienced chemistry teachers, to horrified and excited calls for further explanation – was this something they had missed? What was it exactly? Could I please repeat the name? Where could they find out more? The lack of attention may, as Abell (2007) notes, be that PCK research seeks a uniting paradigm under which to undertake "normal science". In.Kuhnian terms, the field is still at the "pre-science" stage, so despite having occupied significant research time for over twenty years, is not ready for wider dissemination.

This review attempts to move the discussion forward by using extant research to arrive at an overall picture of PCK that may be useful for science teachers and their educators. The paper will examine how PCK has been interpreted within science education, offering suggestions for making more of the concept to aid development of high quality science teachers.

Why is pedagogical content knowledge research in science education important?

International debate about how best to prepare high quality science teachers is on-going. Some organisations assume "knowing more science" makes someone a "better" science teacher. For example, the UK's Royal Society of Chemistry argues:-

> "The best teachers are those who have specialist subject knowledge and a real passion and enthusiasm for the subject they teach…. The Royal Society of Chemistry believes that young people deserve to be taught the sciences by subject specialists" (RSC, 2004, quoted in Kind, 2008)

Similarly, a lobbying group, CaSE, the Campaign for Science and Engineering in the UK argues:-

> "Children need to be taught by specialist [science] teachers. Teachers' qualifications predict teaching quality and are the second greatest predictor of performance in physics after pupil ability" (CaSE Opinion Forum, May 2007)

Although many successful science teachers are academically well-qualified in their specialist subjects, possession of a good Bachelor's degree in a science subject is not a *de facto* guarantee that someone will teach that subject effectively. A recent report from England's Office for Standards in Education (Ofsted) points to the fact that successful teaching, as measured by the numbers of 5 – 16 year olds achieving specific levels on the science National Curriculum, barely changed between 2005 and 2007. The report observes:-

> "Given the extensive subject knowledge of most secondary science teachers much teaching paid scant regard to what and how pupils were learning. In many

> lessons, teachers simply passed on information without any expectation of pupils' direct engagement in the process. The objective appeared to be to get notes into books, then leave the learning to the pupils." (Ofsted, 2008, p 17)

Presumably at least some of these science teachers were "subject specialists" – but clearly were not teaching in ways that actively aided students' learning. Teachers' content (subject matter) knowledge is only part of the story: possession of good teaching skills is also needed. PCK represents the knowledge teachers use in the process of teaching. If we can identify this, our understanding of what "good science teaching" looks like and how to develop this more consistently will be enhanced. Bucat (2005) comments:

> "There is a vast difference between knowing about a topic (content knowledge) and knowledge about the teaching and learning of that topic (pedagogical content knowledge)…."

To date, a reasonably well-agreed claim arising from research is that PCK provides a theoretical framework for examining and understanding teachers' skills (Abell, 2008). Despite this, inconsistencies and disagreements persist about PCK, meaning there is no overriding consensus about how this can best describe successful science teaching.

Education researchers seized on PCK as a means of enhancing both teachers' professional status and the process of educating them. Although there is wide agreement that PCK is a useful construct, finding out exactly what it comprises and using this knowledge to devise good practice in teacher education is not easy. PCK is tacit, or hidden knowledge: when preparing lessons, for example, teachers think pragmatically, "I am preparing a lesson" not, "I am using my PCK". PCK is not (yet) an explicit "tool" used consciously by teachers. Investigating PCK requires researchers to understand processes underlying lesson preparation, and an analysis of how and why a teacher teaches as s/he does. PCK is, therefore, both elusive and attractive. Accordingly, the review examines ways in which researchers have elucidated PCK in different teaching situations. A reasonable expectation from this is to gain a deeper understanding of how PCK develops. How does a novice science teacher become expert? Describing characteristics of both novices and experts, or experienced teachers is relatively easy, but if PCK is to be useful in science teacher education we need an understanding of how teachers develop. Significant research effort has been devoted to investigating PCK among pre-service (trainee) teachers, some of which is reviewed here. PCK, as explained below, is claimed as only one type of teacher knowledge, and involves transforming knowledge for students' benefit. Hence, PCK does not stand alone in a teacher's repertoire: SMK has already been mentioned as a critical component. The relationship between SMK and PCK is examined in this review.

Since the 1970s, science education has argued for academically well-qualified scientists to be trained as teachers, but despite succeeding on this point in many countries, unevenness in the quality of teaching practice remains. This paper argues that understanding how science teachers' pedagogical practices develop, knowing how to "measure" and represent these and establishing what constitutes "effective" pedagogy for teaching science will contribute to our overall understanding of what high quality science teaching looks like. Specifically, such knowledge will:-

- help to make explicit what science teachers actually do when teaching science;
- indicate how teaching approaches relate to students' learning;
- contribute to evidence that subject matter knowledge alone does not make a high quality science teacher;
- ensure that teacher educators are well-informed about the PCK of "expert" or experienced science teachers that can in turn, inform the training of novices.

The expectation is that gaining better overall understanding of science teachers' PCK, its development and the relationship between PCK and SMK will help establish science teaching practice of consistently higher quality.

The origins of pedagogical content knowledge

Pedagogical content knowledge (PCK) originated as one of seven categories of "teacher knowledge" proposed by Lee Shulman (1986a, b; 1987). In making his proposal, Shulman was participating in a US-centred debate about the status of teaching as a profession. At issue was whether school teachers could be regarded as "professionals", aligned with doctors or lawyers, or if they were simply "skilled workers". In earlier papers, Shulman (1985, 1986a) highlighted the transition from the1870s, when teacher training was based largely on factual knowledge, to the mid-1980s examination of general understanding of educational issues. He raised the question "Where did the subject matter go?" (1986, p 11) pointing out that this was the "missing paradigm" in teacher education. Without this, Shulman argued, understanding how subject matter was transformed into instruction, and how lesson content related to students' knowledge and ideas was impossible. These issues lie at the heart of "teaching", yet were absent from analysis of teachers' competences. In contrast, medicine and law were defined by skills, cases and procedures that characterised practice and on which analysis of doctors' and lawyers' competences could be based. To address this "gap" Shulman (1986b) first proposed three categories of "content knowledge" for teachers:-

- Subject-matter content knowledge
- Subject-matter pedagogical knowledge
- Curricular knowledge (p 13)

By subject-matter content knowledge, Shulman meant the "amount and organisation of knowledge *per se* in the mind of the teacher" (op cit). Taking a biology teacher as an example, Shulman argued that this teacher's knowledge of the subject may reasonably be expected to be equal to that of a non-teacher or "lay" biologist. Shulman defined subject-matter pedagogical knowledge as "the ways of representing and formulating the subject that make it comprehensible to others" (op cit), that is, the analogies, illustrations, examples, explanations and ideas that a teacher uses in lessons. The third category, "curricular knowledge" equates to a doctor's knowledge of current techniques and/or treatments to relieve an illness: in teaching terms, current materials include textbooks, software, laboratory demonstrations and other ephemera available to use in the classroom. Shulman went on to argue that:-

> "an understanding of both content and process are needed by teaching professionals… within the content we must include knowledge of the structures of one's subject, pedagogical knowledge of the general and specific topics of the domain and specialised curricular knowledge." (op cit, p 43)

In his 1987 paper, Shulman refined his three categories into a more comprehensive list of seven, here quoted in full so PCK can be seen in its original context (italics added)-

> "- content knowledge;
> - general pedagogical knowledge, with special reference to those broad principles and strategies of classroom management and organisation that appear to transcend subject matter;
> - curriculum knowledge, with particular grasp of the materials and programs that serve as "tools of the trade" for teachers;
> - *pedagogical content knowledge, that special amalgam of content and pedagogy that is uniquely the province of teachers, their own special form of professional understanding;*
> - knowledge of learners and their characteristics;
> - knowledge of educational contexts, ranging from the workings of the group or classroom, the governance and financing of school districts, to the character of communities and cultures; and
> - knowledge of educational ends, purposes, and values, and their philosophical and historical grounds." (p 8)

Shulman identifies PCK as distinctive of teachers' practice, worthy of special attention as a unique feature of their work. Other professions, such as law and medicine, have their own "curricular" knowledge, for example – in law, this comprises knowledge about cases, statutes and procedures; in medicine, knowledge of anatomy, physiology, biochemistry as well as pharmacology, medical and surgical procedures. Law and medicine also have their equivalent of "learners" – clients needing advice, or patients requiring attention. Shulman argues that although the other knowledge types have their equivalents in different fields, PCK remains unique to teachers. In PCK, content and pedagogy are blended - the teacher combines his or her understanding about a topic with instructional strategies and additional knowledge to promote student learning. Shulman describes PCK as:-

> "…the capacity of a teacher to transform the content knowledge he or she possesses into forms that are pedagogically powerful and yet adaptive to the variations in ability and background presented by the students." (1987, p15)

Teacher educators received Shulman's proposals enthusiastically. Subsequently, research effort has attempted to establish these categories of teacher knowledge as an all-embracing paradigm for teacher education. However, although aspects of Shulman's general views are widely accepted, many models of PCK have been proposed, as researchers have interpreted Shulman's ideas differently.

Organisation and scope of the review

The review is organised in four sections. First, a variety of models of PCK are considered. This sets the scene by showing ways in which Shulman's proposals have been interpreted by different researchers. The second section, PCK in practice, describes examples of PCK found in science teachers with different levels of experience. This describes teaching in different settings and the struggles teachers experience in learning to teach. The relationship between PCK and SMK is highlighted as important to understanding this process. Third, the interaction between PCK and SMK is explored in greater depth. Shulman's view is that SMK is separate and transformed using PCK. However, researchers express conflicting views about the extent to which these knowledge base components are separate or merged. The variation of opinion on this leads to fruitful discussion about the nature of PCK itself. Finally, research methods for elucidating PCK are considered. These offer insights into effective ways of investigating this largely tacit construct. Some studies use multi—method approaches, others one or two data collection instruments. Together, the material provided offers insights into PCK as a construct to help understand science teachers' practice and development of teaching skills. In conclusion, suggestions for taking the field forward are offered.

