The Place of Subject Matter Knowledge in Pedagogical Content Knowledge: A case study of South African teachers teaching the amount of substance and chemical equilibrium

Marissa Rollnick a, Judith Bennett b, Mariam Rhemtula a, Nadine Dharsey c & Thandi Ndlovu a

a Wits School of Education, Johannesburg, South Africa
b University of York, UK
c University of Johannesburg, South Africa

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RESEARCH REPORT

The Place of Subject Matter Knowledge in Pedagogical Content Knowledge: A case study of South African teachers teaching the amount of substance and chemical equilibrium

Marissa Rollnicka*, Judith Bennetto, Mariam Rhemtulaa, Nadine Dharshey and Thandi Ndlova

Wits School of Education, Johannesburg, South Africa; University of York, UK; University of Johannesburg, South Africa

This paper presents two South African case studies designed to explore the influence of subject matter knowledge on pedagogical content knowledge (PCK). In the first case study on teaching the mole in two township schools, the findings illustrate that the participant teachers favoured procedural approaches at the expense of conceptual understanding. The second case study examines the teaching of chemical equilibrium to students on a bridging programme in a tertiary institution. Through these data the authors present a model to assist in understanding the amalgamation of subject matter knowledge (SMK) with other teacher knowledge domains to produce what we describe as ‘manifestations’. The model was useful in interpreting the teachers’ practice, especially to highlight the role of SMK, and therefore offers interesting insights into the nature of PCK and its influence on science teaching.

Introduction and Aims

It is now just over 20 years since Lee Shulman (1986) published the paper that coined the phrase ‘pedagogical content knowledge’ (PCK) to describe the knowledge that teachers create by transforming their content into a teachable form. From the attention it has received since 1986, PCK has been seen as a radical move away from the notion of pedagogy as a content-free skill. PCK also shows the importance of subject matter knowledge (SMK) per se in pedagogy for effective teaching.

*Corresponding author: School of Education, University of the Witwatersrand, P.O. Wits 2050, Johannesburg, South Africa. Email: marissa.rollnick@wits.ac.za
In South Africa, one of the legacies of apartheid is that teachers from traditionally disadvantaged groups often had only limited opportunities to develop formally their understanding of science (and other) subjects. The 1998 figures show that fewer than 40% of physical science teachers nationally have a degree in any discipline, including science (Centre for Development and Enterprise, 2004). The majority of Grade 10–12 teachers prior to 1994 generally held a 3-year diploma that included a level of SMK equivalent to 1 year of university physics and chemistry. Although these teachers have upgraded their qualifications, it is typically in education, rather than content areas. Thus, it is important to understand the influence of teachers’ SMK on the teaching of key concepts in chemistry.

This paper uses two case studies to answer the following two questions:

1. What is the influence of teachers’ SMK in the teaching of two chemistry topics?
2. How can the impact of the teachers’ SMK be captured, portrayed and modelled as manifested in the classroom with respect to their:
   - Awareness of curricular demands
   - Use of representations
   - Instructional strategies

Why is PCK Important?

Since PCK is considered one of the cornerstones of teacher knowledge, it is important to understand its composition. If it is possible to describe and model its formation, it may be possible to target areas for improvement in teacher education. If expertise can be captured and portrayed, it may then be passed on to inexperienced teachers and thus assist them in their progress toward enhanced competence in teaching. Developing deeper understandings of the phenomenon that is PCK may also help to create new ways for appropriately discussing issues inherent in the intricacies and application of content knowledge in the growth of practice. In many ways finding, capturing and elucidating PCK may well represent what some might describe as the holy grail of teacher development!

In his 1986 paper, Shulman noted with concern the disappearance of discipline-specific subject matter from programmes of teacher education in the USA. This disappearance was predominantly based on the assumption that pedagogy was a content-free skill; possibly explained by the fact that in most developed countries teachers entering the classroom are assumed to have had adequate content preparation. Unfortunately, as briefly noted above, the latter assumption cannot be made in the South African context where the majority of Grade 11 and 12 teachers have only 1 year or 2 years of post-school study in the subject they are teaching. Their limited content background has led to teachers’ over-reliance on transmission methods of teaching and superficial use of content (Rogan, 2004). It is therefore not difficult to see why SMK draws serious attention in any investigation into the nature of PCK in the South African context.
**What Do People Mean when They Talk about PCK?**

Since Shulman’s time, the notion of PCK has been further researched (e.g., Borko, Bellamy & Sanders, 1992; Grossman, 1990; Wilson, Shulman, & Richert, 1988), either directly or indirectly through describing the attributes PCK would appear to encompass. In simple terms, PCK can be described as how teachers teach their subject by accessing what they know about the subject, the learners they are teaching, the curriculum with which they are working, and what they believe counts as good teaching in their context.

Geddis and Wood (1997) consider PCK as ‘a broad category of those kinds of knowledge involved in pedagogical transformations of subject matter’ (p. 612). They included in PCK the learner’s prior concepts, subject matter representations, instructional strategies, curriculum materials, and curricular saliency. The last term refers to the teacher’s understanding of the place of a topic in the curriculum and the purpose(s) for teaching it. Curricular saliency may be observed, for example, in teachers’ decisions to leave out certain aspects of the topic, and in teachers’ awareness of how a topic fits into the curriculum. Geddis and Wood’s ideas of PCK were based on the view that PCK represents all the kinds of knowledge that are amalgams of subject matter and pedagogical knowledge. However, these authors say very little about the influence of teachers’ actual SMK understandings on their PCK.

