What lies at the heart of good undergraduate teaching? A case study in organic chemistry

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Teaching organic chemistry at the undergraduate level has long been regarded as challenging and students are often alienated by the mass of detail which seems to characterise the subject. In this paper we investigate the practice of an accomplished lecturer by trying to capture and portray his pedagogical content knowledge, PCK, in order to reveal his tacit knowledge as a resource for others. Data analysed from interviews and a set of five introductory lectures showed the framing of Big Ideas designed to underpin later work in the course. Five manifestations of his practice emerged strongly from the data analysis, namely Explanations, Representations, Interaction with Students, Curricular Saliency and Topic Specific Strategies. This realisation allowed us to make inferences about his underlying knowledge and beliefs regarding how the discipline should be taught. We found that the most important aspect of his practice was his recognition of the basic underlying concepts to be mastered before starting the main part of the course, and his strong beliefs related to the learning of the discipline. The extraction and portrayal of these practices are a valuable resource for novice lecturers.

Keywords: pedagogical content knowledge (PCK), organic chemistry, undergraduate teaching

Introduction

What lies at the heart of good teaching in undergraduate organic chemistry? We sought to answer this question by studying the practice of an accomplished lecturer, Professor Mwaamba. 'Kalenga Mwaamba' is a Professor of Chemistry at a prominent South African university. He is a renowned researcher, but is also dedicated to his teaching of undergraduate students. In this paper we explore an approach he used in his first week of teaching a second year undergraduate organic chemistry course, where his carefully selected key concepts lay the foundation for teaching what is regarded by some as a maze of disparate reactions.

Organic chemistry has long been regarded as a challenge for students at the undergraduate level, and the situation in Professor Mwaamba's institution was no exception (Katz, 1996; Huddle, 2000). To confront this challenge a tutorial scheme was introduced to supplement the lectures in both organic and inorganic chemistry (Davidowitz and Rollnick, 2005). The scheme led to improvement of performance in both disciplines, but the improvement was far greater in organic chemistry, a course in which the students had previously performed very poorly. This greater improvement was attributed to the skills of the lecturer, Professor Mwaamba. In this paper we analyse his first week of teaching in order to examine closely the process of transformation of his subject matter knowledge as he makes it accessible to students (Shulman, 1987). In particular we aim to find out:

- how he conceptualised the content to be taught;
- what he considered to be the Big Ideas in introducing organic chemistry;
- how analogies, representations and explanations were used in the process;
- what motivated his choice of strategy.

Much research has been done on the teaching of chemistry but there has been little focus on the central figure in the teaching process at the tertiary level, namely the course lecturer. Like many academics, Professor Mwaamba's practice has been developed largely on intuition, rather than informed by education theory or professional training. There are few detailed studies on the professional practice of university lecturers. This study demonstrates how engaging in practice-based research can advance understanding of the way in which a lecturer transforms his knowledge of organic chemistry to make it accessible to students.

Literature review

Pedagogical Content Knowledge

The majority of teachers at the tertiary level are not formally qualified to teach, and while they have adequate content knowledge, they may lack the ability to transform their content knowledge into teachable form. Shulman (1986) recognised that educators transform their content knowledge into a form that can be understood by the learners, known as pedagogical content knowledge, PCK. Thus PCK embodies the way teachers engage in the business of teaching their subject by accessing what they know about their subject, the learners they are teaching, the curriculum with which they are working, resources and artefacts, what they believe counts as good teaching, research findings, and their local context.

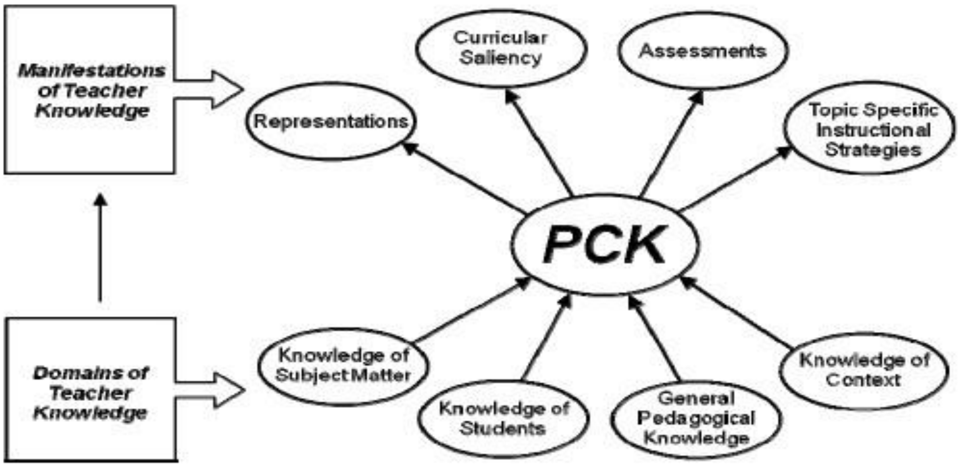

Fig. 1 Model of Rollnick *et al.* (2008).

An essential prerequisite for PCK is content or subject matter knowledge. A useful metaphor for the transformation of this knowledge is provided by Ball *et al.* (2008) who described the process as one of decompression or unpacking of content knowledge. Current understanding of PCK implies that it is primarily knowledge gained through experience, and hence most studies to date have focused on experienced teachers (e.g. Loughran *et al.,* 2004).

Bucat (2004) documented examples of topic-specific PCK of expert teachers as he sees recording PCK as a way of preventing the loss of expertise gained over time by competent chemistry teachers. He noted the paucity of findings on PCK in chemistry and suggested that novice chemistry teachers could benefit from the availability of a number of case studies of expert practice, as do other professionals. The current paper is such a contribution to the teaching of organic chemistry, as it presents a unique view of how a particular professor isolated specific concepts for presentation in the introductory lectures of a second year chemistry course. In the South African system this course would be the first specialist introduction to organic chemistry following an introductory general course.