In selecting papers, well-known and respected databases such as ERIC and ZETOC were searched for papers dating from 1987, using terms such as "pedagogical content knowledge science" and "development of science teacher knowledge". These yielded approximately 500 papers from which selections were made. The review by Abell (2007) and Gess-Newsome and Lederman's (1999) text also provided starting points. Reviewed papers either:-

- discuss a theoretical standpoint on PCK, to inform understanding of models of PCK adopted by researchers, and/or

- report an empirical study investigating PCK in pre-service, novice or experienced science teachers relating specifically to teaching aspects of physics, chemistry or biology, or

- report an empirical study investigating changes in pre-service, novice or experienced science teachers' PCK, either arising from an intervention designed by a researcher or through teaching practice

The reference list is supplemented with further articles which illuminate or explain details requiring clarification of material in reviewed papers. In order to fairly represent the range of work in the field, no criteria relating to the size and scope of research studies have been applied - some offer an in-depth view of one teacher, while others present larger scale work using a number of teachers. Work undertaken in primary, secondary and tertiary settings is included. The points made arose as a result of reading – the review has not been contrived to support the author's pre-conceived opinions.

Models of PCK

Shulman (1986b, 1987) proposed that PCK comprises two components: the knowledge labelled "*representations*" but often referred to more frequently (and in this paper from this point) as "*instructional strategies*" and knowledge of students' subject matter "*learning difficulties*". He suggested that teachers use instructional strategies such as illustrations, analogies, explanations and demonstrations to make subject matter comprehensible to their students. "Learning difficulties" comprises knowledge about students' misconceptions, naïve ideas gained through interpretation of prior learning experiences, or preconceived ideas about a topic, as well as knowledge of any other potential barriers to learning subject matter, such as how concepts inter-relate and strategies to help solve problems. Researchers have modified Shulman's original proposals in different ways, summarised in Table 1 (based on Lee, Brown, Puthoff, Fletcher and Luft, 2005).

[INSERT TABLE 1 ABOUT HERE]

The table shows Shulman's original components shaded grey. The letter "P" denotes a component considered part of PCK; "K" represents knowledge a researcher considers a component of a teacher's knowledge base but not part of PCK "; and "0" is a component not discussed explicitly in that model. Eight other models, including two based on Shulman's original proposals (Grossman, 1990; Magnusson, Kracjik and Borko, 1999) are discussed. Six differ from Shulman's original proposal by including SMK within PCK. Of these, three (Marks, 1990;, Fernandez-Balboa and Stiehl, 1995; and Koballa, Gräber, Coleman and Kemp,1999) draw on empirical research findings. These models combine components from Shulman's list of seven (p X) within PCK. Three propose PCK models that use components from Shulman's list, but develop the concept from theoretical perspectives: Cochran, deRuiter and King (1993) draw on principles from psychology; Veal and MaKinster (1999) place all knowledge components into a taxonomy; and Banks, Leach and Moon (2005) propose a new component, "school knowledge", to subsume others. Similarities and differences between these PCK models are discussed below. Where researchers give different names to components, the alternatives are mentioned.

Models based on Shulman's proposals

Grossman's (1990) and Magnusson, Krajcik and Borko's (1999) models follow Shulman's line of thought explicitly, identifying subject matter knowledge (SMK) as a distinct category, and defining PCK as the special knowledge used by a teacher to transform his /her SMK to benefit students. For example, Magnusson et al comment that they see PCK as:

> "the transformation of several types of knowledge for teaching (including subject matter knowledge)… and ….represents a unique domain of teacher knowledge" (p 85).

Both models add purposes (called "orientations" by Magnusson et al) and curricular knowledge. Grossman included this component in PCK after observing differences in teaching goals in her empirical study of six teachers teaching English Literature. One teacher wanted to ensure students could "make connections between the text and their own lives" (Grossman, p 8), while another wanted his students to learn how to analyse and understand a text. Grossman argued that these different goals influenced teachers' choices of instructional strategies, so contributed to PCK. She defined "purposes" as

> "the overarching conceptions of teaching a subject [that] are reflected in teachers' goals for teaching particular subject matter" (p 8).

Magnusson et al (1999) in devising a model for science teaching, accept Grossman's views. They note possible "orientations" for science teaching parallel to the different purposes observed by Grossman among teachers of English literature. These include discovery, conceptual change, process, didactic and inquiry. A teacher adopts one or more for different reasons: a "didactic" orientation may imply fact transmission, while "discovery" aims that students find out science concepts for themselves. Either will impact on instructional strategies, influencing PCK.

Grossman and Magnusson et al (op cit) also add curricular knowledge. Grossman observed that English teachers required and utilised "horizontal and vertical" (p 8) curricula in their teaching, for example, knowing which books were needed when teaching a specific age range and using their awareness of books studied in earlier and later years. Magnusson et al follow similar reasoning, arguing that curricular knowledge "distinguishes the content specialist from the pedagogue – a hallmark of pedagogical content knowledge" (p 103).

In adding knowledge about assessment, Magnusson et al follow Tamir (1988), who defined this component as comprising knowledge of the dimensions of science learning that are important to assess and knowledge of the methods by which learning can be assessed. Teachers will plan lessons knowing the science that will be examined, and may adjust their instructional strategies accordingly. Teachers must use assessment methods to find out what students have learned. Recent moves in the UK towards assessment for learning ("AfL", Black, Harrison, Lee, Marshall and Wiliam, 2003) make this integral to teachers' instructional strategies, not something imposed by external organisations.

Models based on research evidence that include SMK within PCK

Other researchers see PCK differently: Marks (1990), Fernandez-Balboa and Stiehl (1995) and Koballa, Gräber, Coleman and Kemp (1999) include SMK in their definitions of PCK. Marks (1990) based his PCK model on data collected from eight primary mathematics teachers. He re-names instructional strategies "instructional processes" and learning difficulties as "students' understanding". Marks adds "media for instruction", which aligns with Grossman's curricular knowledge (so is coded "P" in Table 1), to mean knowledge about texts and materials. Marks's inclusion of SMK arises directly from his teachers' views about subject matter. Their personal understanding of mathematical concepts was taken for granted. They did not describe their teaching in terms of transforming mathematical knowledge, but emphasised pedagogy, focusing on "justifications", "important ideas", "pre-requisite knowledge"; and knowledge of "typical school math problems" (p 5) Marks argues that for this group, SMK and PCK were not clearly distinguished knowledge components. In coding this model in Table 1, SMK appears as "P". Note also that although the teachers' descriptions of their PCK overlap with Grossman's "purposes" discussed above, Marks seems to include this knowledge within SMK, rather than as a separate component. Hence, "purposes" is coded "0" for this model.

Fernández-Balboa and Stiehl (1995) found similar evidence to Marks among university lecturers, who seemed to roll SMK into their teaching practices when describing their work. These data led the authors to suggest PCK comprises knowledge about subject matter; knowledge about students; instructional strategies; the teaching context and teaching purposes (p 293). The inclusion of *context* is novel – the authors note that "contextual barriers" contribute to practices characteristic of university teaching, including handling large class sizes, specific time limits, scarcity of appropriate resources, students' attitudes and tenure and promotion issues. Fernández-Balboa and Stiehl contend that lecturers' effectiveness depends on "the specific beliefs and knowledge that guide their decisions and actions" (p 305), so context influences PCK.

Koballa et al (1999) also support inclusion of SMK within PCK. Their study was based on data collected from trainee chemistry teachers preparing to teach 16-19 year olds in German "gymnasium" schools. They propose a "nested" (p 276) structure with chemistry knowledge gained from university and school at the centre of teachers' PCK. Koballa et al add *general pedagogy*, a factor they call "multi-dimensional knowledge" (p 278) to their set of PCK components.

Models of PCK drawing on theoretical perspectives

Cochran, deRuiter and King (1993) adopt a psychological perspective, believing that the term "knowledge" in PCK "[is] too static and inconsistent" (p 266). They adopt "knowing" as a more dynamic word capturing their perceptions that teachers construct PCK on the basis of understanding students' needs. Cochran et al describe themselves as "radical constructivists", arguing that teachers would devise instructional strategies actively, in response to understanding their students:-

> "Increasingly strong PCKg enables teachers to use their understandings to create teaching strategies for teaching specific content in a discipline in a ways that enables specific students to construct useful understandings in a given context" (p 266).

These authors suggest that a teacher's PCK, or "PCKg" develops with time as s/he becomes increasingly aware of students' needs. Rather than being a separate component, SMK is an element of PCK, as this is used to help decide how best to handle students in a class. Their PCK components are student characteristics, subject matter content, pedagogy and the environmental context of learning. They define "student characteristics" as "a teacher's understanding of abilities, learning strategies, ages, development, motivation and prior conceptions of the subject" (p 266). This corresponds to Shulman's "learning difficulties". Their three other components can be found in Shulman's original list (see above). These authors consider that knowledge of instructional strategies lies outside PCK, on the grounds that Shulman implies these are "pre-learned" techniques.

Taking this view, a teacher's PCKg relies on combining SMK, pedagogical knowledge and awareness of the environment in which they work. Cochran et al argue a teacher's environment is influenced by political, social, cultural and physical factors, any or all of which may, in turn, influence PCK. This definition emphasises general pedagogy, rather than subject-specific representations and strategies. The authors stress that “integration of the four components comprises PCKg” (p 268), and that teacher education should promote its acquisition by offering simultaneous experience of the four components.

Veal and MaKinster (1999) suggest that PCK should be based on a hierarchical structure they call a “taxonomy”. This:

> “attempts to represent a hierarchical process by which prospective secondary science teachers obtain different knowledge bases contributing to their PCK development” (p 6).

Four levels of knowledge are presented: general PCK is lowest. This includes an understanding of pedagogical concepts applicable to a wide range of subjects. Above this come subject-specific PCK strategies (equivalent to Magnusson, Krajcik and Borko’s (1999) “orientations” and Grossman’s (1990) “purposes”). The two highest levels introduce new terms - “domain-specific” and “topic-specific” PCK. By “domain-specific”, the authors mean the understanding a teacher has about “how to teach” a specific area within a subject. For example, a teacher may choose a titration experiment when teaching about moles, volume and concentration in chemistry. Above this comes “topic-specific” PCK. At this level, the distinction between the knowledge of science teachers with different SMK backgrounds comes into play. A science teacher with a physics background may explain a chemical concept differently from a chemist. A teacher’s knowledge arises from their intellectual training, is specific to their specialist topic or field and is integrated into their PCK.