Gess-Newsome (1999a) reviewed studies on teachers’ knowledge and beliefs about subject matter and its relationship to teaching. Three areas in that review are most relevant to this present study: conceptual knowledge, subject matter structure, and content-specific orientations to teaching. These areas offered a useful framework for developing and analysing the case studies that form the basis for this paper. The findings most germane to this study are summarised in Table 1.

Gess-Newsome (1999b) makes a distinction between an integrative and transformative model of teacher cognition, and this has important consequences for understanding how SMK may be incorporated into PCK. At the simplest level,

<table>
<thead>
<tr>
<th>Table 1. Relevant findings on teachers’ SMK and beliefs (Gess-Newsome, 1999a)</th>
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<tbody>
<tr>
<td><strong>Area</strong></td>
</tr>
<tr>
<td>Conceptual knowledge</td>
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<tr>
<td>Subject matter structure</td>
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<tr>
<td>Content-specific orientations to teaching</td>
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</table>
the integrative view could be seen as something that is developed individually by a
teacher as he/she gains knowledge with experience so that the individual ‘pieces’
of knowledge fit together in new ways. In the transformative model, PCK is a
well-structured and easily accessible form through which knowledge of teaching
and content become something new and fundamentally different in the way they
combine; hence the knowledge itself is transformed. Our position is that no matter
how the combination of domains occurs, it needs to be achieved in a conscious
manner if the teacher is to have the flexibility to learn and teach new content in
ways that go beyond the simple transmission of information.

In the context of this paper, two features of the research reviewed are particularly
noteworthy. First, whether seen as a component of PCK or as a distinct area, SMK
is crucial to the development of PCK. Secondly, the role played by SMK in teaching
has been explored in two ways—where novice teachers have good SMK but little
teaching experience, and where experienced teachers are attempting to teach outside
their area of expertise (Hasweh, 1987; Sanders, Borko, & Lockard, 1993). In our
case studies, experienced teachers are teaching within their area of expertise, but
there is uncertainty about the depth of their SMK.

Method

Two case studies of the teaching of chemistry content are described in this paper—
the mole in a high school context, and chemical equilibrium in an Access
programme at a tertiary institution. The data for the case studies were collected in a
similar manner—the teachers were interviewed before and after they were observed
teaching two or more lessons on the topic. Teacher resources such as textbooks,
materials, tests, and past examination papers used in preparing their lessons were
also gathered during the interview sessions. The interview before each lesson probed
their understanding of the topic as well as their planning strategies, explanations,
and resources used in their lessons.

In the mole case study, the teachers were exposed to a short workshop before the
observed lessons covering possible strategies for teaching the mole, emphasising
conceptual rather than procedural approaches. The aim of the workshop was to
provide these teachers with a variety of practical ideas for portraying the meaning of
the mole, such as weighing a number of small everyday objects (e.g., rice grains) in
order to count them.

Lesson observations were recorded in the case of the Access programme using
videotape and in the case of the high school using field notes enriched by audio-
recordings. The difference in approach was due to the availability of resources at the
two sites. The post interviews included a stimulated reflection on the lesson. Teachers
were later asked further questions where necessary to clarify issues that arose about
their practice during the analysis of data.

The teachers were selected through willingness to participate, and proximity to
the researchers, who were collecting data for higher degrees. Thus, the teachers
constituted a convenience sample, but it could be that they were likely to be more
confident than the majority of their colleagues, given that they consented to be observed.

In the case of the mole concept, the two teachers (Ms Simelane and Mr Xaba) were teaching in disadvantaged schools in a South African township. Mr Xaba had a science degree with an education honours degree, while Ms Simelane had upgraded her 3-year diploma to a degree-equivalent education qualification and, at the time of the study, was completing an honours degree with a content component. Both had between 5 and 10 years’ teaching experience. Like their students, they used English as a second language but were proficient in the primary languages spoken by their students. The students in the study were in Grade 11, the penultimate year of their schooling, and were aged between 15 and 17 years on average.

In the other case study, Mr Moerane, a lecturer on an Access programme and former teacher with 7 years’ teaching experience, was video-taped teaching the topic of chemical equilibrium. Mr Moerane’s qualifications included a teaching diploma that he had upgraded to a degree-equivalent qualification in education, rather than content courses. He also used English as a second language.

The students in both case studies were drawn from similar communities, although at different stages in their lives. The students in Ms Simelane’s and Mr Xaba’s classes were from black townships in South Africa, attending schools that, in most respects, are generally poorly resourced. These students were largely from lower socio-economic groups and their learning is through a second language. Not many of the students from these schools go on to study science at university, and if they do they are usually accepted into Access programmes; such as the one in the second case study. Mr Moerane’s students would have been selected from the higher-achieving township students, together with some students from other schools who had not received high enough grades to enter directly into tertiary programmes.

Data Analysis

The PCK of the two teachers was captured and portrayed using Pedagogical and Professional-experience Repertoires (PaP-eRs) and Content Representations (CoRes) (Loughran, Berry, & Mulhall, 2004, 2006). Loughran et al. developed PaP-eRs and Cores in an attempt to articulate teachers’ tacit knowledge by linking it to practice. CoRes were developed by engaging small groups of experienced science teachers in activities that were designed to help them to articulate and share with others how to teach particular science topics, leading to the identification of ‘big ideas’ for the teaching of particular topics and subsequently, to the development of framing questions (see Tables 2 and 3, below). CoRes focus on teachers’ understandings of those aspects that represent and shape the content and contribute to the content-specific nature of PCK, while PaP-eRs are narrative accounts of practice designed to bring to life the ideas in the CoRes.