Many models have been employed to trace the transformation of pure content knowledge to subject matter knowledge for teaching as manifested in the classroom, for example Cochran *et al.,* (1993). A model that has been found to be most useful for our purposes is that of Rollnick *et al.* (2008) (see Fig. 1). This model shows the integration of teachers' internal knowledge domains to produce the visible product of integration of these domains in the classroom, which they refer to as manifestations. The internal knowledge domains, drawn from Cochran *et al.* (1993), are shown in the bottom half of the diagram, while the manifestations in the top part of the diagram are drawn from various sources, such as Geddis and Wood (1997). The usefulness of this model is that it separates the teacher's internal thought processes from what can be observed directly in the classroom. This allows the distillation of the overall teaching strategy produced in action, as informed by the teacher's knowledge domains. The manifestations arise from individual teaching situations, and depend on what takes place in a particular class. Hence, different manifestations will lead to different aspects being included in the upper part of the model, marked as manifestations in Fig. 1.

Teaching and learning organic chemistry at the tertiary level

Several reported studies of teaching at the senior undergraduate level exist, such as a complete issue of *Chemistry Education Research and Practice* (e.g. Bodner and Weaver, 2008). The papers range from a discussion of the problems students encounter in these courses to instructional strategies to assist in addressing those problems. For example, Bhattacharyya (2008) found that organic chemistry students only acquire deep understanding of concepts and models after a number of years, suggesting that teachers of the discipline at the various levels should plan their courses accordingly.

One of the main challenges facing second year students of organic chemistry is the need to switch from a product-oriented view of organic reactions to one which takes into account the mechanism, or what Ferguson and Bodner (2008) referred to as a process-oriented view of the reaction. The second year student has to master the use of curved arrows, a vital skill, as it is used routinely by practitioners in the field. Ferguson and Bodner found that students had a relatively poor understanding of the underlying principles of reactions and argued for a more conceptual approach to teaching mechanisms. In an earlier publication Huddle (2000) reported success with the use of posters accompanied by students' oral reports as a means of involving students in their organic chemistry course and enabling their understanding of mechanisms.

Bhattacharyya and Bodner (2005) investigated how the undergraduate studies of a group of graduate organic chemists had prepared them for the problem-solving required of a practising organic chemist. They found that the students were essentially playing with puzzles rather than solving problems, and relied on reproducing a sequence of steps. These studies point to the need for the instructor to be aware of the nature of the discipline and the challenges involved in guiding students on the journey from novice to expert. Overall, there appears to be an emphasis on a mechanical rather than conceptual approach to teaching organic chemistry, a problem addressed in the current study. Student difficulties in learning organic chemistry may also be due to the way in which they think about learning science. Grove and Bretz (2010) found that the way students' thought processes worked affected their success in organic chemistry courses. A further challenge to students of organic chemistry is the need to interpret multiple representations of chemical structures used by practising chemists. In a study of the teaching and learning of organic reaction mechanisms in tertiary level courses Ladhams Zieba (2004) found that students appeared to be cued into thinking that only one reaction type was possible for a given reactant, depending on the representation used for that reactant.

Teacher knowledge and beliefs about teaching at tertiary level

Another issue central to the practice of teachers is the influence of their beliefs about teaching on their teaching. Bryan (2003) attested to a strong message from the literature that teachers' beliefs about teaching are pivotal in how they make teaching decisions. Bryan's attention was focussed primarily on the secondary level, but Kane *et al.* (2002) pointed to the paucity of literature linking tertiary teachers' beliefs about teaching to practice, while citing a large number of studies on beliefs *per se.* However, they do produce a convincing argument that findings related to secondary teachers' beliefs and their relation to practice could be applied to the tertiary level. Hence, Bryan's assertion can be considered applicable at the tertiary level.

Kane *et al.* (2002) bemoaned the lack of consensus in terminology on what constitutes a belief about teaching. We favour the definition of Kagan (1990, p. 423 in Kane, p. 180) that a belief about teaching refers to *"the highly personal ways in which a teacher understands classrooms,students, the nature of learning, the teachers' role in the classroom and the goals of education".* Kane *et al.* (2004) studied accomplished tertiary teachers with the aim of learning how to assist novice tertiary educators. They pointed to the importance of reflection and therefore, self-evaluation and its influence on practice, a point also recognised by Hativa *et al.* (2001). These authors argued that unplanned and unsystematic learning through reflection may lead to fragmented pedagogies. However, self-evaluation can only be effective when the lecturer is receptive to feedback, implying an underlying belief in the importance of teaching. We argue that beliefs can be powerful mechanisms supporting the formation of constructive personal theories, which in turn inform practice.

Research design

As the purpose of the research was to carry out a close study of a specific lecturer's practice, a case study research design was used involving observation and video-taping of lectures, participant observation of tutorial sessions (Davidowitz and Rollnick, 2005), combined with pre- and post-observation interviews about the lecturer's practice as well as questions posed to him informally and via email. Professor Mwaamba revealed in the pre-interview that he placed particular importance on an introductory set of five lectures where he laid the conceptual foundation of the course. It was thus decided to select these lectures for the study. Further data were collected in the form of interviews and questionnaires with tutors and students by the first author who participated as a tutor for the duration of the course. (Davidowitz and Rollnick, 2005)

Rollnick *et al.* (2008) had previously captured and portrayed PCK of secondary school teachers using Pedagogical and Professional experience Repertoires (PaP-eRs) and Content Representations (CoRes) (Loughran *et al.,* 2004). CoRes were initially developed by the brainstorming activity of small groups of experienced science teachers, leading to the identification of Big Ideas for teaching particular topics, and subsequently, to the development of framing questions, while PaP-eRs are narrative accounts of practice designed to bring to life the ideas in the CoRe. In the present study, we constructed the CoRe and used it as a data analysis tool to assist in portraying the practice of the lecturer, and did not deem the Pap-eRs necessary. Professor Mwaamba's CoRe was developed first by extracting the Big Ideas for teaching, followed by responses to Loughran *et al.'s* (2004) framing questions (see Table 2) gleaned from data, such as lecture observations and interviews. The strength of the CoRe is that it focuses on the lecturer's understanding of those aspects that represent and shape the content.

Research participants

Professor Mwaamba is a subject matter expert and has been a very highly regarded researcher in the field of organic chemistry for more than 15 years. At the time of the study he was the principal lecturer for the second year organic chemistry course. He views teaching as important to train the next generation of researchers saying, *"ultimately, I tend to look at feeding into the honours[1] programme".*

Our observations suggest that Professor Mwaamba's style of teaching could be regarded as 'traditional' in that he uses the blackboard and handwritten overhead transparencies. His method slows down the pace of the lecture and encourages students to attend lectures so that they make their own notes and engage with the process of capturing the different representations instead of following a printed set of notes. He prefers to develop ideas on the chalkboard, which allows students to see him taking the time to think about his explanations. His style is in strong contrast with that of another accomplished lecturer in organic chemistry Professor Simons, who uses PowerPoint regularly.

Unlike Professor Mwaamba, Professor Simons provides a skeleton outline of the notes, and expects students to add considerable details to these notes during the lecture.

Professor Mwaamba's choice of material for the first five lectures was based on previous experiences of teaching at the second year level. He recognised that novices regard organic chemistry as a 'huge body of information'. Organic chemistry is an example of a linear sub-discipline where comprehension of basic concepts is essential in order to build a secure knowledge base (Green and Rollnick, 2006). This idea of mastering basic concepts appears to be part of Professor Mwaamba's philosophy in constructing the introductory set of lectures. He is aware that *"by the time they* [the students] *enter second year, they really haven't mastered much"* and believes that it is very important to point out that there are unifying principles that underpin the discipline. On numerous occasions he stressed that there are only a limited number of types of reactions.

The students in Professor Mwaamba's class are taking a second year organic chemistry course which forms part of the curriculum for science majors and chemical engineering. Science students include majors in chemistry, biochemistry, microbiology and geology. The class typically consists of about 60% engineers and 40% science students, all of whom would have completed a first year level introductory general chemistry course. First year level course topics in organic chemistry include: an introduction to structure and reactivity, the language of organic chemistry, describing and predicting organic reactivity, reaction mechanisms, as well as an introduction to the structure, properties and reactivity of biologically important molecules. The duration of the second year course is 12 weeks and consists of 48 lectures and 12 tutorials, each session lasting 45 minutes. The organic chemistry comprises about 60% of the course and includes topics such as structure elucidation of organic molecules, organic reactivity, reaction mechanisms and stereochemistry, elimination, substitution and addition reactions, and chemical biology. The rest of the course consists of topics in inorganic chemistry. The demographic composition of the class is diverse, with many students using English as an additional, rather than their primary language.

Data analysis and findings

Capturing and portraying knowledge

The topics covered during the first five lectures are fundamental to understanding reaction mechanisms for the various types of reactions, which will follow during the course. In the post-interview Professor Mwaamba said:

> *It's really just to make sure that I focus them on the fact that there are only a few things that they have to think about. Three types of reaction that they have to worry about…. we deal with nucleophiles and electrophiles. And I also just again remind them that we'll try to explain, try to understand every reaction.* (KM, Post-interview)

This approach could be described as spiral, in that it returns to earlier material, but presents it at a more advanced level, similar to that of Grove *et al.* (2008), who found that the spiral approach had a favourable effect on student attrition and learning, and prevented overload with respect to the organic chemistry covered. Although the spiral approach may be novel in the USA, it is fairly standard in the United Kingdom and the rest of Europe. In South Africa, however, this conscious attempt to revisit earlier concepts is noteworthy.

Professor Mwaamba told students that he assumed they were familiar with basic concepts, such as the structure of organic compounds, simple nomenclature, resonance and functional groups. Students were encouraged to revise Newman projection formulae, as these were important for the topic of elimination reactions, which would follow later.

Professor Mwaamba's Big Ideas

An understanding of how Professor Mwaamba conceptualised the content for the first 5 lectures is crucial to gaining a window into his PCK. As mentioned above, this was done by using Loughran *et al.'s* (2004) framing questions to construct a CoRe from interviews and classroom observation data. Our analysis of the data uncovered three Big Ideas in the data - stability of carbocations, representation of three-dimensional structures and conceptualising stereoisomerism, stated in full below:

1. The stability of carbocations depends on the nature of the species attached to the electrophilic centre.
2. Three-dimensional structures of organic compounds can be represented in multiple formats, each of which highlights specific characteristics of the molecule.
3. Stereochemistry has a profound effect on the nature of the product in an organic reaction.

These are unpacked in the CoRe in Table 2 using abbreviated forms of the Big Ideas.

As can be seen, the series of lectures consists of three well-articulated ideas extracting the essence of concepts needed for the rest of the course. They are informed by a good understanding of student needs, as well as the demands of the subject. Data taken from another study not reported here show similar Big Ideas from Professor Simons, another lecturer teaching the same material to similar students at a different time, although he did not specifically articulate the stability of carbocations. For example in an interview he said:

> *... two big concepts are, I suppose, stereochemistry and its implications for reactivity, and then also the language of organic chemistry and how one would use that as a tool to describe reactions and so on.* (Professor Simons, Interview)

In both courses the material covered focused on reactions between nucleophiles and electrophiles. Reactions involving radicals were not included, and Professor Mwaamba was well aware of this and made it clear to the students:

> *The second way of breaking a bond, okay, is in such a way that the electron pair ends up only on one of the*

Table 1 Lectures delivered by Professor Mwaamba		
Lecture	Topic	Teaching strategy
1	Stereochemistry, rotational isomers Correct use of line drawings Enantiomers Racemic mixtures and enantiomeric excess	Used large model of ethane to demonstrate rotational isomers Described in detail; pointed out a common student error Used 2-bromobutane as example, labels R and S forms, but no explanation about the R/S assignments General principles, no examples
2	Diastereoisomers, 2 examples: 4-bromopentan-1-ol and 2-methyl-5-(2-propyl)cyclohexanol Brief history of thalidomide Meso compounds, e.g. 2,3-dibromobutane All of the above encapsulated in carefully chosen example based on bicyclic compounds	Structure of compounds drawn on the board; detailed discussion of concepts, including determination of maximum number of possible diastereoisomers Contextualisation of importance of enantiomers as pharmaceuticals Presented the meso and enantiomeric forms; mirror planes vs. axes of symmetry Each structure drawn on board; with carefully chosen captions. Students given adequate time to copy drawing, after which lecturer explained example
3	$\Delta G° = \Delta H° - T\Delta S°$ Homolytic and heterolytic bond fission Primary, secondary and tertiary carbocations,	Defined terms, referred students to relevant text, students reminded of transition states Introduced formation of carbocations Emphasised the correct use of curved arrows Description and explanation of relative stability; inductive effect
4	Hyperconjugation Geometry of carbon compounds Steric effects in formation of carbocations Order of reactivity of carboxylic acids, phenols and alcohols based on the stability of the conjugate base	Alternative explanation for the relative stability of carbocations sp3 geometry of reacting species vs. sp2 geometry of the carbocations; stereochemical implications for the reaction of carbocations with nucleophiles Comparison of 2-chloro-2-methylpropane vs. 2-chloropropane Digressed from main topic to explain the order of reactivity of organic acids
5	Benzylic and allylic carbocations and resonance Order of stability of all the carbocations considered Types of reactions; addition, elimination and substitution; mechanisms and curved arrows Types of reagents	Pointed out features which contribute to the stability of these carbocations Students reminded that reaction rates are related to the stability of the carbocation intermediates Electron donation from the nucleophile to the eletrophile, emphasised importance of using curved arrows Description of nucleophiles and electrophiles

> *atoms that make up the bond, ... okay, we not going to deal with radicals, that's something that's covered probably in third year or fourth year, all the reactions we'll be doing are based on this type* [referring to polar reactions] *of either bond breaking or bond forming process.* (KM, Lecture 3)

Themes emerging from data analysis

Video recordings of lectures and interviews were transcribed and data were analysed using Atlas.ti® and grounded codes, which were then clustered into themes related to the manifestations of knowledge, as suggested by the model of Rollnick *et al.* (2008). For example, grounded codes such as '3D and line drawing propane', 'Analogy', 'Description of model', 'Manipulation of model', and 'R and S representation' were grouped under the manifestation, 'Representations' taken from the model. In this way grounded codes were linked to categories imposed by the model. Data subjected to analysis using Atlas.ti® consisted of 5 lecture transcripts annotated with still images from the video recording and the transcript of the post-interview. These texts comprised the raw data used to extract the themes or manifestations (upper part of Fig. 1) which follow below. The manifestations provided clues about the lecturer's knowledge domains (lower part of Fig. 1) and hence the source of his PCK.

Of the manifestations shown in Fig. 1, the following were found in our data: Representations, Curricular Saliency and Topic Specific Strategies. Others, such as assessment, were not found, due to the nature of the data. Manifestations not shown in Fig. 1 were also found, such as Illustrations, Explanations and Interaction with Students. These additional categories are included in the modified model, shown in Fig. 4. We included illustrations under Representations (after Shulman, 1986) but separated Explanations, which emerged as a large distinct category of its own in our data. This was hardly surprising, as our primary data source was the transcripts of five lectures, which would be expected to consist largely of explanations. We considered Representations to be an important separate category, due to the importance of representations and models in the teaching of organic chemistry (Treagust et al., 2003; Ladhams Zieba, 2004). The data revealed transformations of the lecturer's knowledge domains into the manifestations in the classroom, as shown in Fig. 1.
These are described below.

We use the term Curricular Saliency in the same way as Geddis and Wood (1997), viz., the teachers' understanding of the place of a topic in the curriculum and the purpose(s) in 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. We also introduced a new category that emerged strongly from the data, that of Interaction with Students, which included manifestations of the lecturer's understanding of students, fused with his understanding of the context, and included aspects, such as humour, pacing and awareness of students' prior knowledge and the need to provide constant encouragement. Another emerging category was that of beliefs about teaching, discussed below.

Table 2 Professor Mwaamba's CoRe

Big Ideas on organic chemistry	Explaining stability of carbocations	Ways of representing three-dimensional structures	Conceptualising stereochemistry
What you intend the students to learn about this idea?	Order of carbocation stability, tertiary > secondary > primary Stability of benzylic and allyllic carbocations Stability related to the ability to distribute charge through the molecule	Representing 3D structures in 2D Interpret different representations of the same molecule	To identify asymmetric carbon centres in different representations To identify the two possible configurations at the asymmetric carbon atoms
Why is it important for students to know this?	If they understand carbocation stability, they will understand a series of important reactions To have a principled approach to predicting reaction outcomes Underpins reactions and intermediates Opportunity to push curved arrows	So that they see the same molecule in different ways Provides the tools for writing mechanisms	In order to understand this difficult concept before it is integrated into other explanations Stereochemistry is basis of predicting the geometry of products of reactions For more than one chiral centre, diastereoisomers, meso compounds are possible Axes and planes of symmetry
What do you know (that you do not intend students to know yet)?	Radical reactions not covered Bulk of reactions involve carbocations	Limit to molecules with one or two chiral centres Following the text book sequentially will lose students	Detail of specific reactions e.g. asymmetric synthesis
Difficulties with teaching idea	Inability to visualise stereochemistry of intermediate Stability vs. reactivity	Common incorrect representations Difficulties in relating types of structures to each other Students do not like/do not know how to use the text book	Distinguishing between enantiomers, diastereoisomers and meso compounds Steric effects for reactions
Knowledge about students' thinking influencing teaching of this idea	Just because they passed first-year dimensions chemistry they do not know everything that was taught Students are not convinced that most reactions can be described in terms of 3 outcomes (addition, substitution and elimination) and two effects, namely, steric and electronic	Some students have difficulty in visualizing 3 dimensions	Understanding superposition and symmetry
Other factors that influence your teaching of this idea	Students do not necessarily have/put in the required time to understand Some students' primary language is not English Large lecture context Students' poor preparation from school and an understanding of the first year experience Understanding of where the course is leading		
Teaching procedures /strategy	Emphasise basic principles in introductory lectures Use large models Supplement with group tutorials and suitable examples Remind students that all reactions involve nucleophiles and electrophiles Develop concepts on the chalk board; use transparencies for summaries Allow time for copying structures		
Specific ways of ascertaining students' understanding or confusion around this idea	Use questions posed by students at tutorial sessions and lectures to get feedback. Examination questions based on tutorial tasks; also informed by questions students ask during these sessions. Tests and exams provide feedback of students' understanding of concepts.		

Explanations

As mentioned above, explanations tend to be a natural component of lectures, and therefore they constituted the largest proportion of coded items emerging from the data. The explanations focused on the Big Ideas (see CoRe above), using appropriate examples where necessary. As with Treagust *et al.* (2003), the majority of the explanations could be categorised as model-based, in that the lecturer described models as representations of chemical substances. For example, the ability to depict three-dimensional structures in two dimensions is a fundamental concept underlying the discipline. In the first lecture Professor Mwaamba drew the following structure on the blackboard (see Fig. 2) and having waited for students to copy it, he said:

> *So generally speaking when you draw an organic molecule we tend to use the zigzagged format to represent a carbon chain, … what you'll see when you make a model of this molecule, is that the plane is defined by the zigzag format, … for every carbon, two bonds are in the plane* [points to Fig. 2 on blackboard].

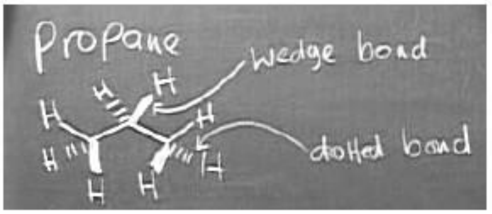

Fig. 2 Zigzag format to depict three-dimensional nature of propane.

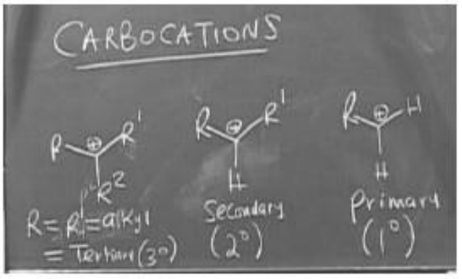

Fig. 3 Examples of carbocations.

... on each carbon there's a bond that projects above the plane and a bond which projects below the plane ... and that's how you write organic molecules. (KM, Lecture 1)

One of the Big Ideas of these introductory lectures (see CoRe above) is the notion of stability of carbocations. As the lectures unfolded, Professor Mwaamba spent considerable time exploring factors affecting the stability of carbocations. By lecture 4 he summarised thus, pointing to examples of tertiary, secondary and primary carbocations on the board (see Fig. 3):

Alright so let me come back to this now, so the one reason that explains this trend is that in a tertiary carbocations you have three alkyl groups, which through the inductive effect each of them is releasing electrons onto this central carbon here therefore quenching the thirst as it were a little bit, and of course this has fewer alkyl groups and the other one has only got one, okay, the inductive effect. (KM, Lecture 4)

Professor Mwaamba's lectures are peppered with signposts, helping to steer students between the various parts of the lecture, for example,

….. because I'm saying goodbye to carbocations, I'll never talk about it again [as a separate topic]. *Okay so in the remaining ten or so minutes, okay let me now switch to what is really, probably the single most ummm challenging thing to know, people, when it comes to organic chemistry and that's dealing with reactions.* (KM, Lecture 5)

This signpost signalled the end of the five lecture series on basic concepts. Professor Mwaamba planned to move into the substance of the course – organic reactions where he would employ the tools he was presenting. The signpost was cleverly phrased to signal both direction and importance.

Representations

Symbols, pattern recognition, multiple representations and application of principles are a central feature of organic chemistry. Different representations are used interchangeably and students who are unable to recognize these formats will easily become confused. Professor Mwaamba was aware of students' difficulties around drawing the correct representations, especially the curved arrows which are used to indicate the movement of pairs of electrons. In the post-interview he refers to the fact that students commit 'chemical heresy' by not applying the conventions related to the use of the arrows to explain the stability of certain intermediates in organic reactions, for example when drawing resonance structures. In the post-interview he said:

So one of the reasons for spending quite a long time on carbocations ... it's one of those situations which gives them an opportunity to push curly [curved] *arrows, ...when you go to allylic carbocations or benzylic carbocations, particularly benzylic, they're my favourite because they really get them to push those arrows ...* (KM, Post-interview).

During the interview he also commented on his feedback to students after a tutorial:

And I just take a sample of the groups and can almost extrapolate that must be going on with everyone else. And I go back and say, guys, it's scary…things I found out about some of you and where you are pushing curly [curved] *arrows and whatever, and the heresy that you were committing...* (KM, Post-interview).

He shared his belief that drawing each structure out in turn on the chalkboard is the most effective way to explain this process to the students, rather than using PowerPoint presentations. For example, he told students in lecture 5:

… but you must understand this, because when you going to decide to write a mechanism for any reaction, you have to appreciate that when you are forming a new bond or breaking an existing bond, electrons must come from what has electrons, to what does not have electrons. The first cut is the deepest [referring to the curved arrows and identification of the nucleophile and electrophile], *if you don't see a result you will never be able to write a mechanism and you will never be able to give me a product unless you get that first cut correct.* (KM, Lecture 5)

During the lectures, Professor Mwaamba stressed the importance of the correct representation of three- dimensional structures, making use of large models to illustrate his explanations where necessary. Models are so important to his programme that students are encouraged to buy small molecular modelling kits and are allowed to bring these into the examination hall. In this connection Professor Mwaamba remarked:

They cannot visualise…not only visualising, they don't want to use models. Even teaching stereochemistry, it's a difficult concept even for the lecturer to communicate. But they don't want to invest in models…you cannot think about stereochemistry, you've got to look at it in some expression through a model. So whether it's making a chair, what does antiperiplanar mean? On a piece of *paper it doesn't make much sense. You've got to visualise it. So I think the use of molecular models is a major stumbling block. They don't use molecular models. Even when we tell them in the exam, you can use molecular models, they don't even bring them.* (KM, Post-interview)

Interaction with students

Since Professor Mwaamba knew from experience that very few students ask questions during lectures, he relied on the input he received from the students who asked questions immediately after the lecture. He used this as an opportunity to gauge whether students had understood key concepts. Professor Mwaamba capitalised on his interaction with students after lectures by utilising the first part of the following lecture to address problematic issues. He regarded this as crucial to ensure that key concepts were understood, often using lecture time to do this in preference to moving on to new material. For example:

> *Okay I realised yesterday after lecture, just what problems some people had with the understanding, trying to explain why tertiary carbocations are more stable than secondary carbocations, which are in turn more stable than primary carbocations. Surprise, surprise I even got an e-mail from, from one of you … and then I realised that maybe this is a general problem.* (KM, Lecture 4)

Over the course of the five lectures there were frequent instances of interaction with students in the form of answering questions, though he seldom, if ever, asked students to answer questions he posed during the lecture. Despite this, students seemed at ease asking questions with in-depth exchanges taking place sometimes during the lecture, but mostly afterwards. Staying after the lecture was a deliberate strategy on his part to enable students to approach him with questions. The following excerpt shows an exchange that took place during the lecture.

Student:

> *Isn't stability defined as a state as something which preserves what it is, so then if you have a stable cation that exists, a cation that exists for a long period of time and secondly you donate things like a cation no longer exists so it is no longer stable.*

Lecturer:

> *Stabilisation I think, I mean I agree with you, but I think you need to look at the stabilisation more in terms of dispersion of a charge, it's this charge that's making the carbon uncomfortable okay, whether it's oxygen or whatever so you want something that can remove that burden a little bit okay in other words what it wants is a minus charge, a real minus charge, so anything that can give it something in the meantime will help to stabilise it.*(KM, Lecture 4)

Weekly tutorials presented a further opportunity to interact with students since he was always present at these sessions. Thus, he said:

> *Because in the lecture you rely on one or two good students who … have picked something up, … but a tutorial … you go around there and you engage with things … That's the only time you get feedback. … Without tutorials you would never see the average, or below average student, who don't even know how to ask a question. … But a tutorial, particularly with the weak students, and I try to proactively engage and say what's going on here and tell me what did you do here … that's the best feedback you actually get from them. (KM, Post-interview)*

Feedback on his course was obtained from students' questionnaires and an interview with the tutors as can be seen from the quotes below:

> *For the inorganic section the lecturers were very fast, organic section, the pace was fine. Prof KM takes time to explain like Dr X.... rather than flood you with concepts and leave you confused. CEM207* [a physical chemistry course] *was also much too fast. I failed. I couldn't keep up!* (Student 41)
>
> *Prof KM is a very good lecturer, in fact he is one of the best and he makes the course a lot easier and explains everything he expects of us to know.* (Student 115)
>
> *It seems when he does his lectures, he sort of knows where the students are having weaknesses or problems, and when he comes to the tutors he tries to fill in that particular gap, so much so that the lectures and the tutorials, really complete the whole story ... so that the students understand what is going on, and he also asks for feedback, to really make sure that if there is a problem in the tutorial he can actually go back in the lecture and try to address those particular issues.* (Tutor J)

However, not all the comments were entirely positive, in the words of one student:

> *In CEM207F* [physical chemistry] *almost everything was ok, but in CEM208S* [organic and inorganic chemistry] *I started experiencing some funny problems, i.e. coping with Prof KM, his style of lecturing, I sometimes find it hard to grasp what he is talking about during the lecture, I then had to see him afterwards which sometimes helped.* (Student 12)

Despite this student's difficulties with the lectures, he found Professor Mwaamba sufficiently approachable to solve his problems.

Curricular Saliency

Curricular Saliency lies at the heart of Professor Mwaamba's decisions to conceptualise the first five lectures of the course. He shared his reasoning enthusiastically both in interview and with the class as exemplified below:

> *So what you see is that the, the syllabus is broken up into a chunk of key topics that we will cover, okay, and as you'll see, the first four or so lectures is really revision ummm it's stereochemistry and a few other things that you've done in first year.* (KM, Lecture 1)

In the interview he justified the importance of a focus on carbocations as follows:

> *So in part it's because the bulk of the reactions we do, subsequently as the course progresses, involves carbocation intermediates. You can look at additions to the double bond. The simple mechanism is always the double bond is nucleophilic. Give electrons to*

The electrophile and because you can only join one bond to one of the carbons that share the double bond with the other one, it's going to become carbocation by implication. We look at electrophilic aromatics substitutions. There again on the benzene ring you're going to have a carbocation that you have to stabilise. (KM, Post-interview)

Professor Mwaamba's understanding of the chemistry curricula has both horizontal and vertical focus. His view is both long- and short-term – for example, in the interview he said:

It really is with that in mind that you know that a lot of what they are doing at honours level is synthesis, and a lot of stereochemical application, especially with making single enantiomers, which is a very big and important subject. (KM, Post interview)

And, also showing his interaction with colleagues:

Yes. In fact, there's very close liaison with the third year lecturers. ...we often tend to consult each other before we start lecturing, about the level, how far did I go? [with a particular topic]. *Because you know, some of the things actually that they* [the students] *pick up…and I emphasise this to them* [my colleagues] *some of the concepts are not formally covered in the lectures, but they crop up in the pracs.* (KM, Post interview)

Topic specific strategies

As can be seen from the CoRe, Table 2, Topic Specific Strategies are the product of an important set of thought processes and relate closely to the Big Ideas. They are an intrinsic part of a teacher's practice and often only observable in action. Professor Mwaamba used a number of these, such as large models, to illustrate the three-dimensional nature of the molecules being discussed, multiple representations of simple structures to signal the importance of being able to interpret these and allowing students sufficient time to copy structures and reactions from the chalkboard. He made frequent use of signposts to signal how the basic principles being discussed underpin the topics which would follow. Another strategy was the use of cleverly chosen problems both in the lectures and the tutorials, which clearly illustrated important principles.

Unpacking content knowledge

The ability to unpack content knowledge is central to the existence of PCK (Ball *et al.,* 2008) who consider the notion of unpacking as equivalent to decompression of content knowledge. In the context of mathematics education Ball *et al.* (2008) say:

"Teaching involves the use of decompressed mathematical knowledge that might be taught directly to students as they develop understanding. However, with students the goal is to develop fluency with compressed mathematical knowledge. In the end, learners should be able to use sophisticated mathematical ideas and procedures. Teachers, however, must hold unpacked mathematical knowledge because teaching involves making features of particular content visible to and learnable by students." (p. 400)

There is ample evidence of unpacking in Professor Mwaamba's lectures. As discussed above, the use of curved arrows in organic chemistry has attracted attention in the literature (e.g. Huddle, 2000; Ferguson and Bodner, 2008). Another place where he showed careful unpacking was in explaining the difference in the stability of the various types of carbocations as intermediates in organic reactions, as discussed previously.

"Keeping the Faith"- the importance of beliefs about teaching

As noted above, research has shown the connection between tertiary teachers' beliefs about teaching and practices, and consequently, their PCK. Professor Mwaamba was transparent about his beliefs both in class and in the interview – he made abundantly clear his philosophy of the subject matter and how to approach it in learning. Although he largely used model-based explanations (Treagust *et al.,* 2003) he employed several other types of explanations to expound more general principles, such as his underlying philosophy of learning organic chemistry. In particular he made frequent use of analogies. There were two major themes, one relating learning organic chemistry to learning to drive a car and another which speaks about keeping the faith. With regard to the first, he said,

… learning organic chemistry is like driving a car … organic chemistry reactions look very easy, but if you can really do them it's a different matter, … so initially, if you're driving, okay when you're changing your gears, you look down, you change your gear and then you look up; the more you do it, you would just drive … you know you'll be comfortable and it becomes part of your nature. (KM, Lecture 3)

Linked to his beliefs about teaching was an understanding of the importance of affective factors in students' success such as the need to encourage students. When he talked about keeping the faith, he was referring to the fact that while organic chemistry appears to consist of hundreds of different reactions, they can all be classified into a few categories. He reassured the students:

The other thing about organic chemistry by the way, is faith,… faith that you have to exercise about organic chemistry and that's to believe that it doesn't matter the chemical structure that's in front of you, it doesn't matter the complexity, it doesn't matter the size, as long as you know the functional groups, then of course that's a faith, just keep your faith, don't be scared by the structure. (KM, Lecture 3)

He advised students who are faced with what looks like a mountain of information to learn:

So unless you master the basic principles you will struggle to capture the information, and organic chemistry appears to be like this vast body of knowledge of different reactions, different structures but in fact we deal with very simple things as you'll see, as long as you understand those fundamentals, if you don't understand the fundamentals it's going to be difficult. (KM, Lecture 3)

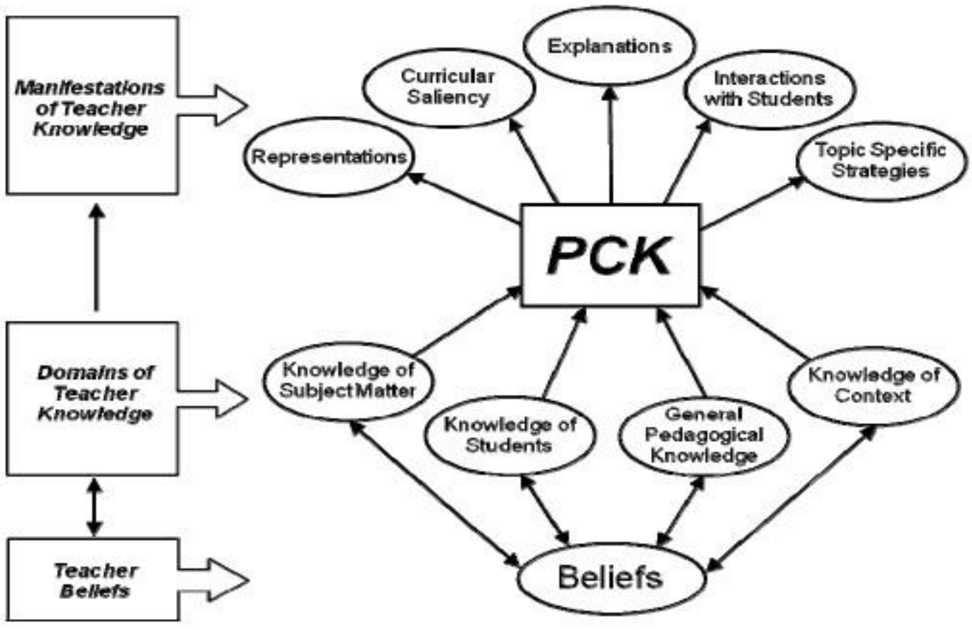

Fig. 4 Modified model for PCK.

Discussion and conclusion

In this paper we have provided insight into the practice of a highly accomplished tertiary teacher with a view to capturing and portraying his PCK. As the themes above reveal, the manifestations of his practice in the classroom are well described by the model developed by Rollnick *et al.* (2008) and can be traced back to the domains of knowledge that produce them.

The material for the lectures under study in this paper produced three Big Ideas.

1. The stability of carbocations depends on the nature of the species attached to the electrophilic centre.
2. Three-dimensional structures of organic compounds can be represented in multiple formats, each of which highlights specific characteristics of the molecule.
3. Stereochemistry has a profound effect on the nature of the product in an organic reaction.

For Professor Mwaamba these three Big Ideas formed a framework on which he planned to build the remainder of his 7-week course, in line with the findings of Ferguson and Bodner (2008). He thus devoted a whole week of instruction to laying a foundation to enable his students to make sense of what would otherwise be a mass of information enveloping them in the weeks to come. A central element of his presentation was the wide variety of analogies, representations and explanations he employs to uncover these ideas. The establishment of his framework is supported by strong beliefs he holds about the nature of the discipline, something he articulates frequently in his lectures, tutor briefing sessions and later, in an interview with us.

The themes emerging from the analysis of data were constructed around the model of PCK of Rollnick *et al.* (2008). However, the strong emergence of the centrality of beliefs about teaching suggested an important shortcoming of the model in this regard. Hence we suggest a modification to the original model to acknowledge the importance of teacher beliefs about teaching and their influence on the teacher's knowledge domains and *vice versa,* and, consequently, what is enacted in the classroom. Other minor modifications were made to the manifestations of the teacher's practice in the classroom. The importance of Explanations in the context of the lecture situation led us to include this as a separate category. On the other end of the spectrum, 'Interaction with Students' was included, as it is a rare occurrence in lecture situations, but nevertheless was a significant element in the data. Professor Mwaamba made a deliberate effort to remain behind after class to answer student questions, and was always present at the tutorial sessions. The literature cited above highlights the centrality of beliefs in the practice of teachers at all levels and we believe that this modification of the model would even be appropriate at the school level.

Fig. 4 shows the modified model of PCK, with Beliefs About Teaching as an underpinning factor influencing the teacher's knowledge domains and *vice versa,* which in turn integrate to produce PCK, which is visible through manifestations in the classroom. The double-headed arrows show the two-way interaction between the teacher's knowledge domains and beliefs.

For example, Curricular Saliency is manifested in Professor Mwaamba's class through the following quotation on Newman projections:

Okay I'm going to skip the Newman projections, I think that this is something that you do in your first year, ummm particularly the Newman projection ... which become very important in a class of reactions we call elimination reactions, which we'll do ummm later on in this course, and I'll encourage you to revise your Newman projections because you will not be able to appreciate elimination reactions without being able to represent your molecule in the Newman projection. (KM, Lecture 1)

The quotation above demonstrates the links between manifestations and domains of teacher knowledge and beliefs about teaching. Professor Mwaamba emphasised to the class the importance of Newman projections for future work (Curricular Saliency) while at the same time making links between various sub-topics in the course (Knowledge of Subject Matter) and his strong emphasis on its importance in the curriculum (Beliefs).

The analysis of the introductory five lectures thus provides important insight into the way Professor Mwaamba unpacked his content knowledge for teaching. Underlying the instruction is his belief in the importance of understanding basic principles in order to master organic chemistry. This belief arises from his very strong background in organic chemistry as a discipline, his understanding of students and their context, which emerged many times in the data, and finally, the general pedagogical knowledge that he has developed through several years of practice, leading to decisions, such as, not to use PowerPoint presentations in his lectures. The manifestations of his knowledge in the class allow us to make inferences about how his knowledge domains interact to produce these manifestations. Researchers, such as Talanquer (2007), may find his use of anthropomorphisms problematic, but our view is that the gains in student understanding and motivation more than compensate for the possible misconceptions that may arise from their use. Findings, such as those from this case study, are important to assist novice lecturers, as artefacts such as the CoRe are invaluable in making the tacit knowledge of experienced lecturers explicit.

To produce the representations and analogies Professor Mwaamba combined his rich content knowledge with his general pedagogical knowledge of the working of models he has used in the past. An important component here is his awareness of the students' prior knowledge and the educational context. The models he uses for teaching would be very different from the type of representations he would use of multiple representations in the classroom is essential to convey meaning to undergraduate students. Hence, the nature of the content produced for teaching purposes differs substantially from that used for chemistry research.

Similarly, his explanations are a product of his content knowledge and his understanding of the students he is teaching – their linguistic competence and their background knowledge. Finally, he learns from his interactions with the students, adding to his knowledge of students and context, thus improving his ability to make the subject matter more meaningful. His extraction of the Big Ideas for these introductory lectures shows an appreciation of the curriculum saliency of these ideas, and the importance of exposing students at an early stage to gate-keeping concepts. His approach may also assist students to make the transition from being dualistic to relativistic thinkers, an important attribute in a subject like organic chemistry where multiple synthetic pathways to the required product are possible (Grove and Bretz, 2010). Moreover, there is evidence of the effectiveness of his teaching, as shown not only by improvement in student performance (Davidowitz and Rollnick, 2005), but also in comments on his teaching by both students and post graduate tutors.

It is rare to obtain an opportunity to study someone with the ability to extract knowledge for teaching in such a meaningful way. Knowledge obtained in such a process is useful to novice lecturers starting to teach at the undergraduate level.

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Notes and References

[1]The South African University three year bachelor's degree is followed by a pre masters one year honours degree.

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