The hierarchy is proposed from theoretical perspectives – the authors don’t claim that teachers acquire their PCK like this. But the description may be helpful – components of PCK for science teaching may be hierarchical. For example, two teachers, one with SMK in biology and the other in physics may have similar general PCK (the lowest level) and, with practice, may acquire similar domain-specific PCK. Their different science backgrounds may mean that acquiring similar topic-specific PCK is much more difficult, relying on intensive input to “overcome” ingrained ways of thinking about scientific ideas.

Thirdly, Banks, Leach and Moon (2005) present a model of teachers’ professional knowledge in which “school knowledge”, “subject knowledge” and “pedagogic knowledge” are linked by a teacher’s “personal subject construct”. In proposing their model, the authors split PCK into “school knowledge”, an entirely new category, and “pedagogic knowledge”. School knowledge describes how subject knowledge is adapted for school use – for example, what can be termed “school science”, the representation of the subject delivered in science lessons, differs from “science” as practised by scientists. The authors suggest teachers need to understand the historical and ideological origins underpinning how their subjects are organised for teaching purposes. This category subsumes Shulman’s curricular knowledge. Pedagogic knowledge comprises the ”practices and beliefs that inform teaching and learning” (p 336), such as knowledge of analogies, illustrations, and explanations needed to teach a topic, as well as an understanding of the relationship between school and subject knowledge. Thus, school knowledge can be seen as a “bridge” or “intermediary” (p 336) between subject knowledge and pedagogic knowledge, facilitating choice of resources for teaching and understanding of the curriculum and how these influence pedagogic practices. In this structure, subject knowledge equates with Shulman's SMK, while pedagogic knowledge includes an "understanding of the crucial relationship between subject knowledge and school knowledge" (p 335 – 336). A teacher's personal subject construct comprises knowledge gained from his/her learning experiences, opinions about "good" teaching and beliefs about the purposes for the subject. The authors claim Shulman's theory presents a teacher's knowledge as "a static body of content lodged in the mind of the teacher" (p 333). They also criticise Shulman for adopting a "teacher-centred" model of cognition focusing on a teacher's skills and knowledge rather than the process of learning. Instead, their model draws on theories of learning suggested by Gardner (1983, 1991) and the French concept of "didactic transposition" (p 334). Gardner's "multiple intelligences" theory stimulates consideration of learners' different understandings, while didactic transposition acknowledges variation and progression in the way a teacher develops his/her practice. The authors argue these principles offer a contrast to Shulman's emphasis on transformation, which implies teachers learn "the" way to teach a concept in a specific setting.

Models of PCK: discussion

Shulman's PCK model has been criticised. For example, Bromme (1995) believes Shulman defines his components in vague terms, and that the model as a whole lacks a theoretical background. This is fair, given that PCK was devised in principle before any research was undertaken that provided supporting evidence. Since Shulman made his suggestions, teacher educators have been making up for this deficiency. The models presented above point to Shulman's views being rather simplistic - one common feature is that all eight proposals *add* components to Shulman's model: researchers seem to agree that PCK is more complex than he implied originally. Bromme (op cit) offers a further criticism that may explain this increased complexity. In defining PCK as "instructional strategies" and "knowledge of students' difficulties", Shulman does not appear to acknowledge the influence of other factors on teaching and learning. The alternative models address this in different ways, adding the additional components described. Picking up Bromme's point about a theoretical background for PCK leads to consideration of the last three models discussed above. If a choice is to be made between these, Cochran et al (op cit) offer the strongest model in theoretical terms, basing their thinking on constructivism. This is likely to resonate with the current generation of science teachers, drilled in constructivist principles applied to students' learning. The notion of constructing personal knowledge about "how to teach" is therefore a relatively easy mental step to take.

Shulman's PCK model is also criticised by various researchers (including Cochran et al, 1993 and Banks et al, 2005) as being "static" – the implication is that instructional strategies and knowledge of students' difficulties can be learned as separate entities. In other words, in becoming a teacher, a novice could, for example, attend a course entitled "instructional strategies for teaching science" which would provide all the information s/he would need to develop expert skills. This is perhaps reading too much into Shulman's statements, which served the purpose of introducing "teacher knowledge" as a general concept and PCK as a component of this. Nevertheless, that teachers' knowledge can develop over time and change in response to different schools / educational settings, students, resources and curricula is a reasonable point for a model to adopt. By using the more active term “knowing” rather than “knowledge” Cochran et al (op cit) acknowledge this. Banks et al (op cit) take “didactic transposition” as a more active principle that shapes a teacher’s PCK over time.

The issue as to whether SMK and PCK are separate knowledge base components or are combined requires further discussion. Of the nine models discussed here, a majority favour combining SMK within PCK. Only three, Shulman’s original proposal and two others, use the principle that PCK “transforms” SMK; six suggest SMK and PCK are not separate. The issue of whether SMK and PCK are separate components or should be merged is discussed more fully later (p X). For the moment, Gess-Newsome (1999b) provides a way of discussing PCK models that gives a means of distinguishing between those that maintain SMK is separate from PCK and others proposing these are merged. She distinguishes between “transformative” and “integrative” PCK models. An integrative model does not recognise PCK as a separate knowledge component: instead, teacher knowledge as a whole embraces SMK, pedagogy and context. Gess-Newsome likens this to a chemical mixture in which components retain their individual identities, but are indistinguishable on a macroscopic level. Thus, in an integrative model, SMK is part of PCK – PCK itself summarises a teacher’s knowledge base, so does not “exist” as a separate type of knowledge. A transformative model defines PCK as the transformation of subject matter, pedagogical and contextual knowledge to create new knowledge for the purposes of instructing students. The transformative model can be likened to a chemical compound, in which elements cannot easily be separated: Gess-Newsome describes them as being “inextricably combined into a new form of knowledge, PCK” (p 11). In a transformative model, SMK is a separate component, while PCK is a unique type of knowledge. A teacher uses his/her SMK in making PCK.

Models based on Shulman’s proposals, Grossman (1990) and Magnusson, et al (1999) are transformative. These authors suggest combinations of knowledge components are used in creating PCK, but that SMK is separate. A teacher will possess SMK and seek to transform this for students’ benefit using his/her PCK, which, they propose, combines four (Grossman) or five (Magnusson et al) components. Each of these selected components requires subject-specific knowledge – for example, purposes (orientations) and curricula differ for individual subjects. Thus, under these models, the PCK of biology and English teachers differ, as the components rely on, for example, instructional strategies appropriate for each subject. The remaining six models fit Gess-Newsome’s integrative definition. Veal and MaKinster’s taxonomy claim all components contribute to PCK except “school knowledge” which is unique to Banks et al (2005).. Three models leave out one or more of Shulman’s original two components: Koballa et al (1999) and Cochran et al (1993) remove instructional strategies and add general pedagogy; Banks et al (2005) make different claims based on their own notion of “school knowledge”. Fernandez-Balboa and Stiehl (2005) and Marks (1990) retain both of Shulman’s components, but add others. Integrative models tend to include components that reflect more general teaching knowledge, recognising the broad range of skills teachers use; lessons involve good classroom management, consideration of the learning environment and other factors, all of which apply equally regardless of subject.

The relative merits of transformative and integrative models need consideration. Abd El-Khalick (2006), for example, argues that integrative models lack explanatory power, as no mechanism is suggested that shows how the interaction between SMK, pedagogy and contextual factors results in PCK. Banks et al (2005) suggest a teacher's "personal subject construct", which could be the missing link. This combines experiences from teaching with other factors held by the teacher such as purposes and orientations – a teacher mixes these with subject, pedagogical and school knowledge to create PCK. Transformative models imply a mechanism exists – this is used to convert SMK to PCK, to use SMK in creating PCK, to adapt SMK for school use and /or more. A highly skilled teacher will have a way of developing his/her knowledge. If we can distil such a teacher's PCK and find out how this develops, then perhaps this, and/or hints about the process of gaining it, can be "taught" explicitly to trainee teachers .

These two possible models offer suggestions for science teacher education. It could be argued that current methods adopt an "integrative" approach, without realising – we offer a mix of individual courses on SMK, pedagogy and contexts but don't explicitly state what knowledge novices are supposed to construct from these, or provide methods for helping them utilise the information. Perhaps unsurprisingly, then, teachers don't recognise PCK, or what this means. A "transformative" approach would make a mechanism explicit, articulating what a novice should do with knowledge, offering strategies for combining material from different sources. Before making judgements on which model may be best suited to science teacher education, we need further information. The next section contributes to this by discussing PCK elucidated in a variety of studies.

PCK in practice

Novices and experts

Novice, pre-service teachers ("trainees") face significant challenges: Davis, Petish and Smithey (2006) reviewed literature on five areas that science teachers are expected to understand; content and disciplines of science, learners, instruction, learning environments and professionalism. Baird, Brodie, Bevins and Christol (2007) summarise the extensive lists of competences comprising the professional standards UK and US teachers must meet in order to be "qualified". Adams and Krockover (1997) analysed concerns and perceptions held by pre-service science and mathematics teachers. They found that trainees expressed concerns about lack of preparation for teaching, classroom management and organising their time, among others. The authors note that "teachers have a need to not only develop content knowledge, but pedagogical content knowledge" (p 48) in order to better prepare them for working full-time in schools. Anxiety among trainees was also found by de Jong (2000) in his study of pedagogical content concerns held by a group of pre-service chemistry teachers teaching aspects of chemical bonding. He identified trainees' lack of self-confidence in their subject matter knowledge; how to make abstract concepts accessible for students and understanding of students' difficulties as important aspects of their early attempts at teaching.