In the present study, CoRes and PaP-eRs were used as methodological tools to assist in the analysis of data and hence represent our construction of what we observed from the various data sources—such as pre-instruction and post-instruction
interviews, and video and audio transcripts. We also obtained a written reflection from Ms Simelane about her teaching. In the case of the mole, teachers’ SMK was also ascertained through diagnostic questions administered to the teachers in the form of a questionnaire modified from Novick and Menis (1976) (see Appendix).

We inferred the big ideas and categorised the data into the various prompts to obtain the CoRes presented in Tables 2 and 3 below. Hence, the CoRes obtained below show a synthesis of data rather than direct quotes from the teachers. Analysis of the data also revealed several categories of transformation of subject matter as suggested by Geddis and Wood (1997); that is, curricular saliency, subject matter representations, and topic-specific instructional strategies. These categories are not separated elsewhere (e.g., Magnusson, Krajcik, & Borko, 1999) but it was thought that the separation made by Geddis and Wood (1997) was important, as many of the subject matter representations were easily identifiable objects, while topic-specific strategies referred to the broader approach used by the teacher. In addition to Geddis and Wood’s (1997) categories, a fourth category—that of SMK—emerged. The data from the various sources were coded according to these themes and are reported below.

Results of Case Study 1: Teaching of the mole

In lay terms, the mole concept is a collective noun for a very large number of atoms or molecules, to allow counting by weighing. When expressed in these simple terms, it underplays the difficulties for both teachers and learners of this topic (e.g., Furio, Azcona, Guisasola, & Ratcliffe, 2000; Tullberg, Strömdahl, & Lybeck, 1994). One of the teaching difficulties of this topic, which is common to a great many concepts in chemistry and physics, is the integration of the meaning of a concept with its use in calculations. Because it is so easy to substitute numbers into equations, teachers invariably devote time to calculations rather than working to understand the concept, especially when the demands of high-stakes external examinations make little or no demand on conceptual understanding.

Curricular Saliency

Both teachers considered memorisation of definitions and the procedural aspects of the mole as an important skill for their learners. For example, Ms Simelane said:

The kinds of activities that I give to learners to create understanding are mainly calculations. I want them to master calculation on the mole because we will use the moles when we do the equilibrium rates and $K_c$.

The reason for this was given by Mr Xaba:

You see the examiners use these textbooks to set questions. If they know the definition they will pass at the end of the year.

This last point highlights these teachers’ understanding of the emphasis they need to place on the teaching of the topic. Their sights are geared to the public examination on which their reputation as teachers rests. They are aware of their students’ limited
background in chemistry and the difficulties of trying to achieve conceptual understanding. It is not possible, however, to tell from these data alone whether the tendency of these teachers to resort to algorithmic approaches was a strategic choice as outlined above, or whether, like the teachers in studies reviewed by Gess-Newsome (1999a), they resort to these strategies because of their uncertainty with regard to their content knowledge.

Subject Matter Representations

Both teachers used analogies but did not try to link them to calculations. In both cases the concept was first explored in the lesson using an analogy, but the teachers quickly moved to using a formula rather than developing the concept, making it difficult for students to grasp the full meaning of the mole.

For example in Mr Xaba’s case:

Teacher: *Akere tsoko e* [You see this chalk], *E e ntswe ka* [it is made up of very small particles]. *Kapa ke maka?* [Isn’t it true?]

Students: yes *Meneer* [Sir].

Teacher: *Bothatha ke hore re batla ho tseba hona jwale* [The problem is that we want the solution very soon.] There are too many small particles in any object and we cannot count them one by one. Because we need the results now we will not finish within a short time. So we use moles to calculate them. Let us calculate the number of moles. Now let us come to calculation of the moles.

Mr Xaba’s understanding of the importance of calculations and formulae in the teaching of the mole is confirmed by the perceptions of student difficulties identified in his interview. Issues highlighted included difficulties in calculating molar mass, changing the subject of the formula, knowing the difference between atomic mass and atomic number, and knowing the symbols of the elements, among others.

He makes use of students’ home language (italic print) to clarify concepts (translations in square brackets), a strategy also used by Ms Simelane. Ms Simelane used analogies, too; a balance to determine the mass of grains of rice, biscuits, and peanuts, as suggested in the workshop held before the lessons. But she moved quickly to algorithmic exercises without linking the conceptual aspects. This may well have been because synthesis of the workshop experience with her teaching may not yet have occurred. However, this question was not explored with Ms Simelane. Nevertheless, her written self-reflection showed that she was disappointed with the lesson. She described herself as disorganised and confused and not using the teaching approaches as she would have wished. She demonstrated discomfort with a new approach as she had not had sufficient time to transform her knowledge adequately. The process of adopting new approaches is a slow one, requiring both time and opportunity to experiment.

Topic-specific Instructional Strategies

Although there were differences between the approaches of the two teachers, there was also a level of commonality amongst them. Both teachers held similar conceptions
of the mole, as equivalent to Avogadro’s number, yet in none of their classes did this conception emerge as important. Both began with an attempt at conceptualisation of the mole, before moving on to a series of exercises involving the use of formula-driven calculations. Ms Simelane’s attempt at conceptualising the mole was more extensive than Mr Xaba, but neither teacher attempted to connect the conceptual understanding to the calculations, no learner exercises were provided on the conceptualisation of the mole, and none of the calculation exercises demanded any thinking beyond the mechanical application of the formula. The message to the students was clearly that the calculations were the most important part of the lesson.