Set against this background are studies of pre-service teachers, whose PCK is naturally limited: contrasts in trainees' practice and that of "experts" are claimed by

Geddis, Onslow, Beynon and Oesch (1993) in their study of chemistry teachers teaching about isotopes. These authors report two novices who adopt a “transmission” model of teaching, providing scientific explanations, together with principles for doing the calculations. In contrast, an experienced teacher ensured students understood the concept, being less concerned about giving scientifically accurate information. His teaching strategies transformed subject knowledge for the students’ benefit. The authors conclude that teachers require a wide range of knowledge types to successfully transform SMK for students, including knowledge of “learners’ prior knowledge”, effective teaching strategies taking these into account, a variety of alternative representations and “curricular saliency” – awareness of the importance of a topic to the whole curriculum. They suggest novices use SMK as a source of information, adopting a “*tabula rasa*” approach to instilling this into students’ minds. Experts focus on students’ learning, devising activities that make content accessible, their own understanding being implicit to the process.

Trainees’ attempts at transforming content knowledge have been explored by a number of researchers, mainly using physics and chemistry concepts as contextual settings. Research based on biology is less frequent, perhaps because as a higher proportion of trainees are biology specialists, the assumption among researchers is that they find teaching physics and chemistry topics problematic, prompting initial investigation of PCK development in these areas. For example, Halim and Meerah (2002) studied the PCK utilised for teaching physics concepts by twelve pre-service teachers with varied science degree backgrounds. They found that a majority of trainees held misconceptions similar to school students. When teaching, trainees repeated their own misunderstandings; their ability to transform SMK for students was “impeded” (p 223) by their lack of knowledge. The authors claim that possession of good content knowledge is a pre-requisite to developing sound PCK. Van Driel, de Jong and Verloop (2002) and de Jong and van Driel (2004) draw similar conclusions. They investigated how pre-service chemistry teachers teach topics involving the *macro-micro* shift – the relationship between observable phenomena and the particulate nature of matter. Results showed that a university-based workshop and high quality mentoring helped trainees become more aware of their tendency to jump between macro and micro levels without considering the impact of this on students. The authors report that PCK developed, in that trainees were more able to consider students’ needs in preparing teaching strategies after intervention. Sperandeo-Mineo, Fazio and Tarantino (2006) used the macro-micro shift applied to thermodynamics as the subject context for their PCK development study, also finding that pre-service teachers show the same learning difficulties and “representations” as school students. They suggest that knowledge transformation “is not a one-way process”, that is, from SMK directly to PCK. They suggest a two-way process, pointing out that SMK differs between teachers, as will learners’ interpretations of what is presented to them. Hence, successful knowledge transformation depends on teachers having a “deep knowledge of … physics…as well as an awareness of the pupils’ spontaneous models in the different content areas” (p 238).

Trainee teachers’ PCK in primary (elementary school) science has been investigated by a number of workers. For example, Jones, Carter and Rua (1999) investigated the role played by children’s science concepts in developing trainee teachers’ pedagogical practices for sound, light and electricity teaching. They devised an intervention combining trainees’ exploration of their own conceptual understandings with those of children. By comparing pre- and post-intervention concept maps, researchers claim that trainees' understanding developed, and awareness of children's misconceptions helped their teaching move towards transformation rather than transmission of knowledge. Warren and Ogonowski (1998) studied PCK development through observing a primary school teacher in her second year of teaching, using aquatic ecology as the context. The paper describes in detail how the teacher, not a biologist, grappled with new content knowledge at the same time as teaching it. The authors comment that in this example, the teacher's ideas and experiences combined with scientific ideas and practices to create learning opportunities for the children. Davis (2003) presents a descriptive study of one pre-service primary teacher's efforts to teach light. She found that at times, even when the teacher understood the science content, her instruction was flawed, suggesting that although good SMK is important, it is not an automatic precursor for good PCK. Concurring with other work discussed here, Davis points out that trainees with poor SMK may struggle to explain science concepts appropriately.

Relatively few investigations have explored PCK among pre-service or experienced teachers working at post-16 or tertiary levels. One such is Koballa, Gräber, Coleman and Kemp (1999), who investigated the knowledge base perceived by nine pre-service chemistry teachers as necessary for teaching in academic, post-16 schools in Germany. Three types of knowledge were identified – university chemistry knowledge, school chemistry knowledge and knowledge about teaching, which included knowledge about how students learn. None of the nine trainees mentioned all three types – and the authors point out that PCK was not mentioned explicitly. In a study based in teaching in a university chemistry laboratory, Wood-Robinson (2005) investigated the skills used by graduate teaching assistants (GTAs) working with undergraduates. As her focus was on the skills required to teach specific chemical knowledge, she modified PCK to "PChK", meaning "pedagogical chemical knowledge", classifying this into four categories or "levels" from basic interaction with students (PChK 0) to teaching chemical concepts (PChK 3). Wood-Robinson found that relatively few GTAs worked at the higher levels, highlighting difficulties they experience in transforming abstract chemical concepts for understanding.

Simmons, Emory, Carter, Coker, Finnegan et al (1999) show that teachers are aware of good teaching skills , but may lack the ability to implement these. They carried out a longitudinal study investigating how the knowledge, beliefs and practices of science and mathematics teachers alter during their first three years in the classroom. Their data, gathered from nine different universities, indicate that about 40% of teachers in their first year of teaching think they teach from a student-centred perspective, taking students' prior knowledge and misconceptions into account, while in fact their practices indicate they adopt the "novice" style described by Geddis et al (1993) discussed above. Further, the study showed that teachers' perceptions of their practices change markedly during the early years of their classroom experiences, suggesting that several years must pass before PCK is fully developed. Instabilities in pre-service teachers' thinking about their subject matter and pedagogical knowledge were also found by Lederman, Gess-Newsome and Latz (1994). They report that the act of teaching prompted changes in trainees' perceptions of the structure of their specialist subjects, moving towards integration of pedagogical and subject matter – after teaching practice, they tended to consider making concepts relevant and taking students' learning needs into account. These occurred alongside development of increasingly complex representations of pedagogy among the participants, reflecting greater emphasis on child-centred approaches, and awareness of a wider range of roles for a teacher, including “counsellor” and “friend”.

However, classroom exposure is no guarantee to creation of an “expert” science teacher: Tobin and Garnett (1988) compare four experienced teachers - two primary science and two chemistry specialists. The primary science teachers were enthusiastic about science and handled classroom management issues competently, but despite years of experience lacked the science knowledge needed to teach concepts well. The authors note that this was not the case with the chemistry specialists, whose background knowledge combined with transformation skills to create good learning environments.

Developing science teachers’ PCK

Research has investigated how science teachers’ PCK develops. Veal (1999) and Veal, Tippins and Bell (1998) monitored PCK using a series of content-specific vignettes, among other methods. They found that PCK developed over time, with trainees reporting classroom experience as the most important influential factor. These authors suggest that PCK development is complex, occurs in phases and relates to trainees’ abilities to integrate knowledge from a variety of sources. Possession of content knowledge is identified as essential to PCK development. Some of their findings concur with those reported earlier (de Jong, et al, 1994; Sperandeo-Mineo et al, 2006; Lederman et al, 1994). Veal (1999) adds a different angle, stating that teachers:-

> “…ground their development of a knowledge base in their existing beliefs. This ultimately effects how they teach in the classroom.” (p 36)

These beliefs relate to how they were taught; how abstract or “magical” they believed a particular concept or event to be; or their personal misconceptions. Veal notes that to develop PCK, changes to these often deep-seated beliefs were required.

A Taiwanese case-study of three pre-service chemistry teachers during their one year teacher education course (Tuan, Jeng, Whang and Kaou, 1995) traced factors influencing the development of their PCK. These teachers held hierarchical subject matter structures based on their school education. This shifted to making more connections with other disciplines and to everyday life towards the end of the training course. Initially, teachers’ PCK was primitive, relying on repetition of information. Later on, some integration between SMK, students’ needs and instructional strategies began to occur. The authors note that trainees’ willingness to improve and reflect were significant factors in making progress.

Angell, Ryder and Scott (2005) used a questionnaire comprising eight items relating to different content areas in physics to compare the PCK of novice and expert physics teachers. They report little difference in the content knowledge of novice and expert teachers, but found experts made more extensive connections between knowledge in different contexts and exhibited a rich set of pedagogical skills, while beginners focused on transmitting content. The authors note the contribution made by teachers’ values and attitudes to pupils’ learning.

These studies indicate that teachers' values and beliefs influence good PCK development. The extent to which novices are able to take in and reflect on feedback seems to contribute to their development as teachers, with significant changes occurring as trainees' practices alter in response. Lederman, Gess-Newsome and Latz (1994) tracked the development and changes in the structures of subject matter and pedagogical content knowledge held by twelve trainee science teachers in the US. Both sets of structures appeared unstable, and highly likely to change as trainees experienced teaching.

Studies reporting the impact of interventions comprising activities designed to help develop teaching skills include Clermont, Krajcik and Borko (1993). They showed that a two-week workshop impacted positively on skills of teachers who were novices at carrying out chemical demonstrations. Specifically, the authors claim that the workshop helped extend teachers' repertoires for representing chemical concepts, and were more able to distinguish between effective and ineffective demonstrations. Justi and van Driel (2005) analyse changes in five teachers' PCK relating to using models and modelling prompted by participation in a specially devised course and completion of a research project on the topic. They found a variety of responses – from one teacher who was able to use material garnered from the intervention to allow her students to express their ideas, to another who blamed lack of success on developing students' thinking on the students themselves. The authors make a number of comments about how their work might influence teacher education, including that analysis of new experiences and reflection on personal development are critical to the success of an intervention.

Studies based on interventions located in training and school settings are also found. Kind and Wallace (2008) analyse the impact of experienced teacher-led sessions specifically designed to help develop trainees' PCK for teaching a range of science topics to 11-14s. The intended emphasis on PCK was not identified by a majority of the 80 trainees, most of whom used the sessions as opportunities to learn content knowledge, not PCK. Among a sub-group of six who were observed teaching, only one explained a "difficult" science idea correctly, while the other five tended to avoid explaining concepts by opting for a basic level description, instead thinking pupils were learning because they behaved well and completed their allotted tasks. Burn, Childs and McNicholl (2007) observed interactions between teachers in a school science department, noting how expertise was shared through collaborative discussions in informal settings. The authors note that trainee and newly-qualified teachers benefited from an environment in which ideas could be shared and concepts explained freely. This enabled them to access expert teachers' PCK in an atmosphere of trust, care and mutual respect, without feeling a sense of failure. Wilson (2005) describes an intervention based on providing trainee science teachers with a framework for planning lessons to help develop a "language" describing how children learn. Her evidence indicates the tool aided trainees' articulation of personal beliefs about learning, prompting use of a wider range of strategies and better understanding of students' conceptual difficulties.