**Teachers’ Subject Matter Knowledge**

Ms Simelane described the mole in the following terms:

> A mole to me is a counting unit. It is just a number and in their textbooks it is explained as a quantity of matter containing exactly the same number of elementary particles of which it is a knowledge I also use.

Mr Xaba thought students should understand that a mole is:

> … the amount of atoms or anything in a substance and these substances are small particles like for example C is made up of small particles.

Thus both teachers considered a mole as a number, although Mr Xaba’s definition appears inaccurate at face value. In fact in his teaching, Mr Xaba made no mention of Avogadro’s number at all, describing the mole to his students as a ‘heap’ of something.

Ms Simelane had to return to her textbooks as she had interpreted the definition idiosyncratically. She was obviously dissatisfied. She was aware of her inadequate conceptualisation of the mole and lack of bridging between the concept and algorithms. She said:

> A mole is a very difficult concept to understand. Even now I am not sure if I understand it so well—it took me more than ten years to be confident … but at least I have a clear understanding now …

It seems from this quote that Ms Simelane is developing a deeper understanding of the concept of the mole and that this change in her understanding is beginning to influence her thinking about her teaching. Hence, her PCK may well be beginning to develop.

From the analysis of the combined data sources we extracted two big ideas—one relating to the conceptualisation of the mole, and the other to its use in stoichiometric calculations. The above data were organised using these big ideas against the prompts in the CoRe presented in Table 2.

In many aspects, the CoRes of the two teachers show similarities. Both place emphasis on knowing definitions of the mole and being able to do calculations; a theme that emerges strongly in their teaching. There is also commonality in understanding their students’ prior knowledge and language background. But there are
Table 2. CoRe for Ms Simelane and Mr Xaba’s instruction on the mole

<table>
<thead>
<tr>
<th>Big ideas</th>
<th>Conceptualising a fixed large number of particles</th>
<th>Use of the mole to calculate reacting quantities in reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. What you intend the students to learn about this idea</td>
<td>The definition of mole from their textbook (B)</td>
<td>Use of the formula to calculate the number of moles (B)</td>
</tr>
<tr>
<td></td>
<td>The mole is equal to the number of atoms (X)</td>
<td>Use of the formula to calculate Avogadro’s number (S)</td>
</tr>
<tr>
<td></td>
<td>The importance of understanding the mole in chemistry (S)</td>
<td></td>
</tr>
<tr>
<td>2. Why it is important for students know this</td>
<td>Related to many subsequent topics (S)</td>
<td>To distinguish quantities (S)</td>
</tr>
<tr>
<td></td>
<td>One of the seven basic SI units used in Physical Science (S)</td>
<td>To know amount of substances to form products (S)</td>
</tr>
<tr>
<td></td>
<td>To know the definition to pass examinations (X)</td>
<td>Makes calculating huge number of small things like atoms easier (X)</td>
</tr>
<tr>
<td>3. What else you know about this idea (that you do not intend student to know yet)</td>
<td>Avogadro’s number (X)</td>
<td>How to solve more complex problems (X)</td>
</tr>
<tr>
<td></td>
<td>The history of the mole (S)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Origin of Avogadro’s number (S)</td>
<td></td>
</tr>
<tr>
<td>4 and 5. Difficulties/limitations/knowledge about students’ thinking that influences teaching of this idea</td>
<td>Poor chemistry background (B)</td>
<td>Difficulties with calculation of molar mass (B)</td>
</tr>
<tr>
<td></td>
<td>Confuse moles with mass, volume and density (S)</td>
<td>Lack of knowledge of the symbols of elements/chemical formulae (B)</td>
</tr>
<tr>
<td></td>
<td>Understanding of the word ‘Number versus quantity’ (S)</td>
<td>Confusion between atomic number and mass number (B)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cannot balance simple chemical equations (S)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Understanding the Periodic Table (X)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Algebraic difficulties, e.g. changing the subject of the formula (X)</td>
</tr>
<tr>
<td>6. Other factors influencing teaching of this idea</td>
<td>Maturity of students (X)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>General background knowledge (X)</td>
<td>New to school and lacking knowledge of specifics of learner background (S)</td>
</tr>
<tr>
<td></td>
<td>New to school and lacking knowledge of specifics of learner background (S)</td>
<td>Learners first group from new junior secondary curriculum (S)</td>
</tr>
<tr>
<td></td>
<td>Have struggled with earlier tasks (S)</td>
<td>Have struggled with earlier tasks (S)</td>
</tr>
<tr>
<td></td>
<td>Ability to do tasks on their own (S)</td>
<td>Need to adopt multilingual practices to assist leaner understanding (B)</td>
</tr>
</tbody>
</table>
also noticeable differences. Ms Simelane identifies conceptual issues with regard to the importance of the topic and her consideration of the students’ background that carry through into her suggested teaching strategies. Mr Xaba’s engagement with the conceptual issues related to the first big idea was minimal. His only contribution to the teaching procedures was a brief analogy using chalk particles, which he passed over quickly in order to concentrate on the second big idea. His understanding of the students’ context was general (e.g., maturity of students), while Ms Simelane’s was more closely linked to the subject matter and the curriculum (e.g., students have struggled with earlier tasks).

**Integration of Teacher Knowledge**

The two big ideas that emerged from our analysis of the CoRe are taught by these teachers as separate entities. The lack of linking of these big ideas suggests that whether one considers teacher knowledge as a result of integration or transformation (Gess-Newsome, 1999a), it appears as though one or more of the knowledge domains is not sufficiently in place to allow a PCK-rich, unified approach to teaching the mole. Since these teachers have some classroom teaching experience and show a good understanding of their learners’ context (prompt 5 in the CoRe) as well as the ability to develop teaching procedures, the difficulty would appear to lie with their understanding of the content. This assertion is supported by the teachers’ reliance on algorithms and their lack of capacity to provide additional challenges in the exercises provided to the learners (Gess-Newsome, 1999a).

These teachers’ emphasis on procedural rather than conceptual aspects of the mole can be justified by their belief in the importance of teaching for assessment—the common external examination does not directly examine the mole concept but only requires learners to use the idea of the amount of substance in calculations. However, it seems fair to suggest that the calculation exercises used in the lessons would need to go further than direct use of the formula to achieve this aim.

<table>
<thead>
<tr>
<th>Big ideas</th>
<th>Conceptualising a fixed large number of particles</th>
<th>Use of the mole to calculate reacting quantities in reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>7. Teaching procedures</td>
<td>Using the ‘dozens’ analogy, counting and weighing peanuts/grains of rice (S) Application questions involving menu items and quantities (S) Analogy of counting chalk particles (X)</td>
<td>Exercises from chemistry books (X) Problems on the chalkboard, more homework to practice (X) Calculations of different types (X) Calculations to create understanding (S)</td>
</tr>
</tbody>
</table>

*Notes: S, Ms Simelane; X, Mr Xaba; B, both teachers.*
This apparent lack of connection between the big ideas highlights the lack of confidence with the depth of understanding of the scientific phenomenon itself, pointing to the crucial role played by depth of understanding of content in the development of PCK. Other work (e.g., Geddis, Onslow, Beynon, & Oesch, 1993) has emphasised the importance of other domains of teacher knowledge, mostly by comparison of teaching attempts by subject matter experts with those of expert teachers. On the other hand, our findings in a context where teachers lack depth in SMK show the root causes of what is referred to as rote teaching and learning (e.g., Centre for Development and Enterprise, 2004) and the poor performance of South Africa in international studies. If teachers do not have in-depth knowledge of a topic themselves, it is clearly difficult for them to provide conceptual depth for their students—hence, the importance of PCK and the role of SMK in its development.

We now turn to the second case study.

Results of Case Study 2: Teaching equilibrium in an Access programme

The idea that chemical reactions do not always go to completion is a problematical idea for high school students to comprehend, and studies reported in the international literature (e.g., van Driel, Verloop, & de Vos, 1998) show the difficulties associated with teaching this topic. As briefly noted above, the preparation for tertiary education offered by many high schools in South Africa is less than ideal. Consequently, almost all tertiary institutions run Access programmes (e.g., Grayson, 1996) in order to prepare students for first year study at university. The students in the programme under study had completed their school education in which they may or may not have studied science, but needed upgrading of their knowledge in order to join science-based programmes at the tertiary institution. At the time of the study, these students were registered on a 1-year programme. We would assert that these students may therefore get a second chance to learn about chemical equilibrium, yet they still struggle to make sense of the idea as some of the underlying concepts are not sufficiently in place to facilitate meaningful understanding.

As in the mole case study, analysis of the data revealed several categories of transformation of subject matter as defined by Geddis and Wood (1997); namely, curricular saliency, subject matter representations, and topic-specific instructional strategies. However in this case study, no diagnostic questionnaire was used for SMK—instead, the status of Mr Moerane’s SMK had to be inferred from the interview and observation data.

Curricular Saliency

Curricular saliency emerges in evidence of understanding of what comes before and after the topic in hand. In the pre-lesson interview, Mr Moerane justified the inclusion of chemical equilibrium thus:
Chemical equilibrium is not included in the syllabus ... I was only teaching it because of the link with acids and bases. ... students have to have the basics before [I] spoke about equilibrium of ionisation and dissociation of acids and bases.

But curricular saliency is also powerfully illustrated by what is omitted from the teaching. For example, Mr Moerane kept his description of a closed system simple, not dealing with open, closed, and isolated systems as one of his colleagues (a content expert) did.

Subject Matter Representations

Mr Moerane began by using a physics diagram to explain equilibrium to represent static equilibrium, drawing on learners’ prior knowledge. In his treatment of phase equilibrium, he used the representations in Figure 1 to show what happens before and after equilibrium is reached.

Mr Moerane used arrows of equal length to illustrate equal rates of the ‘opposing processes’ in Figures 1a and 1b. Figure 1c represents the re-establishment of equilibrium at a higher temperature, again using equal arrows to emphasise the condition of equal rates in either direction, not amounts; a common misconception about equilibrium. The diagram also illustrates both the particulate nature of matter and the need for a closed system; another condition for equilibrium, mentioned later.

Topic-specific Instructional Strategies

Although Mr Moerane did not outline an overall strategy for his lessons, our observation of the sequencing of his instruction and his choice of examples led us to construct a representation of the flow of content in his lessons (as illustrated in Figure 2). This sequencing was informed by Mr Moerane’s understanding of the logic and progression of the content and his perception of his students’ understanding. His simple choice of examples took into account the students’ previous experience—as he noted in the pre-lesson interview:

... [the] starting point was determined by the background knowledge of the learners and that [teacher] would go ‘back, back, back’ to fill those gaps.

Figure 1. Representations of phase equilibrium
The example of phase equilibrium, commonly used in textbooks, took into account the fact that the students had studied phase changes earlier. The simplicity of the system also makes it a good starting point as only one type of molecule is involved. Mr Moerane subsequently added the example of a saturated solution, which took the students a step closer to a chemical reaction.