The role of collaboration in developing PCK features in Daehler and Shinohara (2001), who used a series of "science teaching cases" – similar to Veal's (1999) vignettes – in a study with primary teachers. The cases focused on electricity and magnetism concepts and data were collected through using these to stimulate teachers' group discussions about them. Thus, teachers worked collaboratively to make sense of the concepts and to consider how best to teach them. The authors found that teachers' content knowledge was an important factor – teachers often began discussing how to teach the concepts while not clearly understanding the concepts themselves. Where discussions were "highly interwoven" between content and how to teach, these seemed to be most fruitful in terms of PCK.

PCK in practice: discussion

These and other studies offer confirmation that PCK exists, that novices are not "born" with PCK, and acquire a bank of skills and new knowledge in becoming professional science teachers. The process of transition to expert is lengthy and success is not guaranteed – Tobin and Garnett (1988), for example, found that experienced, "time-served" teachers are not necessarily experts. Clues about creating effective science teachers can be gleaned from these papers.
As a starting point, the studies reviewed here suggest three common factors contribute to development. First, possession of good SMK is regarded as a pre-requisite (Veal, 1999; Daehler and Shinohara, 2001; van Driel et al, 2002; Halim and Meerah, 2002; de Jong and van Driel, 2004). SMK confers a good basis from which to develop: at a pragmatic level, one reason for becoming a teacher cited by many new entrants is the attraction of communicating their favourite subject to others. Where SMK is found to be weak, or in some way deficient, novice and experienced teachers' PCK benefits from interventions or other activities to facilitate changes (Sperandeo-Mineo, et al 2006; Jones, et al, 1999; Clermont et al, 1993). Second, classroom experience is crucial – studies (for example, Simmons et al, 1999; Geddis et al, 1993; Lederman et al, 1994) point to significant changes occurring in the early months and years of working as a teacher. In particular, trainees' perceptions of science alter considerably, moving from thinking of science as a subject which they learned at a high level to realising how the subject is interpreted for school contexts. Trainees learn to adapt their knowledge, taking learners' needs into account (Lederman et al, op cit; Tuan et al, 1995; Angell et al, 2005). Third, emotional attributes seem to play a part in making a successful transition to "teacher" (Adams and Krockover, 1997; de Jong, 2000; Burn, et al, 2007). Good levels of personal self-confidence and provision of supportive working atmospheres in which collaboration is encouraged benefit novices and experienced teachers alike. These may play a role in helping a teacher change deep-seated beliefs that Veal (1999) suggests may impact on practice.

Some papers discussed above offer insight as to whether transformative or integrative models of PCK represent teachers' knowledge (p). Geddis, et al (1993), de Jong (2000), Halim and Meerah (2002) and Sperandeo-Mineo et al (2006) refer explicitly to "transformation" of SMK, for example in "making abstract concepts explicit" (de Jong,op cit) or addressing trainees' misconceptions in physics (Halim and Meerah, op cit). These adopt a transformative model. Warren and Ogonowski, (1998) and Daehler and Shinohara (2001) imply that PCK is integrative in nature. Their studies do not refer explicitly to transformation of SMK, noting that a combination or inter-weaving of knowledge from different sources constitutes PCK. The studies with transformative orientations tend to indicate that a mechanism, as yet unspecified, is involved in PCK development. Two use interventions, such as probing and enhancing awareness of misconceptions (Halim and Meerah, op cit) or workshops focusing on teaching an abstract concept (van Driel et al, 2002) to prompt PCK development. The implication here is that input targeted on specific aspects of science gives teachers the chance to consider their own thinking carefully, leading to changes in practice. In contrast, the two studies identified as taking an integrative-type stance explore PCK with teachers who have completed initial training, rather than complete novices new to the profession. This leads to the possibility that a mechanism of some kind may be involved in developing PCK in the very first stages of becoming a teacher – one factor or component at this critical point may involve mental adaptation of science knowledge for classroom use. Evidence for this is provided by Gess-Newsome (1999a), who reports a biology specialist training for teaching saying:-

> "…I'm a biology major. I took all the required course work for my degree and did quite well. But no one has ever explained to me what it is that I am expected to *teach* about biology…" (p 51)

This trainee distinguishes between SMK learned during her degree and SMK required for teaching. In making the transition to "teacher", SMK needs to alter from pure "knowledge about science" as an academic subject to include "knowledge about school science", recognising that "science" and "school science" are different (Kind and Taber, 2004). Applying this to a PCK model suggests that SMK may be used differently and develop different characteristics as a teacher gains experience – SMK may be more difficult to distinguish as a separate component within his/her whole knowledge base in the PCK of an experienced, effective teacher, leading to an integrative picture. Appleton (2005) suggests that integrative and transformative PCK may be used at different times by the same teacher, depending on classroom events. Thus, there may be places for both transformative and integrative PCK models in the overall picture. So far, though, this is conjecture - we simply don't have sufficient evidence to support this proposal. The next section adds perspectives by examining the relationship between PCK and SMK more closely.

The relationship between PCK and SMK

Although there is broad consensus that SMK impacts on classroom practice, researchers disagree about the extent to which SMK and PCK should be regarded as separate categories of teacher knowledge. The variation falls into three broad categories: studies treating PCK and SMK as separate components; work suggesting SMK and PCK are not entirely separate, but are not completely combined either (referred to here as "blurred boundary" studies); and research that perceives no difference between PCK and SMK. Besides adding to our understanding of ways in which PCK is perceived by various researchers, the discussion will provide further evidence to help resolve the issue of a suitable model for PCK useful for science teacher education.

SMK and PCK are separate components

Sanders, Borko and Lockard (1993) found contrasts in the PCK used by three experienced science teachers when teaching within and outside their subject specialisms. For example, when planning within specialism, the teachers knew

"…how to build the content by presenting key concepts in a logical sequence"; "… how much content to present at a certain time"; and "the interrelationships of various parts of the subject matter" (p 729). They also knew that SMK had to be transformed for the students. When planning outside specialism, the teachers: "had difficulty determining how much to present at a given time"; "how to sequence presentations"; and "how different aspects of the content fitted together" (p 730). They demonstrated uncertainty in teaching, changing plans at the last minute. Overall, the authors suggest that when teaching outside specialism, these "experts" reverted to "novices" in some respects of their practices, using general pedagogical expertise to keep their classes intact. The teachers learned unfamiliar content alongside the students, as well as learning how to teach it. Their weaknesses in SMK thus impacted on their classroom practice.

Childs and McNicholl (2007) probed the same issue as Sanders et al (1993) by analysing the discourse used by a single science teacher teaching within and outside specialism. In some respects, they report similar findings – that when the teacher was secure in her SMK, she could explain the science concept she was teaching more fully and accurately, resorting less often to simplistic dialogue based on interaction-response-feedback. When teaching topics in which she expressed less confidence in her SMK, students were forced to learn by factual recall and information from experiments – the teacher did not explain the concept clearly and dialogue focused on mainly procedural matters.

Gess-Newsome and Lederman (1995) report the perceptions of subject matter knowledge (in their terms, "subject matter structure") of five American biology teachers with between 7-26 years of teaching experience. They found that the level of content knowledge was fragmented, comprising "concepts held together only by elusive threads", continuing to question "the ability shown by these teachers to successfully present biology as a conceptually integrated whole…" (p 317). Thus, the teachers' knowledge "had a significant impact on how content was taught" (p 317). Teachers made more connections and integrated a wider range of knowledge, such as links to the "real" world and science, technology and society issues when teaching aspects of the subject in which they claimed significant expertise. They also found that whole-class instruction tended to be preferred when teachers' confidence was high, while small-group or individual work dominated when they were less confident in the topic (p 317).

Kind (2008) compared trainees' perceptions of their teaching within and outside specialism topics. She found that in the initial stages at least, perceived possession of good SMK can generate over-confidence resulting in poorer quality within specialism lessons compared to outside specialism lessons. Kind's data suggests that some trainees find they know too much about their specialist science, and experience conflict in sorting out information needed for teaching effectively. This could be evidence that these trainees have not yet interpreted their science knowledge for school use (p). Outside specialism teaching presents fewer difficulties, as trainees learn alongside their students and use a richer range of resources, including experienced teachers, to develop and teach their lessons. Picking up the emotional attributes point raised earlier (p X) Kind also reports finding a "super-confident" sub-group, often mature entrants to the profession, characterised by their quick realisation that ensuring students' learning takes place is key to success. These trainees latch on to providing appropriate activities, and do not worry whether or not their academic SMK on the topic will withstand public scrutiny.

Studies suggesting the boundary between SMK and PCK is blurred

Among workers perceiving that SMK and PCK are not fully distinct categories of knowledge, in which the boundary between the two categories of knowledge appears “blurred”, or indistinct are Ball (2000) and Deng (2007). Ball begins her theoretical paper stating:-

> “Subject matter and pedagogy have been peculiarly and persistently divided in the conceptualisation and curriculum of teacher education and learning to teach” (p 241).

She notes that teachers are expected to meet the challenge of integrating SMK and PCK themselves, a process which the studies discussed above (Sanders, et al, 1993; Gess-Newsome and Lederman, 1995; Kind, 2008, etc) show is fraught with difficulties. Ball presents three problems that, if solved, would enable teachers to bridge the gap more successfully. First, she argues, the content knowledge required for teaching must be identified, taking what teachers do and the role played by SMK in their work into account. SMK must be viewed from the learners’ perspective: what they know; their difficulties; what textbooks are appropriate, and so on. This is supported by empirical evidence - the novices cited (p X) by Geddis, et al (1993) had not taken learners’ needs into account. They contrast with the “super-confident” trainees found by Kind (2008), described on p X. Second, Ball challenges the assumption that “someone who knows content for himself or herself is able to use that knowledge in teaching” (p 245). Providing more opportunities to study mathematics, science or history will not make better teachers, but indicating what sort of SMK is needed and how to make use of this may help. Finally, Ball argues that creating opportunities for helping teachers learn how to make use of the SMK required for teaching must be provided.

Deng (2007) suggests that helping teachers learn the SMK required by a school science subject instead of the academic discipline behind it “lies at the heart” of teachers’ specialised SMK (p 503). He challenges researchers who hold that science teachers transform knowledge of their academic discipline, posing the question “Why are academic disciplines being used as a basis for theorizing about teachers’ specialised subject-matter knowledge?” (p 507) En route to an answer, Deng presents data that illustrate differences between the key ideas in academic- and school-physics by observing two experienced physics teachers at work. He concludes that school and academic physics differ in logical, social, psychological and epistemological aspects (p 518), but concepts in school-physics:-

> “… can be viewed as a simplified, qualitative, and transformed version of their counterparts in the academic discipline; they complement or substitute, but not contradict, their disciplinary counterparts” (p 519)

He concludes that school-SMK needs to be presented as an “essential framework” and that secondary science teaching relies more on a teacher understanding a subject from a school-based than an academic perspective (p 527). This argument thus challenges the assumption, raised also by Kind and Wallace (2008, p X) that possession of a high quality degree in a science subject is essential for teaching.

PCK and SMK are not distinct knowledge components

McEwan and Bull (1991) dissolve the PCK: SMK boundary entirely, arguing:-

> "… no formal difference exists between SMK and PCK. To the degree that it is addressed to particular audiences, all subject matter is pedagogic." (p 331)

These authors thus reject Shulman's position that SMK and PCK are separate types of knowledge, believing that teaching and scholarship are mutually influential. Arguing from a theoretical standpoint, they investigate whether teachers' SMK is different "in kind" (p 316) from that of scholars. McEwan and Bull state:-

> "The task of the scholar is to represent the truth; that of the teacher is to make that privileged representation accessible to ordinary mortals by translating it …. Scholarly knowledge represents the world; pedagogical content knowledge represents the scholar's representation to the rest of us" (p 320).

In making assertions, they argue, scholars must take into account whether these can be understood by others, and hence in creating an academic discipline have to consider ways in which they can make their discoveries comprehensible. Thus "teaching" is implicit in the process of "doing science" – as there is no point putting forward proposals, theories and hypotheses or carrying out experiments if they cannot first be understood and then verified by others. In some respects, McEwan and Bull appear to elevate scholarly work but play down teaching, claiming:-

> "The teacher's task could be compared to a… party game where one player knows the answer but cannot say what it is. Instead [s/he] must provide experiences that will lead others to the answer." (p 329)

However, an overlap with Deng (2007) presents here, in that the authors do not ascribe transformation of academic SMK to teachers, but only SMK relating to "the world in which students act" (p 329). Support for McEwan and Bull's position comes from Segall (2004) whose paper presents additional theoretical evidence that teacher education would be improved by helping trainees to recognise that all SMK is inherently pedagogical in nature (p 489). In some respects, Segall's proposal would help address the gap expressed by the trainee quoted earlier (p X). Teacher education courses should make explicit "[among the] 'things' teachers should know in order to make effective instruction is the instructional nature of knowledge" (p 501).

The relationship between PCK and SMK: discussion

Evidence presented in this section supports the points made earlier (p X), that SMK, classroom experience and sound emotional attributes contribute to developing effective PCK. Sanders, Borko and Lockard (1993), Childs and McNicholl (2007), and Gess-Newsome and Lederman (1995) indicate that possession of specific, specialist

SMK background imparts confidence to teachers as they approach within specialism teaching, providing a basis from which to plan and interact with students.
Good SMK confers a sense of security, which supports a teacher in devising appropriate PCK. Where good SMK is absent, teachers resort to more passive and less active instructional strategies, and show less understanding of students' learning difficulties related to the science. The role classroom experience plays in the SMK/PCK intersection is interesting – comparing Kind (2008) and Sanders et al (op cit) indicates that pre-service teachers may be more willing to learn PCK for outside specialism teaching than experienced teachers. A teacher with well-established, good PCK relating to one specialist subject experiences uncertainty and hesitation when faced with teaching new, unfamiliar subjects. A pre-service teacher with no prior PCK on which to draw is more open to developing PCK across science specialist subjects. PCK for outside specialism teaching may be easier to develop initially, as s/he is in the process of interpreting academic SMK for school purposes (p). Emotional attributes such as confidence are referred to by several researchers (Sanders, et al, op cit; Kind, op cit; Childs and McNicholl, op cit). Failure to adapt SMK for teaching purposes may mean specialist subject lessons do not go according to plan. This may lower confidence and impact negatively on teacher development. Over-confidence in SMK can also generate poor quality lessons, perhaps of the type Ofsted describe (p). A teacher may be absorbed by the process of declaiming his /her knowledge, rather than presenting this appropriately for students' benefit. The confidence of an experienced teacher may be vulnerable when faced with the prospect of teaching an unfamiliar science topic, resulting in reversion to novice practices.

The papers discussed in this section also contribute to the integrative /transformative debate (p). McEwan and Bull's (1990) stance is integrative, but is somewhat extreme. In practice, their argument means that possession of a science degree equates to sufficient mastery of the subject for teaching. This may be true up to a point – many secondary science teachers seem to have sufficient knowledge about science gained from their academic studies to teach successfully, although some adjustments may be required for teaching the full range of science topics. Appleton (2005) points to SMK weaknesses persisting among elementary teachers, whose backgrounds may not lie in science – these teachers often need to learn science in order to teach it. However, in terms of developing PCK, McEwan and Bull (op cit) imply it doesn't matter what teacher education courses include, as a science graduate should be able to teach the subject successfully without further training. This position undermines teacher education and the profession of teaching, so must be disregarded. This is not to say that all integrative PCK models should be disregarded, but supports Abd El-Khalick's (2006) view that such models can lack explanatory power for teacher development.

Inevitably, in regarding SMK and PCK as separate knowledge components, Sanders et al (op cit); Childs and McNicholl (op cit) and Gess-Newsome and Lederman (op cit) take transformative stances. Both studies indicate that instructional strategies were influenced by teachers' SMK – where this was lacking, teachers resorted to passive strategies, whereas when their SMK was well-developed, greater confidence in engaging students with more active strategies was in evidence. Contrasting McEwan and Bull (op cit) with these studies illustrates the more general pedagogical nature of integrative models compared to transformative ones. In making their claim, McEwan and Bull rely on teachers developing skills by relying on classroom experience alone, a process which engages a teacher in gaining many types of general pedagogical knowledge simultaneously. Studies taking a transformative stance focus on specific subject-basedissues relating to science teaching, discussing precise strategies and making these explicit. These projects give strong indications that some mental processing, or mechanism, must be occurring as trainees develop their PCK for teaching science.

However, it remains unclear whether or not SMK is part of PCK. Deng (2007), cited above as a “blurred boundary” study, offers a way forward, acknowledging that differences exist between the academic disciplines of science and “school science” by creating “academic-SMK” and “school-SMK”. We can see this notion featuring in different ways in some of the PCK models discussed earlier (p X- X). For example, Banks et al (2005) points to “school knowledge” as an essential PCK component that bridges the gap between subject knowledge and pedagogic knowledge. The “personal subject construct” these authors suggest underpins all teachers’ PCK includes elements based on past learning experiences, beliefs and knowledge about their subject. Veal and MaKinster (1999) distinguish between “domain”-specific PCK describing “how to teach a topic” and “topic”-specific PCK (p X) which recognises the role academic training plays in shaping a teacher’s knowledge base.

Before returning to these issues in the concluding section, the emphasis changes to methods used to elicit PCK. These are of interest, as these indicate ways in which researchers have adapted a range of methodologies and developed new techniques.

Eliciting PCK

As indicated earlier and from the above discussion, an impressive range of studies has investigated PCK. The complexity of teachers’ practice has resulted in researchers devising many different methods to report science PCK, some standard and others novel. Attempts at classification have proved problematic, as inevitably overlap occurs with studies falling into more than one category. Having tried several classification systems, this paper discusses research methods in two groups - studies exploring PCK *in situ* and those using standardised “prompts” as elicitation tasks. This produces the clearest set of categories and fewest number of double classifications. *In situ* studies, investigating how teachers teach science in classroom / laboratory settings, are more frequent. These are sub-divided into those drawing on established methodologies in social science research and those featuring novel “rubrics” designed for PCK research. “Prompt” studies are also sub-divided into two types: those using probes to investigate the PCK teachers perceive in video excerpts or lesson transcripts for example; and those investigating changes to PCK following or during an intervention, such as attendance at a workshop or training course. “Prompt” studies can be found as an integral component of some larger, multi-method *in situ* projects.

To expand the range of papers discussed overall, the studies mentioned here have not been referred to elsewhere in the paper.

“in situ” studies using established data collection methods

The projects discussed below use data collection methods based on established, standard practice in social science research (see for example, Cohen, Manion, Morrison, REF). These studies tend to collect data over an extended period of time, rather than representing a PCK captured at an instant.

A good, relatively recent example is De Jong and van Driel (2005). This project took place over a one year teacher education course. The paper reports the results of interview data gathered from trainees teaching aspects of chemistry featuring the *macro-micro* shift (the ability to visualise matter and chemical reactions in terms of tiny, “micro” particles rather than as undivided, “macro” substances with physical characteristics such as colour, smell, etc). Participants prepared and taught lessons on a topic of their choice, such as “dissolving and precipitation” and “conservation of mass”. Pre-lesson interviews focused on the planning process; in post-lesson interviews trainees reflected on teaching and learning. Data indicate that the process of teaching inevitably enhanced trainees’ awareness of difficulties associated with teaching abstract concepts; pre-lesson interviews showed little awareness of potential pitfalls, a finding the authors attribute to trainees’ SMK – as experienced chemists, they switched between macro- and micro-representations of matter automatically.

Tuan et al (1995) preceded de Jong and van Driel (2005) in a similar type of study. They collected pre- and post-lesson interview data from trainee chemists at intervals during their teacher education course. These researchers also interviewed trainees about their knowledge of chemistry and views about teaching, besides using a range of methods to probe PCK as this developed. These authors report that trainees’ underpinning conceptual structures of chemistry initially featured chemical content alone, with pedagogy regarded separately. As trainees gained teaching experience, the interviews revealed structures that more closely integrated pedagogy with chemical knowledge.

In a smaller scale piece of work, Veal, Tippins and Bell (1999) used multiple-methods including a “probe”-type study (see below), to investigate the PCK of two trainee science teachers. Besides the use of probes, their data collection methods comprised: interviews with the trainees, experienced teachers in their placement schools and a teacher educator responsible for delivering training sessions; document analysis; observation notes and reflective journals compiled by the trainees themselves. The findings concur with other researchers indicating that classroom experience, possession of good SMK and knowledge of students’ needs contribute to sound PCK development.

Studies like these generate rich evidence bases that reveal PCK used in the specific contexts in which the data were collected. The use of multiple methods means that triangulation of data is possible, as interviews, classroom observations and questionnaire answers can be examined for common patterns and corroborations, so data generally have high reliability. A limitation is that many projects of this type tend to use trainee teachers, as these represent captive participant groups with low resistance and usually high motivation to co-operate, especially if their university tutors are directing the research. Collecting data using multiple methods is highly labour intensive – hence such projects are harder to complete on a large scale with experienced teachers in disparate schools, compared to trainees located in a focused training environment. Nevertheless, these studies help to build a picture of the kinds of knowledge that science teachers use, most often in the early stages of teacher development when PCK is limited and/or emerging. Certainly common factors emerge regardless of context – the points made above (p X SMK, experience, etc) appear consistently.

In situ studies using novel "rubrics" for data collection

To date, novel methods for elucidating PCK centre on devising "rubrics" to tabulate teachers' thinking about their work. Two contrasting examples are discussed.

First, Loughran, Mulhall and Berry (2004; see also Mulhall, Berry and Loughran, 2003) have devised "Content Representations" (CoRes) and Pedagogical and Professional experience Repertoires (PaP-eRs) to record teachers' PCK and to make this explicit. A CoRe is a detailed description tabulating the "big ideas" or concepts relating to a topic being taught against points such as what exactly students have to learn about each big idea; their possible difficulties with each concept; why its important for them to know these concepts; how these concepts fit in with others; and any knowledge the teacher holds that connects the big ideas in this CoRe to others. A PaP-eR is a narrative document, written in a teacher's voice, annotated by a researcher. The PaP-eR highlights the teacher's SMK, showing how s/he is thinking about teaching this to students. The CoRe is presented to a teacher as a blank table for completion. To supplement the written information, further data may be collected through lesson observation and/or interview. In their book, Loughran, Berry and Mulhall (2006) provide examples of CoRes and PaP-eRs generated by teachers for chemical reactions, particle theory, force, electric circuits and the circulatory system. Loughran, Berry, Mulhall and Woolnough (2006) describe the technique used in a teacher education setting, noting that encouraging trainees to complete CoRes and PaP-eRs can:

> "…give them a stronger feel for their own professional development … and [enable them] to explore in more detail the underpinnings of their teaching." (p 70)

The approach has been used by other researchers, including Rollnick, Bennett, Rhemtula, Dharsey and Ndlovu (2008) who report CoRes and PaP-eRs of South African science teachers on amount of substance and chemical equilibrium; and Ratcliffe (2008) who used the technique to elicit UK-based teachers' PCK for teaching the Nature of Science (NoS).

Second, Lee, Brown, Puthoff, Fletcher and Luft (2005) devised a rubric to document trainee science teachers' PCK. In contrast to Loughran et al (op cit), this is completed by researchers, rather than teachers themselves. Lee et al's (op cit) rubric is based on Shulman's two categories of teacher knowledge identified as comprising PCK, namely student learning (in science), and knowledge of instructional strategies. The authors report that data for completing the rubric were gathered from interviews with trainees. The trainees' comments were assigned by the researchers to one of three "levels" based on the knowledge demonstrated in each category; "limited", "basic" or "proficient". Data indicate that the trainees, all of whom were well-qualified scientists, had limited PCK, supporting Shulman's views that PCK is a special type of knowledge that is separate from content knowledge.

Loughran et al's (op cit) CoRes offers the most useful technique devised to date for eliciting and recording PCK directly from teachers. The method is clearly centred in teachers' skills and knowledge, so a completed CoRe provides a powerful means of recording the work of an experienced teacher, available for sharing and exemplifying good practice. However, the method is not unproblematic: the questions posed in a CoRe are challenging, making the task of completing one intimidating to some teachers, such as those lacking confidence in their abilities, new to teaching or resistant to producing a lengthy, detailed document "just" for a research project. Training and guidance on completing CoRes is necessary in order to help them understand what they are being asked to do, requiring investment of significant time to ensure generation of good quality data. The complexity of the knowledge required to complete a CoRe means that some may not be able to respond as fully as a researcher really needs. Alternatives are offered by the PaPeRs strategy and use of Lee et al's (op cit) rubric. A PaPeR offers an orally-based method of probing PCK. The account can be coded, and/or entered into a CoRe or an alternative rubric such as that of Lee et al (op cit). The rubric suggested by Lee et al (op cit) may be more suitable for use with some "harder to reach" teachers, who may be willing to participate in lesson observation and interviews, with a researcher analysing their PCK from the information provided. Feedback discussions with the teacher could then take place, making the data-collection process less intimidating than working alone to complete a blank CoRe.

"Prompt" studies

Studies using probes

Probe-type studies utilise video excerpts or descriptive prompts as "standard" instruments for investigating PCK. Teachers are exposed to the probe then respond to one or more data collection instruments to reveal the PCK they perceived in the prompt material. For example, Ahtee and Johnston (2006) interviewed trainee primary teachers about the SMK and PCK featuring in a 10-minute video clip of 10-year olds being taught physics concepts. Interview data were supplemented with questionnaire data that enabled the authors to compare attitudes towards teaching physics with those towards teaching other subjects. The authors compared responses given by UK and Finnish trainees, finding more negative attitudes towards physics teaching among the Finnish group. The more positive responses of the UK trainees were attributed to their learning all three sciences at least to the age of 16.

Veal, Tippins and Bell (1999) included a probe study in their work with two trainee science teachers. In this example, the researchers devised descriptive vignettes as prompt material, using these in a longitudinal way, as trainees responded to these on four separate occasions. Repeated use of the same vignettes enabled researchers to gain an understanding of how PCK evolved and changed over time.

Probe studies have the advantage that the prompt material can be used relatively easily in a wide range of settings, even internationally, as in the first example above. Thus, teachers working in a variety of contexts and with varying levels of experience can be invited to respond, allowing researchers to compare PCK across different backgrounds. A disadvantage of this method is that it relates primarily to PCK perceived in the probe material. The full range or quality of PCK a teacher possesses may not be exposed by this technique; its success relies on the nature of the probe itself. While such a criticism is also true of other methods (the quality of questionnaire data rely on the type of questions asked, for example), care needs to be taken in constructing the probe to ensure it is likely to generate useful and revealing responses. A second possible disadvantage is that if used once only a probe would at best generate a “snapshot” representation of PCK. However, in some situations this may be appropriate - if a researcher wished, for example, to investigate how teachers would respond to students’ misconceptions about a science idea, “one-off” data collection by probe may be a good way forward. When supplemented with other methods and/or used repeatedly over time (see Veal et al, 1999) a richer picture of teachers’ practices could be obtained.

Intervention studies
These studies follow a “before” and “after” pattern of investigating teachers’ PCK pre- and post participation in an intervention. The aim of these studies is to prompt development of PCK on the topic featured in the intervention, for example, a single session designed to help develop skills in doing chemistry demonstrations, or a longer term series of sessions focusing on teaching a new subject specialism. Two examples are discussed.

In their study of teachers’ PCK relating to the *micro-macro* shift (see above, p XX) Van Driel, de Jong and Verloop (2002) used a workshop as an intervention designed to help develop PCK relating to this topic. To investigate its impact on practice, data were collected at three specific points during a one-year chemistry teacher education programme. Questionnaire data provided a baseline of trainees’ PCK and SMK about the topic; video-recording and transcribing of two workshops showed the nature of the material presented; and interviews were conducted, indicating trainees’ practical experiences teaching the topic. In addition, trainees’ mentors were interviewed and trainees responded to a second questionnaire focusing on PCK alone. The authors noted that trainees jumped between macro- and micro-representations of matter without realising that their students could not do the same. They also found that the university-based workshops had significant impact on trainees’ practice, as these were timed to take place after trainees had been made aware, through teaching, of students’ difficulties with the topic.

A second example relates to helping teachers use models and modelling when teaching science. Justi and van Driel (2005) gathered data from five pre-service teachers each of whom completed a questionnaire, gave three interviews, collected data from their students, generated written materials in group meetings and wrote a report. The data were used to analyse teachers’ SMK, curricular knowledge and PCK on the use of models and modelling when teaching science. The range of data collected gave a good overview of teachers’ practices, permitting characterisation of the teachers, and indicated that although models and modelling can be used to teach science concepts effectively, teachers do not have good knowledge about how best to make use of them. The authors also point to the value of encouraging teachers to reflect on their practice – in this case, through report-writing.

Intervention studies, like those using probes, have the advantage of being useful with novice and experienced teachers alike. The participants become captive respondents in the study, so response of high quality are likely. Researchers can tailor “before” and “after” data collection methods to the content of the intervention to track changes in PCK. Thus, interventions can be combined with a variety of other methods. Studies like these are well-suited to evaluating the impact of continuing professional development (CPD) sessions on teachers’ practice. A disadvantage is that investigation of long-term changes to practice may be absent, limiting analysis of the impact of the intervention to short-term (that is, immediately post-intervention) effects. This leaves the procedure open to the “Hawthorne effect”, in which something new generates immediate positive outcomes in those experiencing it: an intervention study may be pre-disposed to claim a number of changes to teachers’ PCK as marked “improvements” on previous practice.

Eliciting PCK: discussion

All methods of PCK elicitation have generated fascinating data. Taking the papers reviewed here as a representative sample leads to the observation that science-oriented PCK research tends to divide into two broad categories: developmental studies attempting to track longitudinal changes in PCK and “what is there?” projects investigating or recording what teachers “do” in a given situation or instance. Both contribute to informing science teacher education practice: developmental studies by helping educators understand how PCK emerges and develops and “what is there?” projects by recording what PCK looks like at a moment in time. (EXAMPLES)

Of the “what is there?” methods, that of Loughran et al (XXXX) offers the most explicit and complete approach to elucidating extant PCK. Their CoRes are thorough, explanatory documents that provide a clear picture of PCK used by science teachers. At their best, when completed by experienced science teachers, CoRes have the potential to guide teacher educators in working with novices towards achieving good practice. In addition, teachers completing a CoRe have reflected carefully on their practice, generating a valuable working tool for recording their teaching at a certain moment, but permitting changes as skills or knowledge develop and/or new ideas arise. The main disadvantages with this method, as indicated above, are that CoRes are time-consuming to complete; training is required to aid teachers in completing at least their first one; and the CoRe may be intimidating and off-putting for some groups of teachers. The use of a rubric completed by a researcher offers a good alternative. However, CoRes and PaPeRs are beginning to gain credence with researchers and as these become more widely used are likely to evolve into more sophisticated forms.

Studies using probes such as video excerpts, lesson transcripts and other materials also offer options for a PCK researcher seeking to investigate “what is there”. These tend to be less time-consuming than CoRes for teachers to complete and can provide insightful data when used in conjunction with for example, a sound-recording of a teacher talking about a probe, an interview and/or questionnaire. A disadvantage is the “snapshot” effect – while some studies may benefit from a one-off sampling of PCK, the probe method is likely to reveal only some aspects of a teacher’s knowledge. In contrast, a CoRe reveals a more thorough and complete picture of a teacher's work. However, the method is adaptable – if used repeatedly, probes can help to generate a series of PCK "snapshots" that could be woven together to create a rich picture, giving the method a developmental aspect.

Inevitably, the methods selected are subject to influence by the researchers' acceptance of one model of PCK over another. An intervention study, for example, is undertaken with the belief that the intervention stands a good chance of changing teachers' PCK. For example, van Driel et al (2002) devised a workshop on macro-micro shift to develop PCK for teaching this topic. This is underpinned by a transformative PCK model in which SMK held by a trainee is transformed for students' benefit. Resulting changes in practice may support the notion of a "mechanism" for developing PCK. In contrast, a "probe" study may imply an integrative PCK model underpins the project. Asking teachers to respond to a probe invites a wide range of teacher knowledge, not necessarily subject-specific. Of course, this depends on the nature of the probe itself – a tightly drawn scenario relating to students' misconceptions about a science topic would not fit this image. The point, though, is that in planning a project, consideration of the PCK model underpinning the work is important, as this contributes to selection of appropriate data collection methods.

Conclusions

There is strong evidence that PCK is a useful concept and tool for describing and contributing to our understanding of teachers' professional practices. That it is a complex concept is to be expected, as PCK arises from intensely varied human interactions in a variety of situations. Difficulties in understanding PCK arise from its elusive nature – trying to get experienced teachers to articulate their practice is problematic, while following the development of PCK among naive novices with little notion of what teaching entails is equally challenging. Nonetheless, the attraction of PCK lies in its ability to tell us something of the unique professional experience that constitutes teaching. In this sense, Shulman is correct in describing PCK as a "special amalgam" that sets teaching apart from other professions. As a concept therefore, PCK does have a value to teaching and teacher educators. This discussion attempts to draw threads together from the PCK literature presented above to suggest ways forward for science teacher education.

Evidence indicates that PCK is more complex than Shulman proposed, and clearly develops over time. A suitable model of PCK to provide a theoretical background for science teacher education needs to take these points into account. Earlier discussions pointed to a division between integrative and transformative models, the former including SMK within PCK and the latter retaining SMK as a separate knowledge base component. The literature points to more integrative- than transformative-type models being preferred, perhaps because these tend to offer a wide-ranging general picture of teachers' skills and knowledge. Transformative models tend to focus on subject-specific PCK. The trend towards integrative models may arise because these reflect current practice in teacher education – initial training courses often present a wide range of components and usually do not indicate how trainee teachers should combine the knowledge presented into a coherent whole, but leave this to occur naturally during classroom experience. Gess-Newsome (1999) suggests that adoption of integrative models can result in trainees not moving on from the “transmission” style of teaching in which a teacher simply lectures, or delivers subject knowledge. In contrast, transformative PCK models have more explanatory power, that is, can provide a clearer statement about how PCK develops. These models imply that a mechanism, as yet unspecified, is involved in developing PCK.

Transformative PCK models seem to be most useful for science teacher education. These home in on subject-specific issues, including how to teach difficult and abstract ideas that are common in science. A transformative model offers a useful theoretical background for training novice teachers to teach science topics effectively, for example, by helping them to internalise expert teachers’ explanations, analogies and instructional strategies. Magnusson et al (1999) propose a model that seems to encompass what is needed. Their five components comprise Shulman’s instructional strategies and knowledge of students’ difficulties, curricular knowledge, orientations for teaching and assessment. The three latter components offer the potential for seeing novice teachers develop in different settings, use different teaching approaches and take into account the ever-pressing need to assess students’ learning and achievements.

However, there is some evidence (for example, from Appleton, 2005; Marks 1990) that the PCK “picture” may differ for experienced, “expert” teachers working within their preferred specialism. Evidence suggests that these teachers tend not to articulate SMK as a distinct component of their knowledge base, but roll SMK into PCK. This feature applies across all phases of education among well-established teachers who have gone beyond the initial stages of induction into the profession. This suggests that part of the process involved in becoming a teacher is a re-shaping of SMK, adapting this to a school setting to such an extent that prior personal knowledge becomes hidden, replaced by a modified version for school use. Deng refers to this as learning “school-SMK”, while Banks et al (2006) propose this as an additional knowledge base component; similarly, Kind and Taber (2004) distinguish between “SCIENCE” as an academic subject and “school science”. Although changing SMK in this way may be the learning of PCK itself, the SMK about chemical bonding learned during a chemistry degree and that required for teaching a post-16 school-based chemistry course are clearly different. Two points arise from this observation. First, in training to be a teacher, adjustment of SMK must take place. Acknowledging that this occurs, and assisting novices through this adjustment may be a way in which training courses could develop. Kind (2008) notes the frustrations that occur among novice teachers in the process of making this adjustment. Second, in examining PCK of experienced teachers, integrative models may provide a more appropriate theoretical background, as these reflect more closely what is observed in practice.

In terms of methods for eliciting PCK, Loughran et al (2004) offer the most useful method currently available. Their CoRes offer the means of gaining a unique insight into teachers’ practices relating to specific science topics. CoRes are working documents that can be changed at will, so can actively reflect development of PCK, thus avoiding the image of a static, unalterable body of knowledge. Training novice teachers in writing CoRes would prove valuable in helping develop their ability to reflect on practice and consider the “real world” of a professional science teacher. Other research techniques, such as responding to prompt material, may also prove useful in training situations. Use of appropriate vignettes (Veal et al, 1999) or video excerpts (Ahtee and Johnson, 2006) could be valuable in drawing novices’ attention to critical classroom events that may help develop PCK.

The research evidence discussed in this paper points consistently to three components being involved in PCK development among novices: classroom experience, possession of good SMK and having well-adjusted emotional attributes. The connection between SMK and PCK was discussed thoroughly (p X – X). In adopting a transformative model for PCK, at least for the initial training stage of teacher education, the implication is that SMK is a separate knowledge base component. Possession of good SMK through academic training seems to provide a secure knowledge base from which to develop effective teaching skills, although as pointed out in the introduction, this is not the only component. A number of studies (Kind, 2008; Veal XXXX) indicate that trainees require good levels of self-confidence and a belief system that enables them to take feedback on their practice, handle setbacks and adapt to school life. These factors may help pre-dispose a trainee to acquisition of PCK, facilitating internalisation of instructional strategies and information about students’ learning difficulties in science, for example. Although many initial teacher education courses are selective, in that potential entrants are expected to demonstrate high levels of academic achievement, teacher educators’ understanding, identification and/or means of developing emotional attributes and beliefs that “favour” teaching are less well-defined. These are, of course, more problematic to reveal – a certificate of “self-confidence” cannot be produced on demand – but undertaking further research on the links between these “softer” aspects of a teacher’s make-up and academic aspects may provide useful insights that benefit science teacher education.

To conclude, science teacher education would benefit from utilising PCK more actively, that is, helping novice and experienced teachers to understand what PCK is, and how knowing about PCK may help their practice develop and improve. In order to do this, three recommendations are suggested. First, we should agree to adopt a transformative model of PCK, for initial training, or situations in which experienced teachers are learning to teach new subjects. These best reflect the process that is involved in starting out as a teacher, offering a mechanism for changing practice. Second, teacher education courses should make explicit what PCK is, for example, by introducing CoRes as a way of describing current practice, and/or using completed CoRes as exemplar material. CoRe completion promotes development of reflective practice skills, offering a means of acknowledging changes in PCK through application of classroom experience. Use of vignettes and other prompts may also be useful ways of highlighting and devising instructional strategies. Third, attention must be given to the emotional side of becoming and being a teacher. While this may be difficult to formalise, it is possible to undertake evaluations of teachers’ self-confidence and efficacy, as well as to analyse belief systems that may impinge on classroom practice. Such evidence, when combined with explicit training in PCK development, would acknowledge that becoming a science teacher involves more than just possessing a good degree in a science subject.

Ofsted (p X) observe that science teachers too often adopt a passive learning approach, transmitting subject knowledge without thought for their learners. This suggests that changes are needed to science teacher education, at least in England and Wales – we need an approach that enables a majority of teachers to move beyond simply "transmission" of knowledge to a much more active and stimulating way of teaching. By placing PCK and its development towards the centre of a science teacher education programme, the precise skills and knowledge involved in becoming a professional science teacher can be better acknowledged, developed and improved.

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