Mr Moerane’s treatment of the equilibrium constant $K_c$ used examples with very large and small values, using extreme case reasoning as anchors to illustrate the concept (Clement, Brown, & Zietsman, 1989). He ended with a traditional treatment of Le Chatelier’s principle. The two reactions that he used were not strictly equilibrium reactions, but he used them to create an understanding of the continuity between reversible and non-reversible reactions.

$$
\text{H}_2(\text{g}) + \text{Cl}_2(\text{g}) \rightleftharpoons 2\text{HCl}(\text{g}) \quad \text{at } 25^\circ \text{C} \quad K_c = 4.4 \times 10^{32}
$$

$$
2\text{H}_2\text{O}(\text{g}) \rightleftharpoons 2\text{H}_2(\text{g}) + \text{O}_2(\text{g}) \quad \text{at } 25^\circ \text{C} \quad K_c = 1.1 \times 10^{-81}
$$

When initially asked in the pre-lesson interview what he intended learners to learn, Mr Moerane provided a list of topics. He described his teaching strategy as teaching topics in a particular order where examples would be used to consolidate the work. He also referred to the use of the overhead projector to illustrate phase equilibrium, and suggested the use of exercises for the students. He gave no reason for
the teaching order chosen, other than that it would work well and that he would work from the known to the unknown.

In constructing Mr Moerane’s strategy in Figure 2 we extracted two big ideas from the lessons he taught—one relating to static and dynamic equilibrium, and the other to the extent of equilibrium. The data analysed above were organised using these big ideas against the prompts in the CoRe presented in Table 3.

As with the study on the mole, this CoRe is constructed from all available data, rather than the interview alone. Comparing his treatment of the two big ideas, the CoRe shows a far richer transformation of his content knowledge for the first big idea than for the second. For dynamic equilibrium he explored the influence of temperature on phase equilibrium, and he used sophisticated representations to highlight the principle

<table>
<thead>
<tr>
<th>Big ideas</th>
<th>Dynamic versus static equilibrium</th>
<th>Extent of reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. What you intend the students to learn about this idea</td>
<td>The concept ‘dynamic chemical equilibrium’ versus static</td>
<td>Expression for equilibrium constant, $K_c$</td>
</tr>
<tr>
<td></td>
<td>Reversible reactions</td>
<td>Homogeneous and heterogeneous equilibrium</td>
</tr>
<tr>
<td></td>
<td>Rates of reversible reactions and factors influencing these</td>
<td>Le Chatelier’s Principle</td>
</tr>
<tr>
<td></td>
<td>Difference between closed and open systems</td>
<td>Conditions and factors affecting chemical Equilibrium</td>
</tr>
<tr>
<td></td>
<td>Heterogeneous and homogeneous equilibrium</td>
<td></td>
</tr>
<tr>
<td>2. Why it is important for students to know this</td>
<td>To understand future topics such as rates of reaction</td>
<td>To understand future topics such as ionisation and dissociation of acids and bases</td>
</tr>
<tr>
<td>3. What else you know about this idea (that you do not intend student to know yet)</td>
<td>Equilibrium ionisation and dissociation of acids and bases</td>
<td>Application of chemical equilibrium to industrial processes</td>
</tr>
<tr>
<td></td>
<td>Open, closed and isolated systems</td>
<td>Advanced calculations</td>
</tr>
<tr>
<td></td>
<td></td>
<td>In depth knowledge of heat associated with chemical reactions</td>
</tr>
<tr>
<td>4 and 5. Difficulties/limitations/knowledge about students’ thinking that influences your teaching of this idea</td>
<td>Lack of prerequisite knowledge for understanding chemical equilibrium</td>
<td>Do not know about chemical reactions, balancing of equations, homogeneous and heterogeneous mixtures, heat of reactions, solutions and crystallisation</td>
</tr>
</tbody>
</table>
that the ‘reaction’ continues in both directions at both the macroscopic and microscopic levels. His knowledge of students’ difficulties with the topic was also more extensive. For extent of reaction, he provided a more limited treatment of Le Chatelier’s principle, but he did display a higher level of flexibility with the concept of $K_c$.

### Integration of Teacher Knowledge

From his classroom practice, Mr Moerane displayed highly developed PCK for this topic; yet in his interview, he was not able to articulate the way in which he transformed his knowledge for teaching. This situation highlights yet again the tacit nature of teachers’ knowledge and the consequent difficulties for teachers to both recognise and ‘say what they know’.

Unlike the teachers in the first case study, Mr Moerane’s practice displayed sound SMK, which he combined with knowledge of his students and the teaching context to produce the pedagogical transformations observed above (Geddis & Wood, 1997). His knowledge of student misconceptions about chemical equilibrium was

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**Table 3. (Continued)**

<table>
<thead>
<tr>
<th>Big ideas</th>
<th>Dynamic versus static equilibrium</th>
<th>Extent of reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Unable to differentiate between static and dynamic equilibrium</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Once equilibrium has been reached, nothing else happens</td>
<td></td>
</tr>
<tr>
<td></td>
<td>They encountered phase equilibrium earlier</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Forward and reverse reaction happening simultaneously in the same container</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Closed system in chemistry</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Equilibrium as static rather than dynamic</td>
<td></td>
</tr>
<tr>
<td>6. Other factors that influence your teaching of this idea</td>
<td>Profile of the student in an access programme</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Nature of materials the students have been exposed to</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Prescribed student guide for Access Chemistry</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Poor command of language</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lack of background in practical work</td>
<td></td>
</tr>
<tr>
<td>7. Teaching procedures (and particular reasons for using these to engage with this idea)</td>
<td>Using static equilibrium and chemical equilibrium to explain chemical equilibrium</td>
<td>Students solve problems in front of class</td>
</tr>
<tr>
<td></td>
<td>Diagrams to illustrate dynamic phase equilibrium.</td>
<td>Equations to develop and explain $K_c$ using examples with very large and very small $K_c$</td>
</tr>
<tr>
<td></td>
<td>Saturated solutions to further elucidate the concept of dynamic equilibrium</td>
<td>Activities that develop problem solving</td>
</tr>
</tbody>
</table>
not informed by a reading of the literature, as he had not studied science education at a postgraduate level. Rather, he drew on his previous experience of working with students, and the knowledge from that learning through experience has been incorporated into his knowledge of practice. His representations have arisen through a study of common texts and his own creativity in modifying and extending them.

Modelling Teachers’ PCK

An examination of the role played by teachers’ SMK in the above case studies suggested the possibility of providing a model that could connect the teachers’ observable practice to their knowledge domains. Other models of the integration of teacher knowledge to produce PCK (e.g., Cochran, DeRuiter, & King, 1993) examine only the underlying knowledge rather than how this knowledge is combined to produce what happens in the classroom. In this paper, we have focused on the role of SMK as this is currently an issue of concern in South Africa. Many of the established models include SMK as a component of PCK (e.g., Borko et al., 1992; Grossman, 1990), but few give prominence to its central role in the construction of knowledge for teaching.

Drawing from these various models we extracted four fundamental domains of knowledge for teaching: that is, knowledge of subject matter, knowledge of students, general pedagogical knowledge, and knowledge of context—drawn principally from Cochran et al. (1993). We consider PCK to be an amalgam of these domains that, when combined, produce directly observable products in the classroom, which we refer to as ‘manifestations’. These manifestations could include any visible products of teaching observable in the classroom. These are many and varied. We have chosen a few of these to represent in the model shown in Figure 3; namely, subject matter representations, topic-specific instructional strategies, curricular saliency, and assessment. These are broad inclusive categories, some of which fit the findings of this study. For example, assessment includes choices made by the teacher for both formative and summative tasks. Modelling the PCK of the teachers in the case studies in this way, we believe, has been a useful tool in understanding their practice as it allows us to make inferences about their knowledge from the manifestations.

The lower part of Figure 3 shows the components of teacher knowledge that are integrated to produce PCK, while the upper section represents the visible features in the classroom (i.e., the products of PCK). The teacher knowledge domains are explained in Table 4.

Manifestations of teacher knowledge, shown in the top part of Figure 3, are now examined using examples from the case studies in an attempt to shed light on the role played by teachers’ content knowledge.

Subject matter representations. This term refers to representations as described by Shulman (1986). The ability to produce effective representations and link them to the target knowledge requires the amalgamation of SMK with the other three knowledge
domains. The case studies show that, without adequate SMK, as in the case of Ms Simelane, it was difficult for the teacher to connect the two big ideas to create a holistic understanding of the mole for the learners.

Curricular saliency. The term refers to that used above, coined by Geddis and Wood (1997). In the above case studies, the emphasis on procedural rather than conceptual approaches to the mole by Mr Xaba could be interpreted as a conscious

<table>
<thead>
<tr>
<th>Domain</th>
<th>Nature of knowledge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knowledge of subject matter</td>
<td>The teacher’s raw untransformed SMK.</td>
</tr>
<tr>
<td>General pedagogical knowledge</td>
<td>Understanding what counts as good teaching, the best teaching approaches in a given context, informed by knowledge of applicable learning theories.</td>
</tr>
<tr>
<td>Knowledge of students</td>
<td>Appreciation of students’ prior knowledge, how they learn, their linguistic abilities, and interests and aspirations.</td>
</tr>
<tr>
<td>Knowledge of context</td>
<td>All contextual variables influencing the teaching situation, e.g., availability of resources, class size, students’ socio-economic background, curriculum, the situation in the country, classroom conditions, and time available for teaching and learning.</td>
</tr>
</tbody>
</table>
decision based on the current assessment regime. Mr Xaba appeared to understand the mole concept but it is possible that his understanding was not sufficiently flexible to make connections between the two big ideas.

Assessment. SMK would play a large part in producing suitable assessment tasks. In the studies reported in this paper, formative assessment tasks in the case of the mole showed limited application of subject matter to the teaching context—all exercises were merely procedural calculations. In the teaching of chemical equilibrium, Mr Moerane’s tasks consisted of writing expressions for $K_c$ from given equations, but the discussion of these tasks involved the creation of meaning for these expressions. The teacher’s choice of formative exercises also displays consciousness of the demands of external assessment. This would have been an issue for the two teachers teaching the mole, and their teaching style would have been influenced by the type of questions asked in the final Grade 12 paper.

Topic-specific instructional strategies. We were able to construct a well-elucidated teaching strategy from our observations of Mr Moerane’s lessons. His CoRe shows that this strategy, although not elucidated by him, was supported by a rich understanding of students’ prior knowledge and contextual factors, underpinned by solid understanding of the content.

Discussion and Conclusion

An assumption is often made that teachers have adequate SMK for teaching. Thus, when difficulties in teaching are encountered, research investigations tend to focus on other domains of teacher knowledge, masking potential difficulties within the subject matter domain. It is only when such difficulties are known to exist that teaching difficulties may be more fully explored and understood. Therefore, studies in a context such as that of South Africa can provide insights into the role played by teachers’ SMK.

With reference to Research Question 1 above, analysis of the teaching of Mr Xaba and Ms Simelane suggests that they are constrained in their teaching by the limitations of their understanding of the concept. Ms Simelane showed signs of moving towards an approach based on the development of conceptual understanding as her own understanding of the content grew. However, when she was placed in the position of a novice teacher in relation to the new knowledge that she had gained, she was not able to incorporate this into her teaching. Instead, she showed characteristics identified by Gess-Newsome (1999a), such as resorting to reliance on algorithms, lack of flexibility in her teaching, and, finally, readjusting her understanding after the lesson. The role of experience in achieving this integration is important due to the development of coherently structured rich subject matter structures (Gess-Newsome, 1999a) of both of these teachers. Similar findings from studies conducted with teachers elsewhere have been reported; for instance, teachers at the primary level (e.g., Lee, 1995;
Smith & Neale, 1989) or teachers teaching outside their area of expertise (e.g., Hasweh, 1987; Sanders et al., 1993). In both these situations, teachers resorted to rote teaching and learning due to their lack of confidence with their SMK. In this study, the teachers were teaching at the secondary level and were, on paper, qualified in the discipline they were teaching.

Mr Moerane was able to display more powerful PCK where his nuanced SMK allowed him the flexibility to produce innovative approaches. This was evident when he combined his knowledge of the teaching context, his general pedagogical knowledge, and his understanding of the students with his SMK. He had well-developed strategies for teaching key sections of the chemistry curriculum; but because his knowledge of practice was largely tacit, it was not easy for him to articulate (although it was observable in his practice as illustrated through the case study itself). It is interesting to ponder whether an awareness of the construct of PCK together with exposure to metacognitive strategies would assist him in articulating his knowledge.

With regard to Research Question 2, the CoRes have proved to be a useful methodological tool for constructing a picture of these teachers’ PCK. It is possible that CoRes could assist other teachers also, in articulating their PCK. The use of the CoRe, and ultimately the model (see Figure 3), allowed salient aspects of these teachers’ PCK—such as their use of representations, their topic-specific strategies, and their curricular saliency—to become visible. For curricular saliency, the study has shown that strategies emphasising procedural approaches may be as much a product of contextual factors—such as demands of external examinations, inadequate student backgrounds, and impoverished classroom environments—as of teachers’ limited content knowledge. The model also made it possible to trace the representations and instructional strategies used to the knowledge domains of the teacher. For example, understanding when to switch languages during explanations shows knowledge of the students and their context. Mr Xaba made use of the students’ primary language in his explanation of the mole as shown in the extract above. The primary language was used for substantive parts of the explanation (e.g., ‘it is made of small particles’), as well as to reach out to the students in a language in which they felt comfortable (with phrases such as ‘isn’t that so?’). Such interjections pointed to their understanding of the students’ context, a combination of two of the knowledge domains in the lower half of the diagram.

Teachers’ choice of representations (or the lack thereof) reveals information about the structure of their subject matter knowledge. For example, Mr Moerane’s choice of examples to explain dynamic equilibrium and his use of extreme case reasoning, as well as the way he built up the complexity of the examples used, showed a flexibility in the understanding of content that he could bring to bear on the teaching situation. The two township teachers did not have a qualitatively different background to Mr Moerane. However, Mr Moerane was working with similar learners but in a university environment where he had control over what to teach and how to assess, as well as a better resourced environment. His teaching of chemical equilibrium was characterised by a coherent strategy that included commonly used approaches from text books as well as his own carefully thought out examples. In his teaching there was
evidence of approaches honed by several years of experience that provided opportunities to restructure his understanding of teaching the topic. Ms Simelane and Mr Xaba, on the other hand, had to spend time grappling with the physical realities of their environment, such as large classes, shortage of textbooks, and disrupted schedules. When Ms Simelane was given an opportunity to engage with a new teaching approach, she embraced it, but she encountered difficulties integrating it with her existing knowledge. Given more time and opportunities, it is possible that she may be able to develop her content knowledge for teaching further. In terms of the model developed in this paper, the SMK may be similar in the knowledge base of all three teachers, but the context in which each is working is qualitatively different. The manifestations in the classroom will also be qualitatively different. Thus, the call by policymakers to improve teachers’ subject matter alone may be too simplistic—for real change in teachers’ practice to occur, improvement in content understanding needs to take place alongside change in the assessment regime and enrichment of classroom conditions (Johnson, Monk, & Hodges, 2000). In South Africa, a new curriculum is currently being implemented at the senior secondary level that makes higher demands on teachers both in terms of content and in the flexible treatment of the content. Research into how teachers manage this change will provide further insight into how they are able to transform their content knowledge into rich pedagogical practices.

References


Appendix. Questions on the mole (from Novick & Menis, 1976)

QUESTION 1
Which of these three sets best shows 1 mole of tin, 1 mole of magnesium and 1 mole of sulphur in each tube?

Give a reason/s for your answer below:

QUESTION 2
Each container represents a volume of 22.4 l at STP. In which of the three pairs of containers, if any, is there one mole in each container?

Write your answer below. Give reasons for your choice as well as for not choosing others.

QUESTION 3
In your own words explain what is the mole.
QUESTION 4
Given that:

\[ \text{Mg} + \text{S} \rightarrow \text{MgS} \]

What mass of Mg would react completely with 32g of S?

Work out your answer in the space below:

QUESTION 5
Given that:

\[ 2\text{NaOH} + \text{H}_2\text{SO}_4 \rightarrow \text{Na}_2\text{SO}_4 + 2\text{H}_2\text{O} \]

What amount of H\textsubscript{2}SO\textsubscript{4} is required to react with 6 moles of NaOH?

Work out your answer in the space below: