> The various phases did not work out according to plan, due to the large number of absent students. I adjusted my planning on the spot, which did not cause any further problems. It did lead to a chaotic beginning of the lesson, however, and I started the lesson later than planned. I had no part in this, I hadn't been informed by the school management.
>
> (Cindy; M3, reflection practice, enactment practice, micro-politics –)

The observed personal factors appear in various frequencies and combinations. For example, Alice's texts contain by far the most positive self-efficacy indications. Texts of Alice and Ben showed positive emotions more frequently than those of Cindy and Debbie.

> One of the groups mentioned in their presentation: "Instructive and very nice to do. We have learned a lot and had a lot of fun." Isn't it just super if that is the case?
>
> (Alice; M2, M3, reflection practice, emotion +)
>
> After having read the first part together, I broke the students into groups. Last time dividing the students was hard. That is why I first explained the assignment clearly. I used a 'group maker' on the Internet to make student groups for the assignment: they got to work within 1 min. That went fabulous! The students noticed their groups and started working immediately. Meanwhile I had time to write things on the blackboard.
>
> (Ben; M3, reflection practice, enactment practice, efficacy +, emotion +)

Differential Features of Student Teachers' pPCK Development

We were able to typify the student chemistry teachers' pPCK development in terms of the three models above, using the following combinations of differential aspects: the reflection-enactment ratio and appearance of pathways/loops rather than single steps (for Clarke and Hollingsworth's model of professional growth), co-occurrence and chemistry content (for Magnusson's components), and the presence and relative frequencies of positive and negative perceptions of personal factors—especially emotion (for Hong's model).

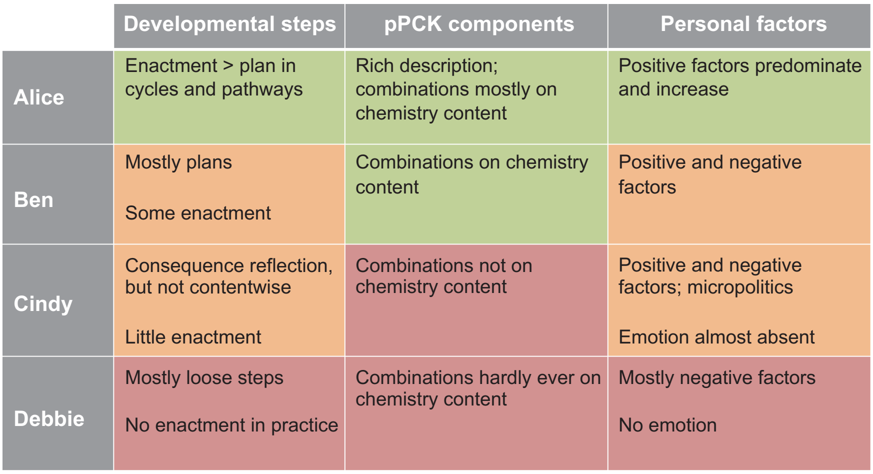
The colours in Table 9.5 indicate the resulting typification of the student teachers' pPCK development, with green representing significant development, orange some development and purple little/no development.

Discussion

Our analysis using three analytical frameworks allowed us to effectively characterise individual differences within student chemistry teachers' pPCK development. The characterisation contained some surprising aspects that we had not been able to reveal before. One of these is the influence the amount of chemistry content has on student teachers' pedagogical reasoning (see pPCK components, Table 9.5).

Moreover, when examining the student teachers' developmental steps (see Table 9.5), we see a lack of subsequent pedagogical cycles, where only a reflec-

Table 9.5 Typification of student teachers' pPCK development



	Developmental steps	pPCK components	Personal factors
Alice	Enactment > plan in cycles and pathways	Rich description; combinations mostly on chemistry content	Positive factors predominate and increase
Ben	Mostly plans Some enactment	Combinations on chemistry content	Positive and negative factors
Cindy	Consequence reflection, but not contentwise Little enactment	Combinations not on chemistry content	Positive and negative factors; micropolitics Emotion almost absent
Debbie	Mostly loose steps No enactment in practice	Combinations hardly ever on chemistry content	Mostly negative factors No emotion

tion step was observed without any follow-up enactment step or just a conception of a plan. This observation suggests that three of the student chemistry teachers were tending to operate at the stage of planning actions based on their reflections rather than actually following up and enacting those plans (as with Alice). On the other hand, this finding can be seen as evidence that the mechanism we described for enhancing pPCK via ePCK (see Stepwise development of pPCK in the Theoretical Framework) can be supported by the applied assignments (i.e., Lesson Preparation Form, Lesson Evaluation Form and Lesson Reflection Form). How exactly the complexity or depth of the student teachers' reflections and the personal factors account (as amplifiers and filters, see Table 9.5) for the remaining individual differences in student teachers pPCK is an interesting subject for future research—so too is the relationship of pPCK development with the student teachers' (evolving) stages of cognitive development (see the Introduction). We also look forward to clarifying the role and position of extra-personal factors (i.e., aspects of the Learning Context in the RCM) as further research, which we look forward to. Finally, it would be interesting to relate the above findings to the four challenges connected to a one-year teacher training programme as mentioned in the introduction.

Despite many unanswered and/or new questions arising, we think our findings so far can inform new ways of tailored scaffolding of (student) science teachers' pPCK development. On a more theoretical level, our method allowed for a cross-sectional analysis combining three models connected to PCK development. The extreme cases in Table 9.5 show an interesting co-occurrence of differential features in terms of the respective models. This finding suggests a deeper relationship, which is worthwhile studying in more depth. Our typification of student science teachers' pPCK development was supported by their self-portrayals as a teacher, by means of metaphors elicited from them at the end of the teaching methodology course, independently of our study (cf. Saban, Kocbeker, & Saban, 2007). The student teachers' self-constructed metaphors were *silversmith*, *encyclopaedia*, *puppy* and *new-born deer* for Alice, Ben, Cindy and Debbie, respectively. These metaphors support the view that the student science teachers' personal knowledge and beliefs (including PCK) are related to perceptions of their professional role, as in Hong's (2002) study. As a consequence, one can imagine additional ways to stimulate PCK development by incorporating deeper levels of reflection that implicate the student science teachers' sense of mission in their work, and their perceptions of professional identity (c.f., CoRe Reflection; Korthagen & Vasalos, 2005).

A limitation of the method we used in our study is its sensitivity to incomplete data sources, which explains why the data concerning the remaining three student teachers had to be excluded from our analysis. Another limitation is the absence of method triangulation through our decision to use only authentic sources. The incorporation of two lesson series in the data collection (data triangulation) was meant to (partly) compensate for this shortcoming.

The Lorentz workshop in December 2016 followed up on the work of the PCK Summit held in Colorado Springs, 2012. Whereas the Colorado Springs Summit focused on the concept of PCK resulting in a consensus model, known as the Consensus Model (CM), at the Lorentz Center meeting we focused on the instruments used in PCK studies, the data that were collected with these instruments, and the procedures used to infer PCK from these data. Strengths and weaknesses of different instruments and procedures of PCK data collection and analysis were discussed leading to a refinement of the CM stemming from the First (1st) PCK Summit. For us personally, the fruitful discussions with fellow PCK investigators led to interesting reflections on the study discussed in this chapter, in particular about the value of student teachers' evaluations immediately following execution of a lesson. The evaluation forms (Table 9.2) turned out to be the richest information source for analysing the student science teachers' pPCK development. The apparent importance of this evaluation moment led us to extend the corresponding form, most importantly presenting the lesson as a learning opportunity for the student science teachers with a question regarding their most important learning experience, and a question referring to meaningful moments for the learning of their students, thus stimulating evaluation of the lesson in a more comprehensive way.

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Chapter 10

Investigating Practising Science Teachers' pPCK and ePCK Development as a Result of Collaborative CoRe Design

Jared Carpendale and Anne Hume

Abstract This chapter reports on one case from a cross-case study exploring how collaborative Content Representation (CoRe) design can be used to develop science teachers' personal and enacted pedagogical content knowledge (pPCK and ePCK). These conceptualisations of PCK are components of the Refined Consensus Model (RCM) of PCK (see Chap. 2 of this book). The cross-case study focused on three cases involving science teachers with a limited physics background. Each case study teacher's initial pPCK and ePCK for teaching an *Electricity and Magnetism* topic to a class of 14-year-old New Zealand students were determined prior to the CoRe design intervention using data from interviews and classroom observations. These teachers then engaged in a collaborative CoRe design workshop with other science teachers and experienced physics teachers, where individuals shared their PCK with the whole group and together developed an agreed-upon collective PCK (cPCK) for teaching this topic. The case teachers were subsequently observed teaching a second class (similar age and ability students) and re-interviewed about their pPCK and ePCK development as a result of collaborative CoRe design. The findings from the reported case study reveal that the intervention had a discernible impact on the teacher's pPCK and ePCK, notably: deeper understanding of physics concepts; new ways to represent concepts to students; and greater awareness and consideration of what students may be thinking in their lessons.

Introduction

The study presented in this chapter was part of research conducted for a Doctor of Philosophy degree, which built on the previous work investigating ways to enhance and monitor science teachers' pedagogical content knowledge (PCK) development using collaborative Content Representation (CoRe) design. The conceptualisation

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of PCK portrayed in the Refined Consensus Model (RCM) of PCK, in Chap. 2 of this book, informs this study into the development of science teachers' personal PCK (pPCK) and enacted PCK (ePCK) for teaching an *Electricity and Magnetism* topic to 14-year-old students in New Zealand after taking part in collaborative CoRe design. The rationale for using the RCM to inform this study was twofold: first, the model incorporated ideas from previous PCK conceptualisations and frameworks, along with opinions of well-respected members of the PCK research community; second, it provided a useful framework for viewing and researching the knowledge exchanges that occurred between a group of teachers working collaboratively, and how those exchanges may influence their individual knowledge and practise.

Two research questions from the Doctor of Philosophy project form the focus of this chapter. They are:

1. In the New Zealand context, what does the personal and enacted pedagogical content knowledge (pPCK and ePCK) of junior science teachers with a limited physics background look like for teaching *Electricity and Magnetism* to 14-year-old students?
2. What impact does collaborative CoRe design have on the pPCK and ePCK development of junior science teachers with a limited physics background for the topic of *Electricity and Magnetism* for 14-year-old students in New Zealand, when working collaboratively with experienced physics and junior science teachers?

Context

Data collection took place in a large boys' secondary school (approximately 2250 students, 13–18 years old) in New Zealand. The science department had 22 science teachers, nine of whom took part in this study. The junior science programme (first two years at secondary school) encompasses the disciplines of physics, chemistry, biology, and Earth science, while in the senior school (last two years at secondary school) these disciplines become separate programmes. All science teachers at the school are required to teach junior science, irrespective of their particular subject specialisation. Thus, it is very common for some teachers to be teaching topics in junior science where they have a limited background, especially in terms of content knowledge.

The researcher's (1st author) initial contact with the school, to introduce the study and identify potential participants, occurred in a meeting between the researcher and the school principal. During discussions about the intentions of the study and the roles of participants, the principal began singling out potential participants with respect to their attributes and how these aligned with various roles within the project. Nine teachers were identified and placed into three groups (three teachers in each). Whilst all nine teachers took part in the study, the Group One teachers were the primary focus and each teacher represented an individual case for investigating pPCK and ePCK development.

Details of the membership of each group are provided below, including key attributes and roles within the project. A summary of the teachers' personal background information is also provided in Table 10.1.

Teachers were assigned to the three groups:

Group One: Practising science teachers with a limited physics background. The principal identified these participants as teachers who would benefit from their PCK being strengthened for the *Electricity and Magnetism* topic. When approached to take part in the study, these teachers were enthusiastic about developing their PCK for this topic and willing to have their PCK development as the focus of the research.
Group Two: Experienced junior science teachers who do not have a strong background in physics. The principal regarded these teachers as effective teachers for junior science, but they were not physics specialist teachers. The principal and researcher felt the presence of these teachers would bring useful pedagogical insights into the CoRe design process, thus contributing to the PCK development of the focus teachers.
Group Three: Experienced physics teachers. The principal endorsed these teachers as effective junior science and physics teachers and felt these teachers would be able to tap into their extensive professional knowledge and experience to support and enhance the professional development of the whole group.

Table 10.1 Background information of participating teachers showing group memberships, names (pseudonyms), subject specialisations, years at the study school, and total years of teaching

Group	Name (pseudonym)	Subject specialisation(s)	Years at study school	Years of teaching (total career)
1	Tony	Biology	6	6
	David	Horticulture and Agriculture	20+	29
	Alan	Physical Education	3	10
2	Harry	Biology	20+	35
	Kate	Chemistry	8	8
	Lucas	Biology and Horticulture	7	10
3	Nick	Physics and Electronics	17	17
	William	Physics and Electronics	15+	40+
	Chris	Physics and Electronics	15	35

Study Design and Literature Review

An interpretivist-based methodology (Guba & Lincoln, 1989) was used in this study as it sought to develop theories and explanations that are contextually bound (Cohen, Manion, & Morrison, 2011; Treagust, Won, & Duit, 2014). The methodology at its heart had a multiple-case study approach (Yin, 2014), which utilised qualitative research methods. Each Group One teacher represented an individual case, which was developed separately. Cross-case comparisons followed and conclusions were drawn.

As stated earlier, the RCM presented in Chap. 2 of this book was used as a conceptual framework to inform this study (see Fig. 10.1). The strength of this model lies in the incorporation of multiple researchers' ideas and conceptualisations of PCK in science teacher education, its identification of the unique and personal nature of PCK (via pPCK), and its acknowledgement of the multiple sources and influences on a science teacher's personal professional knowledge for teaching particular content to particular students. By introducing enacted PCK (ePCK), as a form of PCK firmly placed within the classroom context, the model shows how science teachers access and utilise their pPCK when they are planning, teaching, and reflecting.

The study presented here focuses on the knowledge exchanges occurring between different layers of the RCM, represented in the model above by the double-headed arrows. Of special interest is the impact these exchanges have on the knowledge transitions that occur for individual science teachers as they transform collective PCK

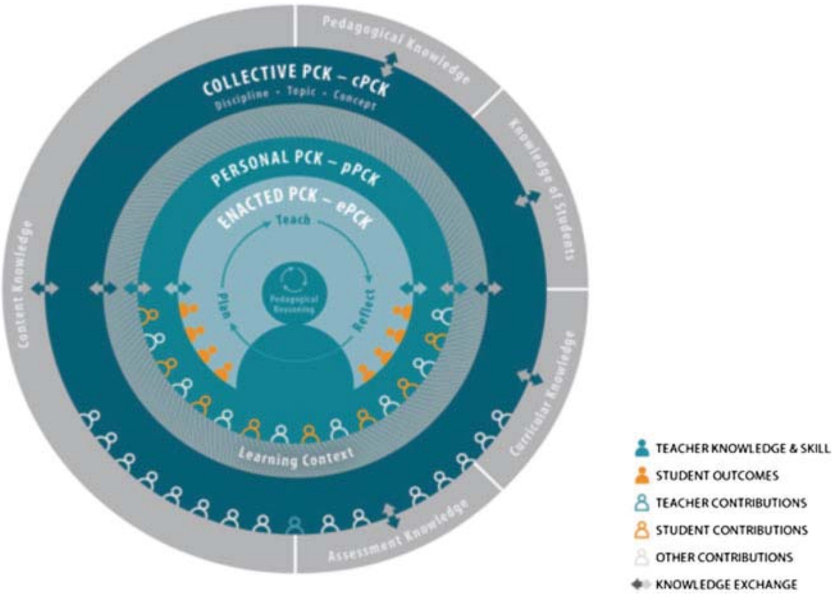

Fig. 10.1 Refined consensus model (RCM) of pedagogical content knowledge (PCK) (see Chap. 2)

(cPCK) to pPCK and ePCK. These transformations are influenced by the moderating effects of the learning context and the amplifying and/or filtering effects of teachers' attitudes and beliefs. In the RCM, ePCK encompasses a cycle of planning, teaching, and reflecting. However, while elements of teachers' planning and reflecting were revealed in this study during data gathering (e.g., discussions about the CoRe for planning after taking part in the workshops and asking teachers to reflect on lessons, and how that might influence future lessons in final interviews), the primary focus when exploring ePCK was on teaching science and the teachers' classroom actions. This focus was necessary to keep the project manageable for a doctoral study.

As a PCK form, cPCK is described in Chap. 2 as the knowledge shared by different science educators, which can be documented, shared, and understood by other teachers in a broader community. Formal documented and/or published cPCK provides a guide of canonical best-practice professional and pedagogical information for teaching particular science content to particular students, in a particular "learning context" as portrayed in the RCM (see Fig. 10.1). A less formal articulation of information and knowledge, such as that synthesised within a CoRe document by a group of science teachers working collaboratively, is potentially a useful practice-based conceptualisation of cPCK for professional learning and research purposes in science teacher education—the CoRe produced represents "localised" cPCK with respect to a particular learning context, which may/may not be in contrast with documented or canonical cPCK.

CoRes were originally devised in a template form (see Table 10.2 on the following page) in an effort to capture a holistic picture of the PCK possessed by a group of expert science teachers for a particular topic (Loughran, Berry, & Mulhall, 2006). These original CoRes proved to be valuable pedagogical tools for teacher educators because they unpack PCK in explicit ways that reveal the key ideas to be learned by students, their prior knowledge, learning difficulties and likely misconceptions, suitable instructional approaches and strategies, and appropriate assessment. Like any innovation in education, others took this original idea and gave it new uses. For example, some science teacher educators challenged their pre-service teachers or early-career teachers to create their own CoRes (e.g. Hume, 2010; Hume & Berry, 2011, 2013) using a CoRe template (see Table 10.2) to illustrate aspects of their emerging and developing pPCK for science teaching.

When filling in a CoRe template, either as an individual teacher (to represent their pPCK) or a group of teachers working collaboratively (to represent their localised cPCK), decisions must be made about what they believe are the big ideas of a science topic to be learned by students. Then a series of pedagogical prompts and questions, within the template, serve to interrogate and draw out teachers' pedagogical reasoning behind their choice of actions to help students develop an understanding of the big science ideas. When addressing these prompts and questions as they complete the CoRe, "teachers access canonical knowledge about their topic and organise it in a way that will be useful for planning instruction" (Gess-Newsome, 2015, p. 33). The resultant CoRe, which can be viewed as a manifestation of cPCK, can also create a platform for initiating and/or strengthening individual science teachers' pPCK development for each of the participating teachers. CoRe design has been shown to

Table 10.2 Template for a Content Representation (CoRe) (adapted from Loughran et al., 2006, p. 28)

Pedagogical questions/prompts	Big idea 1	Big idea 2	Big idea 3
What you intend the students to learn about this idea?			
Why is it important for the students to know this?			
What else you know about this idea (that you do not intend students to know yet)?			
Difficulties connected with teaching this idea			
Knowledge about student thinking which influences teaching about this idea			
Other factors that influence your teaching of this idea			
Teaching procedures (and particular reasons for using these to engage with this idea)			
Ways of ascertaining student understanding or confusion about the idea			

have positive effects on pPCK development of teachers (pre-service, early-career, and out-of-field), especially when done in collaboration with experienced mentor teachers or content experts (e.g., Hume, 2015; Hume & Berry, 2011, 2013; Hume, Eames, Williams, & Lockley, 2013; Nilsson & Loughran, 2012).

Building on the previous research that explored collaborative CoRe design for developing PCK in science, this study investigated the development of the Group One teachers' pPCK and ePCK after working collaboratively with six other science colleagues from their school to develop a CoRe. The resultant CoRe represents the cPCK of all nine participants who teach within the Learning Context of Year 10 *Electricity and Magnetism* at their school. To mitigate the identified issue of needing support from people outside of the school environment (Hume et al., 2013), pedagogical and content expertise was sourced within the school from current teaching staff (i.e., other participants detailed in Table 10.1).

This study involved three distinct phases:

Phase 1: Generating a baseline understanding of Group One teachers' pPCK and ePCK.

Group One teachers were interviewed to explore aspects of their initial pPCK about teaching *Electricity and Magnetism* to 14-year-old students and then observed teaching this topic to determine their initial ePCK.

Phase 2: CoRe design workshops for professional learning.

All nine teachers participated in two CoRe design workshops. The first workshop was an introduction to CoRe design, where participants shared experience and expertise while collaboratively creating a CoRe for teaching *The Nature of Science and Scientific Inquiry* topic to 14-year-old students. In the second workshop, all nine teachers worked collaboratively again to design another CoRe for the *Electricity and Magnetism* topic for 14-year-old students.

Phase 3: Evaluating the influence of CoRe design.
Guided by the collaborative *Electricity and Magnetism* CoRe, the Group One teachers planned and taught this topic again to a different class of similar ages and ability to the class in Phase 1 of the study. After CoRe design and prior to re-teaching this topic again, Group One teachers were interviewed about their self-perceived pPCK development and their experiences with collaborative CoRe design. They were then observed teaching this unit to determine their ePCK post-CoRe design. After teaching the topic again, they were interviewed one final time about changes to their professional knowledge and what they did differently in the classroom. After the CoRe design workshops, Group Two and Three teachers were interviewed about how collaborative CoRe design could enhance pPCK and their experiences with collaborative CoRe design.

Data Collection

Table 10.3 summarises the data that was collected during the study.

Detailed information is now provided about each of the data collection methods and tools.

Table 10.3 Data collected during this study

Phase	Data collected
1	Audio-recorded, semi-structured individual interviews with Group One teachers about teaching science and *Electricity and Magnetism* topic to 14-year-old students
	Video-recordings of Group One teachers' classroom lessons when teaching *Electricity and Magnetism* topic (Class 1)
2	Audio-recording and observations using field notes of teachers participating in *The Nature of Science and Scientific Inquiry* CoRe design workshop
	Audio-recording and observations using field notes of teachers participating in the *Electricity and Magnetism* CoRe design workshop
3	Audio-recorded, semi-structured individual interviews with Group One teachers exploring their perceptions of CoRe design and its effectiveness for enhancing PCK
	Audio-recorded, semi-structured focus group interviews with Group Two and Three teachers exploring their perceptions of CoRe design and to judge its effectiveness for enhancing PCK
	Video-recording of Group One teachers' classroom lessons when teaching *Electricity and Magnetism* (Class 2)
	Audio-recorded, semi-structured interviews with Group One teachers to explore how they think their pPCK and ePCK had developed as a result of collaborative CoRe design

Interviews

As each of the Group One teachers represented a separate case for this study, each semi-structured interview was individual. In contrast, when Group Two and Three teachers were interviewed, a semi-structured focus group format was utilised to increase time efficiency and to allow for rich data as multiple people can be interviewed at once, which can encourage participants to build on each other's ideas (Flick, 2014; Patton, 2014; Watts & Ebbutt, 1987). The semi-structured style was employed using a set of predetermined guiding questions, with the flexibility to explore responses further or seek clarification (Bogdan & Biklen, 2007; Kvale, 1996). The same guiding questions were used for all interviews, except for the final interviews as only Group One teachers were involved.

For the Group One interviews in Phase 1, the RCM, along with previous PCK models such as the work of Magnusson, Krajcik, and Borko (1999) and Gess-Newsome (2015), were used to develop interview questions about researchable entities of pPCK. Questions were asked about participants' knowledge of curricula, knowledge of students understanding in science, knowledge of instructional strategies, and knowledge of assessment strategies.

After taking part in collaborative CoRe design, all participants were questioned about their experiences with the process, including what they saw as being valuable and what limitations they faced. They were also asked about how the process could develop pPCK for science teaching and how their own pPCK may have been affected. For their final interview, after teaching their second class in the last phase of the study, Group One teachers were questioned about their self-perceived pPCK and ePCK development and any causal links with the content and/or process of collaborative CoRe design.

Observing Lessons

The complexity of capturing science teacher's professional knowledge meant that an approach using both interviews and observations was advisable. The approach used in this study reflects information and guidance found in the literature for capturing PCK and ensuring conclusions are trustworthy (e.g., Bryman, 2016; Henze & van Driel, 2015). However, during data collection, the principal researcher (1st author) was teaching full time, so personally attending and observing an adequate amount of lessons for a dependable and trustworthy analysis were not feasible. After discussion within the supervisory team, the pragmatic decision was made to video-recorded lessons.

Most of the *Electricity and Magnetism* lessons taught by the Group One teachers were video recorded and available for observing by the researcher later. Lessons were one-hour duration. Four lessons from each teacher were chosen for analysis pre-CoRe design and another four post-CoRe design. Those chosen for both pre-

CoRe and post-CoRe design included the introductory lesson, a practical lesson, and two others, which reflected discussions the teacher had during the workshop. These lessons were analysed using an observation protocol, which is discussed later in this chapter.

Facilitating the CoRe Design Workshops

Taking part in collaborative CoRe design can be a challenging experience (Hume & Berry, 2011, 2013), so it was decided that the first workshop would be a pilot/trial exercise for the participating teachers. To facilitate the development of the participants' capabilities in CoRe design, a *Nature of Science and Scientific Inquiry* CoRe was developed in the first workshop since elements of its design could be connected to an existing science topic at the study school. Thus, participants were likely to have varying levels of experience and understanding of teaching related science concepts. As further support, participants were asked to read an article about the nature of science and scientific inquiry (see Lederman, Antink, & Bartos, 2014a) before the workshop. This initial workshop, facilitated by the 2nd author, started with an introduction to the construct of PCK, the use of CoRes in capturing PCK, and the purpose of CoRe design in this study. Further discussions and works around the nature of science and scientific inquiry resulted in participants establishing the following key understandings: the nature of science refers to *knowledge* in science, while scientific inquiry refers to *practices* in science.

After the first hour of discussion, the teachers were asked to complete the views about scientific inquiry (VASI) questionnaire (see Lederman et al., 2014b) to explore their views on the nature of scientific inquiry. Responses were then discussed, after which the teachers were assigned to one of three Working Groups—each comprised three members, one from Group One, one from Group Two and one from Group Three, as shown in Table 10.4 below.

In these Working Groups, the teachers discussed what they understood to be key concepts and skills underpinning the nature of science and scientific inquiry, writing each on separate pieces of card. The facilitator promoted a whole group discussion where all the ideas were shared, collated, and themes identified. The key themes were recorded on the whiteboard and used by the whole group to develop big ideas (in the form of propositional statements) for the topic. These big ideas formed the basis upon which the teachers could begin working in their Working Groups to complete

Table 10.4 Working Group memberships for CoRe design workshops

Original study group	Working Group One	Working Group Two	Working Group Three
Group One	Alan	Tony	David
Group Two	Lucas	Harry	Kate
Group Three	Chris	Nick	William

a CoRe. As they worked, the facilitator moved amongst the groups and interacted with each group in turn as they addressed the pedagogical prompts within the CoRe template. In the final stage of the three-hour workshop, each Working Group shared and collated their outcomes as a single partially completed CoRe, which represented the groups' cPCK on the topic.

One week later, the teachers took part in another CoRe design workshop, this time for the *Electricity and Magnetism* topic (in the same Working Groups). Since they had recent experience working with CoRe design, introductory discussions were brief. The workshop facilitator recapped key PCK ideas and then addressed and/or revisited four CoRe-related points on the whiteboard:

1. Possible resources—what resources would be useful for this particular exercise?
2. Brainstorm concepts and skills—the first step in CoRe design for any topic.
3. Use of these concepts/skills to identify themes from which "big ideas" are developed.
4. Complete CoRe—for sharing of professional knowledge (stay in groups to create three separate CoRes, or work as one big group on one shared CoRe?)

This introductory discussion lasted 10 min, and then teachers commenced work on identifying key concepts and skills for *Electricity and Magnetism*. Resources, which the teachers identified and used to inform their decisions, included a copy of the New Zealand Curriculum (NZC) document (Ministry of Education, 2007) and NCEA assessment information for the Year 11 topic *Electricity and Magnetism* (NZQA, 2010). After 30 min, all identified concepts and skills were shared in the larger group where participants discussed the suitability of each particular science concept/skill for teaching to 14-year-old students in turn and collectively decided on its inclusion or not. Using these selected concepts/skills, the individual groups then worked to identify big ideas, which were to be written as propositional statements. Again, the information from the groups was shared, and seven big ideas were generated from this collective information. In the interest of time, the groups decided to select two or three big ideas per Working Group to address, and afterwards, the work of each Working Group was combined with that of others to produce a completed CoRe. This workshop was three hours in duration.

During both CoRe design workshops, all discussions were audio-recorded. Recording discussions was achieved by having digital recorders placed where each group was working—the recorders also captured whole group discussions. In addition, throughout the workshops, the first researcher also took detailed field notes about interactions that took place. At the end of each workshop, all CoRe materials were submitted to the researcher who collated the materials into one CoRe document. This single CoRe was then sent back to all participants for verification purposes.

Data Analysis

To determine the pPCK and ePCK of each Group One teacher, and any possible development, the data were analysed thematically via a deductive approach (using the RCM primarily to inform the analytical framework) and an inductive approach (by identifying any emergent themes from the data pertinent to the research objectives). To construct the analytical framework for analysing pPCK and ePCK, key parameters of the RCM needed to be identified. For example, these analytical parameters for analysing pPCK from interviews were the teachers' knowledge of curriculum; students' understanding and learning; topic-specific instructional strategies; and, assessment strategies.

To analyse the Group One teachers' ePCK from the video-recorded lessons, an observational protocol was developed that included a rubric identifying three components of ePCK along with 10 quality indicators. Each quality indicator was assessed as being either limited, basic, proficient, or advanced. The design of this rubric was based on: the previous PCK research (e.g., Alonzo, Kobarg, & Seidel, 2012; Gardner & Gess-Newsome, 2011; Lee, Brown, Luft, & Roehrig, 2007; Park, Jang, Chen, & Jung, 2011); the pedagogical prompts from the CoRe (i.e. Loughran et al., 2006); and, outcomes of discussions from the second PCK Summit about generating a "grand rubric" (reported in detail in Chap. 12 of this book).

The components and their quality indicators (and abbreviations) were:

Subject Matter Knowledge

- Appropriateness of the concepts (appropriateness)
- Scientific accuracy of the explanation of the concepts (accuracy)
- Links and/or connections made to other concepts (concept links)
- Links made (implicit or explicit) to the nature of science or scientific inquiry (NoS/SI links)

Knowledge of Student Understanding

- Recognition of possible prior knowledge, difficult concepts, or misconceptions (prior knowledge)
- Variations in student understanding and learning are identified which is used to guide instruction (variations in understanding)
- Questions are used to probe or extend student understanding (questions).

Knowledge of Instructional Strategies

- Appropriate sequence for teaching concepts (sequencing of concepts)
- Relevant examples and/or representations are used, which appear to be pedagogically effective at portraying the concept (example and representations)
- Strategies that allow for metacognition (metacognitive strategies).

A copy of the full rubric used for analysis can be found in Appendix 1 of this chapter.

Findings

This study yielded an extensive and rich database, which cannot be reported upon fully in this chapter. However, to give an indication of how collaborative CoRe design impacted on teachers' pPCK and ePCK in this study, the findings from one case study will be presented (i.e., one Group One teacher). Tony's case was selected for presentation since it signals, and at times confirms, the potential of the intervention for pPCK and ePCK enhancement.

Tony's Initial pPCK for Teaching Electricity and Magnetism to 14-Year-Old Students

During his initial interview, Tony saw science as an important school subject, reasoning it helps students to understand the world around them. However, when talking specifically about teaching the *Electricity and Magnetism* topic, his focus appeared to change as he commented, "I want them [*students*] to do well in the test". Tony explained that the test referred to a departmental assessment created by the head of junior science to assess "certain outcomes that we have to cover". Tony was unsure about the source of these outcomes, but suggested they could be from the NZC. Responding to further questions about the role of these outcomes in his teaching, he felt they were his top priority and he did not teach beyond their scope, emphasising "first and foremost, I need to make sure I cover those, because of the time limitations we have … I don't go beyond them, I try and cover them".

Tony felt the nature of science was about "finding out why things happen", and he tried to incorporate that notion into his lessons by promoting students to be inquisitive, stating "I like them to ask questions. I want them to be curious about what's going on. I want them to be interested in what's around them. I like to encourage then to, if you want to know something, then try and find out". He was unsure about the phrase "scientific inquiry"; however, with prompting from the researcher about scientific processes, he offered some insights about their inclusion in his lessons, notably around his use of questions and some contextual restraints. He explained, "if you want to do that, you need more questions at the start of the topic. It comes back to a time limitation to be honest, and then how do you measure how successful it is? How do you tell if they've learnt something?"

Regarding students' prior knowledge, Tony felt they needed some basic understandings before starting this unit. He was aware students had different learning needs and styles, commenting "they all learn differently". To accommodate for students' needs, he mentioned using videos initially for enjoyment purposes, but focused on ensuring that students had the opportunity to make circuits, so they could make cognitive linkages to concepts. He argued "I reckon a lot of students are tactile learners – they like to make things. Then once they can see it, hopefully they can make sense of it when it comes to circuit diagrams. Or doing stuff like that, it will make sense".

When he taught this unit, Tony's strategy was to "start with something fun", then "give them some notes about what is electricity, some definitions for voltage and current. I try and get them practical work as soon as possible … So, try and get them onto those to make a circuit". He gauged students' understanding by their ability to "pass the test" and his approach to formative assessment during lessons featured strategies for preparing students for their test. When asked about how he might use information obtained from these formative assessment strategies in class, Tony explained "I don't record it. But I do identify students who I think need work. So, you know, you can figure out who's onto it and who's not".

Tony's Initial ePCK for Teaching Electricity and Magnetism to 14-Year-Old Students

The four video-recorded pre-CoRe design lessons selected to determine Tony's baseline ePCK included his: introductory lesson; third lesson, featuring explanations and discussions around series and parallel circuits; fourth lesson, where students made simple circuits; and sixth lesson, developing explanations about voltage, current, and resistance. In the lessons, most students were engaged in the learning tasks, particularly during practical activities.

Tony's teaching style was identified as teacher-centred with lessons frequently featuring a pre-made PowerPoint, unless the lesson involved practical work. He typically directed students to copy notes from the PowerPoint, drawing attention to underlined keywords that were to be tested. This PowerPoint was used with other classes, and on one occasion when the data projector failed, he expressed frustration and said "right, plan B… I have to write this, this [*is a nuisance*]".

Tony's lessons were analysed for his ePCK using the rubric discussed earlier, and Table 10.5 shows a summary of these results.

Linking Tony's Initial pPCK and ePCK

When comparing findings from Tony's interview and lesson observations, six key links were seen between his initial pPCK and ePCK, which are summarised below:

- The influence of assessment on Tony's teaching was a prevalent theme throughout his pPCK interview and classroom actions. During the interview, Tony spoke about wanting his students to pass tests, and whilst teaching, he made frequent references to taking notes from the PowerPoint and learning definitions as they would be in the test.
- Tony talked in his interview about wanting his students to be inquisitive in class and ask questions. However, the observations reveal when students did ask questions

Table 10.5 Summary of the results from analysing Tony's four video-recorded lessons using the rubric developed for this study

ePCK indicator	Lessons			
	1	2	3	4
Subject matter knowledge				
Appropriateness	Proficient	Proficient	Advanced	Advanced
Accuracy	Proficient	Proficient	Proficient	Proficient
Concept links	Basic	Basic	Basic	Proficient
NoS/SI links	Limited	Basic	Proficient	Basic
Knowledge of student understanding				
Prior knowledge	Basic	Basic	Proficient	Limited
Variations in understanding	Limited	Limited	Basic	Limited
Questions	Basic	Basic	Basic	Basic
Knowledge of instructional strategies				
Sequencing of concepts	Basic	Proficient	Basic	Proficient
Examples and representations	Proficient	Proficient	Basic	Proficient
Metacognitive strategies	Limited	Limited	Limited	Limited

in class, he rarely engaged with what they were asking and sometimes appeared to ignore them.

- Tony spoke about students learning science, so they could understand the world around them. He used examples in his practice, but these were largely ineffectual in the teaching of the desired concept.
- Tony's lack of understanding about the nature of science and scientific inquiry in the interview was also apparent in the lessons, as he made very few explicit or implicit references and/or links to these aspects in his teaching.
- In his interview, Tony talked about finding out about student understanding (in an informal way) and using that information to guide instruction. However, this strategy was rarely used in lessons with Tony following a tight schedule dominated by his PowerPoint notes.
- In the lessons, Tony did use practical work to help student understanding, as indicated during his interview. However, the practical work undertaken by the students appeared largely ineffectual in the teaching of the desired concept(s).

Tony's CoRe Design Contributions and Experiences

Tony collaborated with his teaching colleagues Nick and Harry for the CoRe design workshops. All three teachers engaged in relevant discussions around what the teaching and learning of the important *Electricity and Magnetism* concepts and skills entailed. In this discussion, Nick (experienced physics teacher) frequently took the lead, offering ideas that he believed to be pertinent to the pedagogy of *Electricity and Magnetism* for 14-year-old students. For example, early in the workshop, when analogies were first mentioned by Tony, Nick explained "teachers need to be careful and selective when using analogies for teaching some difficult-to-understand concepts in Electricity and Magnetism, because the result could be that students develop strong misconceptions".

During these discussions, Nick also offered detailed explanations to his colleagues about the importance of understanding the conservation of charge and energy to teach this topic. In one instance, he drew diagrams showing series and parallel circuits and explained that "it doesn't matter which way charges go, they lose energy". Tony mentioned that this concept can be confusing, to which Nick responded "yes, it is, you need to distinguish between everything … it is all about gaining and losing energy, and that energy in must equal energy out". This explanation and the diagrammatical representations Nick provided proved to be key points that Tony took away from the CoRe workshop. When interviewed about what impact the *Electricity and Magnetism* CoRe might have on his practice, Tony recalled this information and redrew the diagrams indicating that he would teach it this way in the future.

During the determination of the concepts and skills for determining the big ideas for the CoRe in his group discussion, Tony's first comment was students need to learn "definitions of current and voltage", to which Nick replied "it's not definitions. It's understanding of what it actually is". As the workshop progressed, Tony also commented that "you need to give them [*students*] enough to understand, but not too much to confuse them" in reference to some of the suggested ideas being pitched at a level that was too advanced. Tony's group subsequently identified the following six big ideas:

1. Voltage is the difference in energy between two points.
2. Magnets produce magnetic fields which exert a force on other magnets.
3. Rubbing materials together can lead to a separation of charge.
4. Current is the flow of charge.
5. Wires are full of charges and they all move, or none move.
6. Charges produce electric fields which exert a force on other charges.

Their big ideas were shared and compared with the other groups' big ideas, and through a process of negotiation and mediation, guided by the facilitator, seven key big ideas emerged that reflected the collective thinking of all nine participants.

The collective big ideas were:

1. Charges produce electric fields which exert a force on other charges.
2. Current is the flow of charge.
3. Voltage is the difference between the two points.
4. Ohm's law is the relationship between current, voltage, and resistance in a closed circuit.
5. Circuit diagrams are representations of electrical circuits.
6. Electrical circuits can be constructed to solve problems.
7. Magnetism is another effect of moving charge.

To ensure the CoRe was completed within the timeframe, the seven big ideas above were split amongst the groups. The first three listed above were addressed by Tony's Working Group, and their contribution is shown in Appendix 2.

In the post-CoRe workshop interview, Tony commented that he found working collaboratively in that style to be useful and would be interested working in that way in the future. He recognised that the CoRe design process "enables you to break a topic into smaller bits, so it seems less overwhelming", and during the design of the *Electricity and Magnetism* CoRe "it was useful to get some clarification and confirmation about teaching certain concepts". Tony also acknowledged how useful it was to have Nick in his group, as he could learn from his expertise, stating "having a guy who knows what he's doing, and then you can just get clarification and confirmation, or if you have a question you can ask straight away… If you want to know about physics, go and talk to a physics guy".

Tony's pPCK Development

Post-CoRe design, Tony felt that collaborative CoRe design can enhance a teacher's pPCK for science teaching as it has potential to "give people different ideas about doing stuff. There might be other ways of doing things that haven't been thought about". While he judged the first workshop did not enhance his pPCK about teaching *The Nature of Science and Scientific Inquiry*, he felt the second *Electricity and Magnetism* workshop did have an impact. In his post-CoRe design interviews, Tony identified aspects related to his subject matter knowledge and knowledge of topic-specific strategies as two areas of enhancement for his *Electricity and Magnetism* pPCK. He was particularly focused on a new way to teach students about energy and charge in both series and parallel circuits, which he had taken from the workshop:

> Nick talked to me about how to explain the concept of voltage… Why voltage is the same in a parallel circuit and different in a series circuit. He explained it in quite a good way. He drew a series and parallel circuit and explained how the voltage is shared. [Tony redrew Nick's diagrams]

He described how these explanations had helped his understanding and how he wanted to use them in the future with his students as it made the concept easier for them to visualise and understand. He also spoke of how he and David (another Group One teacher) had worked together with the completed CoRe to prepare for teaching their post-CoRe design class.

Tony indicated that his knowledge of students' understanding and learning had also improved, but did not elaborate or give examples. Similarly, he felt that the CoRe design process was focused on teaching concepts as opposed to assessment strategies, so he did not offer any information about how his knowledge of assessment strategies may have developed.

Tony's ePCK Development

The four video-recorded post-CoRe design lessons selected for analysis included his: introductory lesson; second lesson, featuring explanations about charged particles, voltage, and current; third lesson, where students explored differences between series and parallel circuits and the Ohm's law relationship; and fifth lesson, where students made simple circuits and took measurements. Again, most students were engaged in the lessons, particularly during practical work.

Tony's teaching style was again identified as predominantly teacher-centred with a focus on students taking notes. However, there were now some instances during his lessons where Tony engaged with students and challenged their thinking, particularly why they thought in a certain way. Again, Tony had a PowerPoint for this class, but the slides were different to those used previously.

To evaluate ePCK enhancement, post-CoRe observational data was compared to that obtained pre-CoRe. A summary of the post-CoRe rubric analysis is presented in Table 10.6, along with an indication in the last column of enhancement (or not) to each of the ePCK quality indicators compared to pre-CoRe results, where "–" represents no change, and "↑" represents development.

In both pre- and post-CoRe Y10 classes, the concepts that Tony taught were appropriate for students at that level. Links to the nature of science and/or scientific

Table 10.6 Summary of the results from analysing Tony's four video-recorded lessons (post-CoRe design) using the rubric developed for this study and an indication of enhancement

ePCK indicator	Lessons				Enhancement
	1	2	3	4	
Subject matter knowledge					
Appropriateness	Advanced	Advanced	Proficient	Advanced	–
Accuracy	Advanced	Advanced	Advanced	Advanced	↑
Concept links	Advanced	Advanced	Advanced	Proficient	↑
NoS/SI links	Basic	Basic	Basic	Proficient	–
Knowledge of student understanding					
Prior knowledge	Proficient	Basic	Proficient	Proficient	↑
Variations in understanding	Basic	Proficient	Advanced	Proficient	↑
Questions	Basic	Basic	Proficient	Advanced	↑
Knowledge of instructional strategies					
Sequencing of concepts	Advanced	Basic	Proficient	Proficient	↑
Examples and representations	Advanced	Proficient	Advanced	Proficient	↑
Metacognitive strategies	Basic	Basic	Basic	Proficient	↑

inquiry, by the way of implicit links, were similar into those in his pre-CoRe design class, so this aspect of his pPCK and ePCK appeared little changed.

The summary below outlines the developments that occurred in eight of 10 identified quality indicators of ePCK:

Subject Matter Knowledge

Accuracy

After the CoRe design workshop, Tony's explanations became more in depth, and he focused on the underlying principles as well as rules and definitions.

Concept links

Tony made some links in his pre-CoRe design class, but the explanation that linked the concepts needed further development. After taking part in the workshop, he made more links between concepts and offered students well-thought-out explanations about the linkage.

Knowledge of Student Understanding

Prior knowledge

While Tony sought some prior knowledge from students in his pre-CoRe design lessons, the information obtained was often used in a very limited way. However, after being involved with CoRe design he seemed much more aware of this information and attempted to use it more to inform his lessons.

Variations in understanding

Before CoRe design, it was apparent that Tony had certain content he wanted to get through during lessons, and he often did not deviate from that plan. However, after the workshop, he became more aware of students' needs and areas where they were having difficulty. As a result, he was able to change tack and vary his pedagogical approach at times to address learning issues that arose.

Questioning

Compared to his pre-CoRe design classes, Tony used many more questions with his students and his questions also had more variety. For example, extending beyond one-word factual questions to asking students to predict and explain phenomena.

Knowledge of Instructional Strategies

Sequencing of concepts

In his pre-CoRe design lessons, it appeared that the *intended* sequence of concepts was quite suitable and appropriate for that level of students most of the time. However, explanations to link changes in concepts were lacking, which resulted in students being unsure about what they were learning. In contrast, in his post-CoRe design lessons Tony offered insightful explanations to students about why they were changing concepts and how concepts were related.

Examples and representations

While Tony used these strategies in his pre-CoRe design lessons, they were often ineffectual for portraying the desired concept and his explanations linking the strategy to the concept were brief, incorrect, or missing. In contrast, his post-CoRe design examples and representations appeared much more effective at enabling student learning by being more targeted at building student understanding. He used Nick's analogies and diagrams that he encountered during the workshop.

Metacognitive strategies

Tony significantly improved his use of instructional strategies that provoked metacognition. In his pre-CoRe design class, there were no instances that indicated purposeful stimulation of students' metacognition. However, post-CoRe design he actively encouraged students to think about their own thinking and to express their ideas.

Discussion and Conclusion

This section interprets, discusses, and evaluates the findings from Tony's case study in relation to the research questions and pertinent literature. Each research question is restated and addressed in turn.

Research Question One

> In the New Zealand context, what does the personal and enacted pedagogical content knowledge (pPCK and ePCK) of junior science teachers with a limited physics background look like for teaching *Electricity and Magnetism* to 14-year-old students?

The findings presented above indicate that Tony's initial pPCK and ePCK were characterised by four features: one related to *what* he was teaching and three to *how* he was teaching. Regarding *what* concepts were being taught, Tony's decisions were dictated by the outcomes provided in the departmental guidelines; that is, he adhered to these outcomes in his planning and teaching. There is little evidence that he made autonomous decisions when selecting appropriate concepts to teach, which is an important attribute of a well-developed pPCK (Park & Oliver, 2008). As he worked through those outcomes, links to other concepts during lessons were often overlooked in his teaching, indicating a basic level of pPCK and ePCK (Gardner & Gess-Newsome, 2011).

When teaching in science, Alonzo et al. (2012) argue the need for teachers to appropriately sequence concepts, so students can identify the connections and develop their understanding of those concepts and their relationships with other concepts. As concepts transition to others, the sequencing often requires insightful explanations from teachers about how the concept(s) is changing to ensure students are developing their conceptual understanding appropriately. The findings revealed such sequencing of concepts in Tony's pre-CoRe design class were at a basic proficient level of pPCK and ePCK (Alonzo et al., 2012; Gardner & Gess-Newsome, 2011).

In terms of *how* Tony was teaching these concepts, the three identified features were: responsiveness pedagogically to student's understanding and learning; the use of representations and examples, and promoting metacognition; and, the influence of context.

Responsiveness is regarded as an essential attribute of well-developed PCK, that is, a teacher's ability to recognise students' learning and understanding, and then to vary his/hers next pedagogical move (Alonzo et al., 2012; Gardner & Gess-Newsome, 2011). In other words, teachers need to be pedagogically responsive to student needs during lessons and adapt their pedagogical approach as required. Since Tony was reliant on the provided outcomes, his lessons tended to be tightly organised around delivery of the required information to students. This approach meant he did not adapt his lessons to be pedagogically responsive when students required learning assistance, implying a limited to basic level of ePCK (Alonzo et al., 2012; Gardner & Gess-Newsome, 2011; Lee et al., 2007).

To help students develop their own conceptual understanding, teachers with a rich PCK for science teaching employ strategies where examples and representations are used to aid student understanding and metacognition is promoted (Alonzo et al., 2012; Gardner & Gess-Newsome, 2011; Lee et al., 2007). Students utilise these examples and representations to explain concepts and to relate new knowledge to their existing understanding and think about their thinking. In contrast, Tony's teaching was characterised by the transmission of information. There were times when he attempted to use examples and representations, but these were often ineffectual and instances that provoked metacognition were not seen in lessons, reflecting a limited to basic ePCK.

The RCM (see Fig. 10.1) places "learning context" as a key influence on teachers' pPCK and ePCK. This influence was clear for Tony, as contextual constraints within the learning environment (i.e. the school's focus on assessment and student achievement in national qualifications) underpinned his teaching decisions. The findings show that assessment requirements featured prominently in Tony's pPCK and ePCK.

Research Question Two

> What impact does collaborative CoRe design have on the pPCK and ePCK development of junior science teachers with a limited physics background for the topic of *Electricity and Magnetism* for 14-year-old students in New Zealand, when working collaboratively with experienced physics and junior science teachers?

When CoRe design is used as a collaborative process, it has been shown to enhance teacher's PCK, particularly for pre-service and early-career science teachers (e.g., Hume & Berry, 2011, 2013; Nilsson & Loughran, 2012). During the CoRe design workshop, there were many instances where knowledge was shared within the Working Group. Desimone (2009) and Daehler, Heller, and Wong (2015) predict this sharing of knowledge through collaborative efforts supports science teachers' professional learning, which was indicated in Tony's case. Findings showed his pPCK was enriched, which in turn enhanced his classroom practice, a key aspect of ePCK. This knowledge sharing underpins the knowledge exchange that occurred between cPCK, pPCK, and ePCK, as predicted and represented in the RCM of PCK by double-headed arrows, and evidenced in the knowledge transitions that Tony experienced.

Tony's case study reinforces the effectiveness of collaborative CoRe design as a means of developing pPCK and ePCK with significant enhancement to his subject matter knowledge, knowledge of instructional strategies, and knowledge of students' understanding and learning. During post-CoRe design interviews to explore his pPCK development, Tony explicitly identified his subject matter knowledge and knowledge of instructional strategies as areas of personal improvement. He particularly appreciated strengthening his understanding of voltage, charge, and energy concepts, and how to relay that information to students. Comparison of the two sets of classroom observational data, pre- and post-CoRe design, confirmed this enhancement. In addition, observational comparisons showed Tony's knowledge of students' understanding and learning had also improved, as he was more pedagogically aware of students learning needs, responsive to those needs, and used questions more effectively.

In conclusion, Tony's case signals that the use of collaborative CoRe design within a school learning community, to access and collate aspects of cPCK of teachers, promotes the pPCK and ePCK development of those science teachers with less content knowledge for that topic. One advantage of collaborative CoRe design in this setting is the ability of a school to capitalise on in-house expertise, rather than seeking it from outside sources, which may place undue pressure on a school's financial and organisational resources. This in-house use of collaborative CoRe design also addresses a limitation raised by Hume et al. (2013) about the logistical difficulty of organising various teachers (and content experts) from different locations to collaborate face-to-face.

The RCM has proved a useful and applicable conceptualisation of PCK for guiding this study. In particular, there are three features of this model that have facilitated this study. They are:

1. The conceptualisations of pPCK and ePCK, and showing how they interact. The separation of the professional knowledge that a teacher possesses and can talk about from the teacher's actions in the classroom aids comparisons and, at the same time, enables any synergy and/or dissonance between the two to be identified. To these ends, targeted research methods including quality indicators can be developed to investigate and capture these forms of PCK.

2. The introduction of cPCK. This form of PCK recognises the contributions of multiple people and encapsulates what a CoRe document represents when it has been developed as a collaborative process.
3. The emphasis on knowledge exchanges between different knowledge bases, including the different forms of PCK. These exchanges, represented by double-headed arrows in the diagrammatic form of the RCM, show how knowledge can be shared and how that process can influence/be influenced by classroom practice and the learning context. The discussion presented in this chapter reinforces the importance of this process, as knowledge that was shared within the cPCK realm was transferred into and enhanced the pPCK and ePCK of an individual science teacher via his knowledge transitions and/or transformations.

This study recommends that schools should consider the use of collaborative CoRe design, as portrayed in this study, as an effective professional development intervention for enhancing the cPCK, pPCK, and ePCK of its science teachers, particularly those without specialist science content knowledge.

Limitations

There are three main limitations, which should be taken into consideration when interpreting the findings and conclusion from this study. In this chapter, there is an account of only one teacher's experiences with collaborative CoRe design and his subsequent pPCK and ePCK development. While it is reported that collaborative CoRe design was a positive experience for him, enhancing his professional knowledge and practice in particular ways, this conclusion may not be drawn from these findings for others. However, it can be reported that both of the other Group One teachers (not included in this chapter) had positive experiences with CoRe design that enhanced their pPCK and ePCK, albeit in different ways and to different degrees.

In both the RCM of PCK and the previous Consensus Model (CM) of PCK (i.e., Gess-Newsome, 2015), student outcomes were included. However, in this study for pragmatic reasons, no data was obtained from students. In future studies, it would be important to make comparisons between students' science learning from the teacher pre- and post-CoRe design to see the effect changes in their teachers' pPCK and ePCK may have on their learning. This type of data would shed more light on the impact of collaborative CoRe design.

Similarly, the link between the pedagogical reasoning undertaken in pPCK and ePCK was not explored in this study. While Gess-Newsome (2015) encouraged the use of data collection methods such as stimulated recall interviews to investigate this aspect of teachers' PCK, these were not used in this study. Again, the researcher's commitment to teaching full time necessitated the decision not to explore this aspect of PCK. Researching science teachers' pedagogical reasoning in the act of teaching, after taking part in collaborative CoRe design, will also provide rich insights into the effects of collaborative CoRe design.

Appendix 1: Rubrics for Analysing ePCK

ePCK indicator	Limited	Basic	Proficient	Advanced
Subject matter knowledge				
Appropriateness of concept(s) in relation to NZC—physical world (level 5)	No alignment of concept(s) in lesson with NZC—physical world (level 5)	Little alignment of concept(s) in lesson with NZC—physical world (level 5)	Adequate alignment of concept(s) in lesson with NZC—physical world (level 5)	Close alignment of concept(s) in lesson with NZC—physical world (level 5)
Scientific accuracy of the explanation of the concept(s)	Explanation(s) were mostly inaccurate, which did not address the concept(s)	Explanation(s) were somewhat inaccurate, which loosely addresses the concept(s)	Explanation(s) were mostly accurate with only small inaccuracies seen, or they were too brief	Explanation(s) were accurate, which addresses the concept with no inaccuracies
Links and/or connections made to other concepts	No possible links and/or connections are made	Few of the possible links are made, but not connected with explanations	Some of the possible links and connections are made	Many of the possible links and connections are made
Links made (implicit or explicit) to the nature of science (NoS) and/or scientific inquiry (SI)	No links made to NoS and/or SI	Few of the possible links to NoS and/or SI are made	Some of the possible links to NoS and/or SI are made	Many of the possible links to NoS and/or SI are made
Knowledge of student understanding				
Teacher recognises and acknowledges possible student prior knowledge, difficult concepts, and misconceptions	No recognition or acknowledgement of possible student prior knowledge, difficult concepts, and/or misconceptions	Recognises some possible student prior knowledge, difficult concepts, and/or misconceptions	Recognises and acknowledges some possible student prior knowledge, difficult concepts, and/or misconceptions	Recognises and acknowledges most/all possible student prior knowledge, difficult concepts, and/or misconceptions

(continued)

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ePCK indicator	Limited	Basic	Proficient	Advanced
Teacher uses identified variations in student understanding and learning to guide instruction	No acknowledgement and/or use of variations in student understanding and learning to guide instruction	Acknowledgement of variations in student understanding or learning, but not used to guide instruction	Some acknowledgment of variations in student understanding or learning are used to guide instruction	Many instances where teacher acknowledged variations in student understanding or learning and used these to guide instruction
Teacher uses questioning to probe or extend student understanding	No questions are used to probe or extend student understanding	A few questions are used to probe or extend student understanding	An adequate range of questions are used to probe or extend student understanding	Many and varied questions are used to probe or extend student understanding
Knowledge of instructional strategies				
Appropriate sequence for teaching concepts	No overall flow between concepts and the sequence confuses students	Some flow between concepts and the sequence allows some concept building to occur	Suitable flow between concepts and the sequence allows satisfactory concept building to occur	Clear flow between concepts and sequence allows effective concept building
Relevant examples and/or representations are used in the lessons, which appear to be pedagogically effective at portraying the concept	No examples and/or representations used	Examples and/or representations used that do not appear to be pedagogically effective	Examples and/or representations used have some relevance, but appear pedagogically limited	Relevant examples and/or representations used that appear pedagogically effective
Use of strategies that allow for metacognition	No use of strategies that allow for metacognition	Limited use of strategies that allow for metacognition	Adequate use of strategies that allow for metacognition	Much use of strategies that allow for deep levels of metacognition

Appendix 2: Tony's Working Group's CoRe Contribution

	Big ideas (Tony's Working Group)		
Pedagogical prompts	Charges produce electric fields which exert a force on other charges	Current is the flow of charge	Voltage is the difference in electric potential energy between two points
What do you intend students to learn about this idea	• Rubbing different materials together can separate charges • Like charges repel and opposite charges attract	• Current flows from positive to negative • Charge is conserved • Current is the same in all parts of a series circuit • Current divides in a parallel circuit • Current (I) is measured in Amperes (A) • Ammeters are used in series so that all of the current flows through them	• Energy is conserved • The supply voltage is divided over the components in a series circuit • Voltage is the same for each branch of a parallel circuit • Voltage (V) is measured in Volts (V) • Voltmeters are used in parallel to measure the difference between two points
Why is it important for students to know this?	• It explains everyday phenomena—e.g. shocks on trampolines or lighting • Basis for current electricity	• These are foundational concepts for understanding the behaviour of all electrical circuits	
What else you know about this idea (that you do not intend students to know yet)	• Electromagnetic induction	• Conventional current versus electron flow	• Volts = joules per Coulomb
Difficulties and/or limitations connected with teaching this idea	• Humid conditions can wreck electrostatic experiments	• You can't see it • Analogies can lead to misconceptions • Conventional current versus electron flow	• You can't see it • Everyday use of the word—'power'

(continued)

(continued)

	Big ideas (Tony's Working Group)		
Pedagogical prompts	Charges produce electric fields which exert a force on other charges	Current is the flow of charge	Voltage is the difference in electric potential energy between two points
Knowledge about students' thinking which influences your teaching of this idea	• Students usually have some prior experience of static electricity	• Common misconception of single charge units moving as opposed to a wire full of charges that are all moving	• Students get hung up on wire colours
Other factors that influence your teaching of this idea	• Weather	• Students need to be able to build circuits	• Voltage is difficult to model
Teaching procedures (and particular reasons for using these to engage with this idea)	• Rods and clothes to demonstrate static charging—picking up paper and electroscopes • Van der Graaf Generator • YouTube videos	• Definitions • Measuring current in series and parallel circuits and establishing rules • Discussion of why the rules work • Can use model of students as charges moving single path/multiple paths	• Definitions • Measuring voltage in series and parallel circuits and establishing rules • Discussion of why the rules work
Specific ways of ascertaining students' understanding or confusion around this idea	• Can explain applications—e.g. why a person's hair stands up when touching Van der Graaf	• Can measure current and voltage in circuits • Can calculate current and voltage in series and parallel circuits	

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Chapter 11
A Grand Rubric for Measuring Science Teachers' Pedagogical Content Knowledge

Kennedy Kam Ho Chan, Marissa Rollnick and Julie Gess-Newsome

Abstract Rubrics are increasingly used to differentiate the quality of science teachers' pedagogical content knowledge (PCK), both qualitatively and quantitatively. Well-designed PCK rubrics can guide the judgement of PCK quality for valid assessment. This chapter considers the possibility of a "grand rubric" that allows measurement of different variants of PCK as depicted in the Refined Consensus Model (RCM). To achieve this goal, the chapter first reviews the characteristics of rubrics in current use in the science education field. It examines the critical considerations in the construction of a grand rubric through an analysis of an expert discussion group. Based on this analysis, the paper proposes a grand rubric and describes its layout and characteristics. The grand rubric is generic in nature and can be customised for use with different science content topics as well as for measurement of specific variants of PCK in the RCM, including individual science teachers' personal or enacted PCK (pPCK and ePCK) and the collective PCK (cPCK) of a group of science teachers.

Introduction

Assessing teacher knowledge has been a subject of interest for decades (Gitomer & Zisk, 2015). Teacher knowledge is important as multiple strands of evidence support the notion that what a teacher knows impacts the quality of classroom instruction and hence student learning (e.g., Baumert et al., 2010; Kersting, Givvin, Thompson, Santagata, & Stigler, 2012). Pedagogical content knowledge, or PCK, is an important province of knowledge within the professional base of teachers that is most germane

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to teaching (Shulman, 1986). PCK includes the knowledge and skills needed for a teacher to teach a "particular topic in a particular way for a particular purpose to particular students for enhanced student outcomes" (Gess-Newsome, 2015, p. 36). In order to validate the efficacy of efforts to enhance teacher knowledge in teacher preparation programmes and professional development activities, as well as to certify teachers, measures of teacher knowledge and skill (including teachers' PCK) are needed.

Since the first (1st) PCK Summit in 2012, there has been an upsurge of interest in PCK research and its measurement particularly in the science education field (e.g., Kirschner, Taylor, Rollnick, Borowski, & Mavhunga, 2015; Park & Suh, 2015; Smith & Banilower, 2015). Given that data sources related to PCK are often qualitative in nature (such as interviews, completion of surveys and written prompts, teaching artefacts, and classroom observations), the use of scoring rubrics (hereafter, rubrics) has become popular. Rubrics are descriptive scoring schemes comprising scoring categories with specific pre-established performance criteria (Mertler, 2001). Well-designed PCK rubrics provide operational definitions of the key dimensions of PCK for measurement by demarcating the scope and range of the construct. As such, well-designed PCK rubrics can guide the analysis of performance and support the judgement of PCK quality.

At the second (2nd) PCK Summit in the Netherlands in 2016, the majority of the participants were keen on the idea of a "grand rubric" for measuring science teachers' PCK, so a subgroup of participants formed a discussion group to discuss this possibility (hereafter, the rubric group discussion). The driving force behind the discussion was the premise that a grand rubric would be valid, ubiquitously accepted, and support clear and unambiguous communication across researchers. If sufficiently generic in nature, a grand rubric could be customised to various science content topics and would allow for comparison of PCK scores across topics, for triangulation across data sources, and provide evidence of growth in PCK pre- and post-intervention (i.e., determine individual teachers' PCK development). Such a rubric would make a significant contribution to the establishment of international standards for articulating PCK for a number of commonly taught science topics.

In this chapter, we raise key considerations in the construction of a grand rubric for measuring science teachers' PCK that can be used to determine all variants of PCK as depicted in the Refined Consensus Model (RCM), including individual teachers' personal or enacted PCK (pPCK and ePCK) as well as the collective PCK (cPCK) of a group of science teachers. To achieve this goal, we reviewed the characteristics of PCK rubrics in current use, identified through a systematic literature review. As the authors of reviewed works seldom make explicit their underlying rationales or considerations in the process of rubric construction, we also analysed a recording of the rubric group discussion held at the 2nd PCK Summit to uncover critical considerations needed to create a grand rubric for measuring PCK. Using this information, we propose a generic grand rubric, which can be customised for use with different content and grain sizes as well as for measurement of specific variants of PCK for science teaching.

Research Questions

The following research questions guide this chapter:

1. What are the characteristics of rubrics used to differentiate the quality of science teachers' PCK in the existing literature?
2. What are critical considerations in the construction of a grand rubric for measuring science teachers' PCK?
3. What would a grand rubric for measuring science teachers' PCK look like?

Methods

This chapter employed a systematic review of published and unpublished literature (i.e., literature in the public domain as well as the research summary outlines provided by the 1st and 2nd PCK Summit participants) and qualitative data collected at the 2nd PCK Summit about the use of rubrics in PCK research. Bennett, Lubben, and Hogarth (2007) note the strengths of such reviews are found in the characteristics of the review process, such as: the use of explicit criteria for the selection of studies for review; exhaustive coverage of the studies published; and the involvement of at least two researchers in decision-making.

For the first research question, the three authors of this chapter selected studies involving the use of PCK rubrics through a systematic literature search. In the first round of the literature search, eleven peer-reviewed journals primarily in science education and three journals in the field of teacher education were searched using the keywords "pedagogical content knowledge" and "rubric". The journals searched included: *African Journal of Research in Mathematics; Science and Technology Education; EURASIA Journal of Mathematics, Science and Technology Education; Chemistry Education Research and Practice; International Journal of Science Education; International Journal of Science and Mathematics Education; Journal of Research in Science Teaching; Journal of Science Teacher Education; Research in Science Education; Research in Science and Technological Education; School Science and Mathematics; Science Education; Teachers and Teaching: Theory and Practices;* and *Teaching and Teacher Education*. The lead author screened each of the articles for inclusion using the following selection criteria:

- The empirical studies were written in English and focused on science teachers' domain, topic, and/or concept-specific PCK.
- The article contained sufficient description and details about the rubric.
- The rubric was primarily used to differentiate the quality of science teachers' PCK.
- The rubric was adequately informed by the PCK literature.

The above selection criteria resulted in studies that *self-identified* the use of a rubric to differentiate the quality of teachers' PCK. Studies that made use of a rating manual, coding manual, or simply described the scoring procedures were not included in the analysis, as the scoring scheme was not a rubric. The selection criteria also excluded articles that used rubrics to differentiate the quality of teachers' discipline level PCK such as PCK for argumentation or PCK for inquiry practices since PCK is related to the teaching of particular subject matter of different grain size (see Chap. 2). In the second round of the literature search, we further enriched our article sources by:

(1) searching the ERIC database (https://eric.ed.gov/) using the same keywords,
(2) identifying rubrics in the research summary outlines of the two PCK Summits, and
(3) inviting PCK Summit members to suggest additional rubrics.

All articles generated by all these three search processes were examined for inclusion using the criteria detailed above. The final list comprised 37 sources, including 10 outline papers from the second PCK Summit and 27 journal articles and chapters. The sources are listed in *Appendix 1* (obtainable from https://www.researchgate.net/project/Grand-Rubric-for-PCK).

To analyse characteristics of current PCK rubrics in use (Research Question 1), we first decided on eight rubric characteristics.[1] The lead author then analysed all papers according to these characteristics. The second author peer validated a subset of 13 of these papers. For the purposes of this chapter, 5 of these 8 characteristics were considered relevant: (1) structure and purpose of the rubric, (2) the variants of PCK investigated, (3) the PCK model and components, (4) the quality indicators for PCK and (5) data sources. Broad agreement was reached between the two authors and the differences were resolved by discussion. Based on the above analysis, we further clustered the rubrics into distinct groups and described their characteristics.

To identify critical considerations of a grand rubric for measuring science teachers' PCK (Research Question 2), we transcribed verbatim and analysed an audio recording of the rubric discussion group held at the 2nd PCK Summit (1 h and 10 min). The rubric discussion group comprised eleven PCK researchers[2] from eight countries, referred to hereafter as PCK experts. In the discussion, these PCK experts discussed the possibility of constructing a grand rubric for measuring science teachers' PCK. The discussion transcript and voice file were sent to all participants to check for transcript correctness and validation. The transcript was analysed inductively to identify, categorise, and explore the main themes that emerged on the issues involved in creating a grand rubric using standard qualitative research techniques

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[1] The eight characteristics are: (1) primary research focus of the articles; (2) PCK model and components/categories; (3) PCK variant(s) explored; (4) the data sources; (5) the rubric development process; (6) the structures and purpose of the rubric; (7) the quality indicators for PCK; and (8) the scoring process.

[2] The eleven summit members involved in the rubric group discussion were Alicia Alonzo, Julie Gess-Newsome (USA), Amanda (Mandi), Berry (Australia), Jared Carpendale (New Zealand), Kennedy Chan (Hong Kong), Sophie Kirschner, Sven Liepertz (Germany), Elizabeth Mavhunga, Marissa Rollnick (South Africa), Pernilla Nilsson (Sweden), and Christopher (Chris) Wilson (UK, based in the USA).

(Patton, 2002). The analysis revealed several critical considerations for constructing a grand rubric.

Lastly, based on our analysis of existing rubrics and the rubric discussion from the PCK Summit, we conceptualised a potential structure for a grand rubric for measuring science teachers' PCK (Research Question 3).

We employed investigator triangulation (Denzin, 1989) to ensure the trustworthiness of the data. The three authors arrived at consensuses concerning the main themes as they relate to the analysis of the literature review, the themes from the 2nd PCK Summit, the implications derived for the grand rubric, the final grand rubric template and the sample rubrics via face-to-face meetings, email exchanges, and Skype meetings.

Findings and Discussion

Our findings and discussion are organised according to the three research questions. First, we present a detailed analysis of the rubrics found in the literature and their characteristics. We then discuss the main themes that emerged from the analysis of the rubric discussion group. Finally, we propose a grand rubric for measuring science teachers' PCK and describe its characteristics.

Characteristics of PCK Rubrics in Use

From the systematic review, 37 journal articles, chapters, and extended outlines produced for the 2nd PCK Summit met the search criteria. Further analysis revealed that several of the papers, though dealing with different science topics and methods, used rubrics that shared the same characteristics. These documents were grouped together, resulting in 26 distinct rubrics. The full list of papers and their grouping can be found in *Appendix I* (see https://www.researchgate.net/project/Grand-Rubric-for-PCK). Based on an analysis of the 26 distinct rubrics, we offer a summary of the five rubric characteristics that are most relevant to guiding the creation of a grand rubric for measuring science teachers' PCK. Other rubric characteristics are mentioned as appropriate.

(1) *Structure and purpose of the rubric*. When sorting the PCK rubrics according to their structure and purpose, all aimed to differentiate the quality of science teachers' PCK. Of these, 20 of the rubrics measured science teachers' PCK. The remaining 6 served more qualitative intentions.

While existing rubrics vary in intent, clearly there are a significant number of researchers that believe that PCK can be effectively *measured* using rubrics. We concur and believe that the grand rubric for measuring science teachers' PCK should be designed in a manner to allow measurement of science teachers' PCK against normative standards defined by researchers, experts, and/or best practice and empirically determined. In other words, we contend that PCK exists in a continuum from weak to strong and can be measured using a rubric.

PCK rubrics have different structures. Quality indicators may form the rows of the rubric, or alternatively, PCK components may be used as the rows—some rubrics delineate sub-dimensions of PCK components as the rows of the rubric. Most rubrics are analytic rubrics (rubrics specifying more than one key dimension) with PCK components constituting the rows of the rubrics. The number of performance levels commonly ranges from two to seven with the most common number being four.

(2) *Variants of PCK.* Berry, Depaepe, and van Driel (2016) describe PCK as static or dynamic. To these writers, static PCK is a fixed form of teacher knowledge, in contrast to dynamic PCK that interacts with other knowledge types and may develop in situ. This classification is in line with the consensus definition of PCK from the 1st PCK Summit that delineates two variants of PCK representing the opposite ends of an enactment spectrum: (1) "teachers' knowledge of, reasoning behind, and planning" and (2) "the act of teaching" (Gess-Newsome, 2015, p. 36). The former is related to investigating what teachers know or think (i.e., static PCK) or knowing '*that*', *without* investigating what teachers actually *do* inside the classroom (i.e., dynamic PCK), while the latter refers to know-*how* (i.e., skills and techniques) and knowing-to-*act* in the moment (Mason & Spence, 1999) that is inherently linked to, and situated in, the *act of teaching within a particular classroom*. In relation to the RCM, static PCK corresponds to collective PCK (cPCK), personal PCK (pPCK) or enacted PCK in the planning and reflection phases (ePCKp, ePCKr) while dynamic PCK pertains to ePCK in the interactive phase of teaching (ePCKi) - see Chap. 12.[3]

Of the 20 rubrics measuring PCK, seven targeted dynamic PCK (ePCKi) while the rest measured static PCK. Of the six rubrics with qualitative intentions, three targeted static PCK. It can thus be concluded that most rubrics, whether quantitative or qualitative, were more often used for static PCK.

(3) *The use of a model and components.* Another characteristic with implications for rubric development is the choice of a model to guide the work that locates PCK in relation to other categories of teacher knowledge. All but four of the rubrics made a commitment to a particular model. The most popular was the Magnusson's PCK model (Magnusson, Krajcik, & Borko, 1999) or an adaptation of it. Three used Shulman's initial conceptualisation (Shulman, 1986), two used the Consensus Model (CM) from the 1st PCK Summit (Gess-Newsome, 2015), and two used the Mavhunga model (Mavhunga & Rollnick, 2013).

In those rubric developments using models, almost all the rubrics are organised around, "knowledge of students understanding of science" and "knowledge of instructional strategies." These are two of the original components used in Shulman's oft-quoted original conceptualisation of PCK in 1986.

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[3] For the purpose of clarity, in the following, the terms static PCK and dynamic PCK will be used below.

Other components that were emphasised as part of these characteristics for rubric development include content knowledge, use of representations, orientations towards teaching science, and pedagogical reasoning. Considerations of content also need to take into account grain size (i.e., whether the rubric considers PCK at the domain, topic, or concept level). Most rubrics in this survey targeted the topic level, for example force and motion, photosynthesis or chemical equilibrium.

The rubrics not committing to any existing models make interesting reading. Three of the rubrics (Alonzo & Kim, 2016; Gess-Newsome et al., 2017; Lee, Brown, Luft, & Roehrig, 2007) provide thorough reviews of the literature. While these three studies do not commit themselves to a single PCK model, they eventually emerge with empirically derived components similar to those in the Magnusson model.

(4) *Quality indicators for PCK.* A thematic analysis of the quality indicators suggested for the rubrics shows an emphasis on attributes flowing from a constructivist view of teaching and learning. The most common themes referred to conceptual approaches, sense-making, and teaching for meaning (in almost all rubrics), followed by an emphasis on awareness of student thinking and ideas, student-centred approaches, and links between student ideas and teaching strategies. Criteria not related to the above themes relate to accuracy, completeness, or nature of the content (in at least nine rubrics). Some rubrics make reference to big ideas, which also link to a conceptual view of content. Another recurring theme was the quality of pedagogical reasoning and the degree of integration between PCK components, although these two areas were not explicitly identified as a single dimension/row in the rubric.

(5) *Data sources.* Science teachers' PCK knowledge was most often determined using a single type of data source (e.g., open-ended written test). Seven distinct rubrics used paper-and-pencil responses and all of these measured static PCK (e.g., Davidowitz & Potgieter, 2016; Jin, Shin, Johnson, Kim, & Anderson, 2015). The remaining rubrics measuring static PCK used data sources such as interviews and videos, and one used a CoRe[4] (Loughran, Mulhall, & Berry, 2004). In the case of the video analysis (e.g., Alonzo & Kim, 2016), respondents were typically asked to analyse the science teaching of a teacher on video, thus calling for the respondents' knowledge rather than action. The rubrics measuring dynamic PCK (i.e., ePCKi) all used either lesson videos or observations of a teacher's teaching acts in the classroom.

Critical Considerations in Constructing a Grand Rubric for Measuring Science Teachers' PCK

The findings presented above related to the analysis of PCK rubrics reviewed in the current literature. We now turn to data from the rubric discussion group at the

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[4] CoRe stands for Content Representation—an array to portray PCK structured by big ideas related to a topic with responses to key pedagogical prompts.

2nd PCK Summit to identify critical considerations in constructing a grand rubric for *measuring* science teachers' PCK. The discussion provided a window into the experts' thinking and rationales underpinning the *process* of designing the rubrics, including the critical considerations needed to create a rubric. Included below are quotations from the rubric discussion group, slightly edited to increase their clarity. Five main themes about the critical considerations in the construction of rubrics emerged from the analysis of the rubric group discussion transcript: (1) the role of content knowledge, (2) the integration of PCK components, (3) the placement of pedagogical reasoning, (4) the role of an underlying learning theory, and (5) the core components that represent the essence of PCK. These are discussed below:

(1) *Should content knowledge (CK) be assessed in the PCK rubric?* Early in the discussion, the experts reached a consensus about the centrality of content in the PCK construct. Although the content is considered important within the PCK construct, it was not clear to the experts *how* CK should be measured when assessing teachers' PCK. For example, Chris suggested that CK should be measured in a *separate* test:

Chris: I think we can measure content knowledge in ways that are well established. If in this rubric we're measuring (PCK), then we don't need to measure content knowledge in that in the same measure.

Alicia agreed with Chris that CK does not need to be assessed in the PCK rubric and added that:

Alicia: Content knowledge is part of how people understand students' ideas. So if you're thinking about student understanding and you have a misconception yourself, then you're going to have a weak understanding of student misconceptions. … I wouldn't want to separate that out and say that content knowledge is a separate component [in the rubric].

Although it seems that Alicia agreed with Chris' rejection of a separate row in the rubric for CK, her reasoning was somewhat different; she believed that a teacher with inadequate CK would naturally be unable to identify student misconceptions (i.e. that CK is part of PCK). Pernilla echoed this idea and added:

Pernilla: I totally agree with this [i.e., your ability to tease out misconceptions depends on an accurate understanding of the relevant content]. … I don't know if we lose something if we focus too much on content and not with *how* content is integrated *with pedagogy* in the classroom, i.e. PCK.

Pernilla was of the view that the rubric should focus on, 'how content is integrated *with pedagogy'* rather than content alone. This debate was well summarised by Julie's comment below:

Julie: It seems like this is the debate. Is there some kind of measure of CK that is separate, and is it a prerequisite to looking at teachers' PCK that could also include accuracy, or is there a component of PCK, which includes CK?

To summarise, the experts identified CK as a key attribute of PCK, but whether and how the assessment of CK should be included in the grand rubric for measuring science teachers' PCK remained unresolved.

(2) *How to measure the integration between PCK components?* Another consideration became obvious when the experts discussed how the PCK components should be included in the rubrics.

Elizabeth: Do we want to look at them [the PCK components] individually or are we looking at their interactions? … Maybe the listing of components is important, but going back to the criteria, are we looking at the criteria from the perspective of amalgamation or interaction? I don't know. I just find it really difficult to consider each component [separately].

Mandi: I think that's just the thing. We don't want to lose the problem. Once you start to disentangle it [the PCK construct] and those things [i.e., PCK components] become valued alone compared to the re-integration of those things as something that's also done.

Above, the experts were highlighting the importance of the interconnection between PCK components, in line with the thinking that PCK components interact in a complex and dynamic way that are synergistically applied in practice (Abell, 2008; Magnusson et al., 1999; Park & Chen, 2012). However, it remains unclear how the rubric should be structured to take into account the quality of the integration between the PCK components. With respect to this issue, Chris, coming from a measurement perspective, had this to say:

Chris: If we were to start with the premise of interconnectedness, our rubric would look very different. Our rubric might be something that's more akin to the way we might measure networks or social systems or the connectedness of ideas.

Collectively, the above discussion raises the issue of how to design a rubric that can take into account the assessment of the integration between the PCK components. How can the rubric take into account the assessment of each PCK component on the one hand and the integration between the components on the other?

(3) *How to measure quality of teachers' pedagogical reasoning?* As the discussion ensued, another distinct attribute of PCK became apparent. This acknowledgement was represented by the following quotes:

Julie: One thing that I don't see here is the idea of pedagogical reasoning.

Sven: It seems like selection [of instructional strategy] only becomes meaningful if the person can argue why he selects a certain strategy. This is especially true if you're not looking at what is happening in the classroom but more about his knowledge and how he works with his knowledge.

It appears that the experts subscribed to the views of Shulman (1987), who argued that a teacher's knowledge base only becomes useful when it is tied to judgement and teaching actions. For Shulman, the translation of knowledge to action involves a complex process called pedagogical reasoning where teachers reason about their judgment and decisions. Although the PCK experts affirmed the role of pedagogical reasoning within the PCK construct, how to define high-quality pedagogical reasoning remained less clear. Pernilla's statement illustrates this concern:

Pernilla: What I struggle with is, how do we find good quality reasoning in terms of how those different components interact and connect? If we can see that all the components actually interact and they are interconnected, [that is important]. I mean, [if actions] are reasoned and reflected [upon], is that high quality PCK? … I think it's more than only interaction between components.

Another issue that emerged was about *how* the assessment of pedagogical reasoning can be represented in the rubric, as evident in the following exchanges:

Mandi: [Pedagogical reasoning is to] explain and reflect on the "why." And I think it might be that pedagogical reasoning is more than a dimension of PCK. I might even say that pedagogical reasoning could be something which exists in all the different [components].

Elizabeth: I'm wondering whether, in each of these components in the rubric, if you'd have a particular criterion that elicits the reason for what you see. Even [for the PCK component], the next step is to decide whether those are appropriate [strategies]. You now have to find a reason and judge against your own understanding of what you see as well. You need to make the judgment whether this is an appropriate next step.

In this last comment, Elizabeth suggested embedding the measurement of pedagogical reasoning within each row of the rubric. In response, Alicia was quick to point out the drawbacks associated with this way of constructing the rubric:

Alicia: I think the thing you miss by putting pedagogical reasoning only at the top level of all the other [components] is you miss variation in the quality of the reasoning. So if you're just saying its present or absent as opposed to there's depth and quality of reasoning that might vary. I think [where you put pedagogical reasoning in the rubric] is a statement about how we think about it, whether we put it as something separate or at the top of everything.

In sum, it appears that the experts acknowledge the importance of pedagogical reasoning as part of the PCK construct. Their argument for placement of pedagogical reasoning in the rubric is an indication of the value placed on the construct; however, there is less clarity amongst the experts on how to construct a rubric that can measure the quality of pedagogical reasoning.

(4) *What is the learning theory underpinning the rubric?* While the experts discussed how to populate the different performance levels of the rubric, another issue emerged. The issue, implicit in the early part of the discussion, was pointed out explicitly by Julie:

Julie: Comments keep coming up [asking], do we have a learning theory behind this? It seems to me that at least part of our learning theory is that "teaching is not telling." What are we doing to promote student [learning], whether it is creating disequilibrium or helping students make meaning?

There were some dissenting voices as to whether it is important to specify a particular learning theory in the rubric. Chris, for example, described what he thinks below:

Chris: I just worry about taking the value approach with something like constructivism. I'm worried about it, especially since we're such an international group. Different countries value different approaches. I wonder what this [discussion] would look like in the Japanese context, German context, or an American.

Embedded in Chris' view above is the issue that teaching is a cultural activity (Stigler & Hiebert, 2009), which may cast doubts on whether the same learning theory is equally valued in different contexts when assessment of PCK is concerned. Proposing a single learning theory also goes against the very nature of PCK which is context-specific (Park & Oliver, 2008). With respect to this issue, Alicia took another perspective.

Alicia: Fundamentally, I think there's a connection. For PCK there has to be a connection between what you're doing and the students. So even if there's not an explicit learning theory like constructivism, it would be difficult to describe high PCK in a manner of "I'm just going to stand up and talk and not care about who's in front of me," right?

The above discussion suggests that while a learning theory may help guide the delineation of quality in different levels of performance in the rubric, there has yet to be a consensus on whether it is really needed and, if so, which learning theory should be drawn upon in the construction of a rubric.

(5) *What are the core components of PCK?* The experts were aware that the CM that emerged from the 1st PCK Summit (Gess-Newsome, 2015) did not adequately unpack the composition of PCK. With this need to expand upon PCK composition, the experts' discussion also revolved around the core attributes that should be included in the rubric. Julie commented:

Julie: So my observation is, as people talk about PCK, they have stayed or gone back to the Magnusson model. But if you look at the research that's been done, almost nobody, as Kennedy points out, has done much with the assessment or curriculum [components]. Everybody included student understanding and instructional strategies. … As I think about what is essential to PCK, it seems that student understanding and instructional strategies are a large part of that.

As most of the existing research on PCK studies drew on Magnusson's PCK model, it appears that this model provided a good starting point for the experts to think about a consensual view on the core components of PCK for science teaching. As the discussion continued, the experts in the discussion group identified several more core components within PCK. The discussion group members finally reached an agreement on the following key PCK components:

1. *Selection and connection of big ideas*: The big ideas selected are relevant to the students and are pedagogically appropriate. There is coherence among big ideas.
2. *Selection of instructional strategies and representations*: The instructional strategies and representations selected are appropriate for the students and content. A student-centred learning approach that promotes meaningful learning is used.
3. *Recognition of variations in student understanding*: There are opportunities for students to reveal their thinking, a climate for students to expose their thinking, and activities that engage students´ interests and student misconceptions/prior knowledge are included in the teaching.
4. *Selection of next appropriate steps*: The teacher is adjusting instructional moves based on student learning of concepts. The teacher uses productive representations to advance student thinking.
5. *Pedagogical reasoning*: There is an interaction between the components above and the teacher possesses the ability to justify his/her teaching.

From a measurement perspective, a clear delineation of the exact composition of PCK is a prerequisite for valid measurement of PCK. As the RCM does not delineate the composition of PCK, the discussion demarcates the scope and range of the PCK, as a specialised integrated form of professional knowledge and skills, for measurement.

To summarise this section, the discussion of the PCK experts raised important considerations in the possible construction of a grand rubric for measuring science teachers' PCK. These include: what the critical PCK components should be; the placement of content knowledge in the grand rubric; the possible need of a learning theory in populating a rubric; as well as how to measure the interaction of PCK components and pedagogical reasoning.

The Grand Rubric for Measuring Science Teachers' PCK

Across conversations in the two PCK Summits, the review of the literature using PCK rubrics, and the transcripts from the rubric discussion group, there are a number of implications for the key characteristics of a grand rubric for measuring science teachers' PCK. Most importantly, there was a commitment to *measuring* PCK and a recognition that a rubric offered an effective means of doing so. Characteristics of the grand rubric are presented below along with justifications from the literature review and rubric discussion group for their inclusion.

Overall Characteristics of the Grand Rubric for Measuring Science Teachers' PCK

- Although rubrics appear to be a useful way to measure PCK, current science PCK research uses over 20 distinct rubrics for measuring teachers' PCK, making communication across researchers almost impossible. The construction of a grand rubric allows for more effective communication and aggregation of results across studies.
- The rubric needs to be flexible enough to measure the different variants of PCK in the RCM: the cPCK of a group of teachers (what a group of teachers know); the pPCK of a teacher (what a teacher knows); and ePCK (what a teacher does); and pedagogical reasoning (the reasons for his/her judgment and actions). Such flexibility allows more versatility in PCK research and education.
- To be universally adoptable and adaptable, the grand rubric must be sufficiently generic to allow its customisation for use with different content and grain sizes—discipline, topic, or concept levels. The final rubric would be customised to each study, though the basic structure remains the same in order to compare data across studies on science teachers.
- The rubric needs to be designed to be used with multiple data types, allowing triangulation of data from different sources. Prior research suggests that the quality of science teachers' PCK may be different when different data sources were used to determine the teachers' PCK (Gardner & Gess-Newsome, 2011).

Structure and Components of the Grand Rubric for Measuring Science Teachers' PCK with Rationales

- For our model, we are proposing five components generated from the 2nd PCK Summit. We believe that this structure, based on expert opinions, establishes the content validity (i.e. relevance and representativeness of PCK) of the rubric. These five components are not explicitly articulated in the RCM (see Chap. 2).
- The rubric is composed of five rows, each corresponding to one of the five components that resulted from the 2nd PCK Summit These components are named below, with insights for each into the types of evaluation criteria that might be used to measure the component. The arrows between the lowest level and highest level boxes in Fig. 11.1 indicate a need to determine the number of the column in the rubric and to establish quality indicators for each evaluation criteria identified.

    1. Knowledge and Skills Related to Curricular Saliency: appropriate selection, connection, and coherence of big ideas; accuracy of content;
    2. Knowledge and Skills Related to Conceptual Teaching Strategies: selecting and using appropriate instructional strategies; using multiple representations;

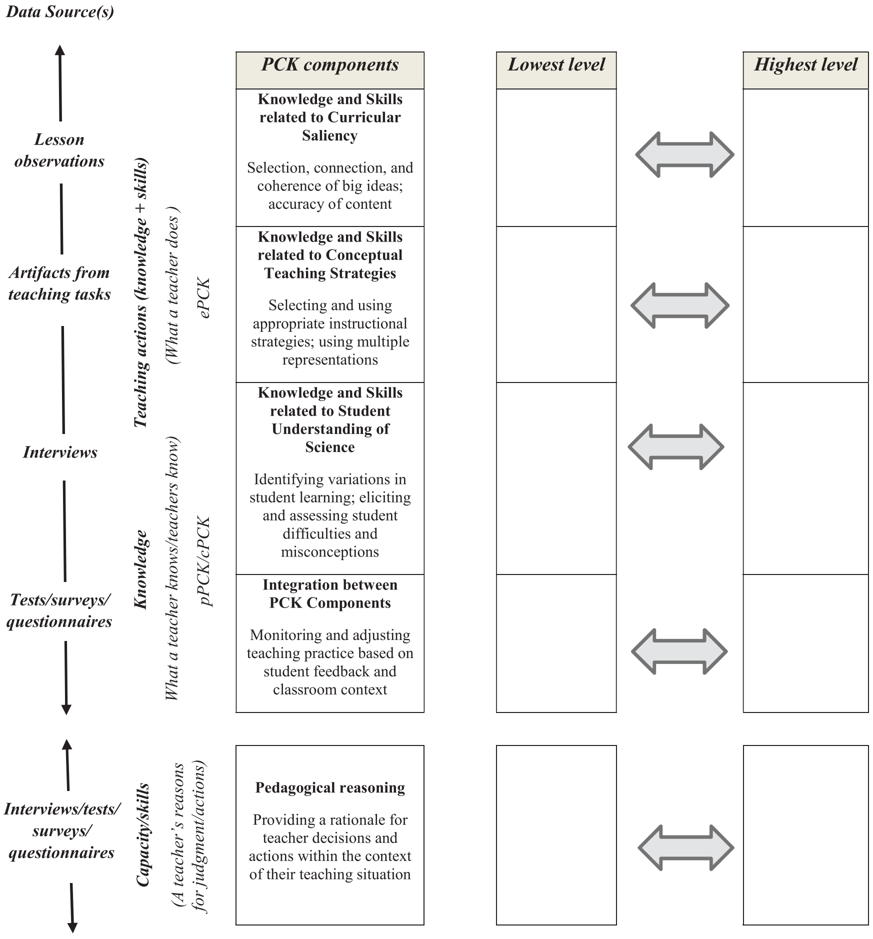

Fig. 11.1 Grand rubric template for measuring science teachers' PCK

3. Knowledge and Skills Related to Student Understanding of Science: identifying and acknowledging variations in student learning and eliciting and assessing student difficulties and misconceptions;
4. Integration Between PCK Components: monitoring and adjusting teaching practice based on student feedback and learning of the big ideas as well as the classroom context;
5. Pedagogical Reasoning: providing a rationale for teacher decision-making and actions within the context of their teaching situation.

- The first three components represent ideas that are consistent with the rubric discussion group and are similar to those found in the literature review (see Chap. 1).

- Integration between PCK components (row 4) is becoming a focus of investigation in recent PCK studies (see Chap. 1) and is considered important by the rubric discussion group. Such a measurement establishes that PCK is more than the sum of its parts.
- Pedagogical reasoning (row 5) acknowledges the importance of decision-making behind a science teacher's actions and is considered essential in the RCM (see Chap. 2).
- Since PCK represents a distinct category of knowledge distinct from CK in the RCM (see Chap. 2), we chose not to use a separate role for CK in the rubric to reflect this consensual view. However, it is quite clear that CK can influence the quality of the proposed PCK components.
- Quality indicators should be based on evidence from the research literature. For instance, when considering Knowledge and Skills related to Student Understanding of Science, teachers' ability to identify students' most common wrong answer is related to student learning is supported by research evidence (Sadler, Sonnert, Coyle, Cook-Smith, & Miller, 2013). Similarly, accuracy and hierarchical organisation of content knowledge is recognised as a feature of knowledge held by experts (Bransford, Brown, & Cocking, 1999).
- The rubric delineates a spectrum of performance levels (lowest level to highest level). Each categorical end of the spectrum represents the level of performance achievable by a subset of science teachers.
- While we did not gain consensus on the importance of an underlying learning theory, it was agreed that an underlying learning theory will influence the construction of quality indicators. We acknowledge that the indicators provided here are based on a broad constructivist framework. By citing research to support the selection of indicators, the theoretical features of the rubric will become more evident and should be acknowledged explicitly.

Data Sources

- The first column highlights the types of data sources that lend themselves to measurement.
- The first four components may be used to measure science teacher knowledge and/or actions. Teacher knowledge can be measured through the teachers' articulation of their pedagogical decisions in their planning (interviews, tests/surveys/questionnaires/lesson plans), or through examination of reflections. Alternatively, teacher knowledge may be *inferred* from their teaching actions (lesson observations) or teaching artefacts. Science teachers' PCK may be manifested in teaching actions through the use of pedagogical moves. The interaction between PCK components can also be measured directly or indirectly from teacher's statements, actions, or artefacts.
- The last row (i.e., pedagogical reasoning) relates to the science teachers' capacity to provide rationales for justifying their teaching actions. Pedagogical reasoning

cannot be accessed using *only* observation data. Stimulated recall interviews may be conducted with the teacher to access the teacher's pedagogical reasoning. In addition, a teacher may have a very good understanding of what they should do and why (i.e., knowledge and reasoning), but limited ability to implement that knowledge/skill in the classroom due to poor pedagogical skills (i.e., classroom management), contextual considerations (i.e., mandated curriculum), or motivational factors. The inclusion of teachers' pedagogical reasoning takes into account the teacher's sensitivity and responsiveness to the context.

How to Use the Grand Rubric Template

Generic guidelines for creating a rubric already exist. For example, the construction of a rubric often involves an iterative process comprising one or more of the following steps: articulating observable attributes; identifying characteristics for each attribute; identifying performance levels and corresponding criteria; and, revising the rubrics based on the empirical data (Mertler, 2001). We hope that by using the grand rubric template (Fig. 11.1) described in this chapter, science education researchers and practitioners can create a PCK rubric for the specific context in which it is needed.

The grand rubric can act as a generic template since it is designed to be customised to each setting. The science content topic under consideration and its grain size will need to be explicitly noted, as well as the age group of the students. To create or use a scoring guide, the researchers themselves will need to have strong PCK on the science topic and use evidence from empirical and canonical research and best practice. The terms that describe the level of performance will need to be proposed by the developer to better articulate the level of performance (e.g., limited, basic, proficient, and exemplary) and empirically defend via the data. Concrete descriptions/descriptors of each performance level, as well as detailed exemplars, would need to be included in the scoring guide, making them available to other researchers drawing on the research. A scoring guide will need to identify issues, such as the appropriateness of various instructional strategies or representations, the range of potential student misconceptions and those that are most common, and the evidence that will be used to judge the soundness of a rationale for specific actions. Published scoring guides will assist in articulating PCK for a given science topic and allow for their use across multiple settings. Scorer training would need to include the application of the scoring guide to actual data and inter-rater agreement, which might also result in refinement of the scoring guide.

Data collection tools should be carefully designed to elicit the ideas included in the rubric. For instance, purposeful questions about the selection of big ideas or specific misconceptions of concern might need to be asked directly, rather than assuming that such topics will arise spontaneously in a data source.

Finally, considerations for the validation and use of the rubric will need careful attention. What scoring strategy will be used? What is the meaning of a score related to a single component row? Is there an overall PCK score associated with the rubric?

How are component scores derived when there are different numbers of evaluation criteria? Does the rubric discriminate between individuals that we judge to have high and low PCK? Will a factor analysis provide evidence for the proposed PCK components?

Conclusion

This chapter explored considerations in the construction of a grand rubric for measuring science teachers' PCK. We examined the existing literature where PCK rubrics were developed and used, as well as critical considerations surfacing at the second PCK Summit. The proposed characteristics of the grand rubric for measuring science teachers' PCK provide it with several advantages: it can be used with multiple data sets and with different content and grain sizes, it is built on the RCM, and it draws on best practices found in the PCK literature. This grand rubric contributes to the field as it is an important tool for the measurement of science teachers' PCK. We hope that this chapter provides science education researchers and/or practitioners with guidance in the important work of creating purpose-built rubrics and associated data collection tools and scoring guides by customising the grand rubric template for use in their own contexts.

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Chapter 12
Unpacking the Complexity of Science Teachers' PCK in Action: Enacted and Personal PCK

Alicia C. Alonzo, Amanda Berry and Pernilla Nilsson

Abstract This chapter focuses on enacted PCK (ePCK), i.e. the specific knowledge and skills that science teachers use in their practice, as it plays out in specific classroom contexts while teaching particular content to their students. In unpacking this aspect of the Refined Consensus Model (RCM) of PCK, we consider both the nature of ePCK and its interactions with other realms of PCK, primarily personal PCK (pPCK). Recognising the complexity of classroom practice—in terms of both the uniqueness of each classroom situation and the necessarily spontaneous nature of classroom interactions—we propose a mechanism through which pPCK is transformed into ePCK, and vice versa, throughout the plan-teach-reflect cycle. We then illustrate these ideas using several empirical examples of efforts to capture and analyse science teachers' ePCK (and associated pPCK). We conclude with discussion of some of the opportunities, challenges and implications of using the RCM, along with our unpacking of ePCK and its relationship to pPCK, as a means of understanding the knowledge that science teachers utilise in the midst of planning, teaching and reflecting.

Introduction

The Refined Consensus Model (RCM) of PCK (Carlson, Daehler et al., this volume) builds on a model of teacher professional knowledge and skill developed from the First (1st) PCK Summit (Gess-Newsome, 2015). As compared to the earlier model and in the context of science education, the RCM has a stronger emphasis on making

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explicit the different variables, layers and complexities associated with PCK and highlighting in a clearer way the relationship between PCK and teaching practice. The RCM identifies three distinct "realms" of PCK: collective PCK (cPCK), representing the specialised professional knowledge held by multiple science educators in a field; personal PCK (pPCK), representing the personalised professional knowledge and skills held by an individual science teacher; and enacted PCK (ePCK), the unique subset of knowledge and skills that a science teacher draws on and that play out while planning, teaching and reflecting on a lesson. Within the model, these realms are represented as concentric rings, with cPCK in the outer ring, pPCK in the middle ring and ePCK in the centre (see Chap. 2, Fig. 2.3). The design of the model is intended to emphasise the practitioner perspective through the central placement of ePCK.

To date, research on science teachers' PCK has mostly focused on cPCK, e.g. assessing whether teachers know "canonical" PCK, and pPCK, e.g. getting teachers to articulate what they know about teaching a particular science topic in a particular context. However, there has been relatively little research focused on ePCK, i.e. how PCK is utilised in teachers' actual practice. Therefore, in this chapter, we focus on ePCK,

> the specific knowledge and skills utilised by an individual science teacher in a particular setting, with a particular student or group of students, with a goal for those students to learn a particular concept, collection of concepts, or a particular aspect of the discipline. (see Chap. 2)

We unpack this aspect of the RCM, providing our interpretation of ePCK in order to focus attention on the knowledge that science teachers make use of in action. Consistent with the interpretations in Chap. 2, we note that ePCK plays out not only when enacting instruction (i.e. when interacting directly with students), but also when planning for and reflecting on instruction. Thus, we consider ePCK to exist in three forms: ePCK_P (for planning), ePCK_T (for teaching) and ePCK_R (for reflecting). Below we argue that because ePCK focuses on specific and, thus, unique classroom situations, it must involve more than static, declarative knowledge or scripts and procedures. Further, we explore how ePCK, as constantly evolving in response to these unique classroom situations, not only relies upon but also drives modifications to science teachers' pPCK.

Thus, in the sections below, we start with a brief overview of pPCK. We then unpack our interpretation of ePCK as a form of knowledge in action. Next, we explain how we view ePCK and pPCK as mutually influential, proposing a mechanism through which these two realms of knowledge interact and evolve through the plan-teach-reflect cycle, as pPCK is transformed into ePCK, and vice versa. In order to illustrate these ideas, we then present several examples of efforts to capture and analyse science teachers' ePCK and pPCK. Finally, we discuss some of the opportunities, challenges and implications of using the RCM and, in particular, our unpacking of ePCK and its relationship to pPCK, as a means of understanding the knowledge that science teachers use while planning, enacting and reflecting on instruction.

The Nature of pPCK

Personal PCK (pPCK) refers to the knowledge resources that an individual science teacher brings to the classroom enabling her/him to think and perform as a teacher in order to promote student learning about specific science subject matter. In understanding pPCK as a form of *personal knowledge*, we draw on Eraut (2000) who defines personal knowledge as

> the personal, available for use, version of a public concept or idea…[that] incorporates codified knowledge in its personalised form, together with procedural knowledge and process knowledge, experiential knowledge and impressions in episodic memory. Skills are part of this knowledge, thus allowing representations of competence, capability or expertise in which the use of the skills and propositional knowledge are closely integrated. (p.114)

Hence, pPCK is a specialised form of personal knowledge that includes different knowledge resources related to the teaching and learning of specific science topics. Consistent with Eraut (2000), who considers skills to be part of knowledge, in this chapter we refer to knowledge and skills collectively as knowledge. pPCK includes both explicit (i.e., articulable) knowledge and tacit knowledge (e.g., experiential knowledge, impressions in episodic memory) and is therefore unique for each science teacher. pPCK differs from cPCK in that cPCK represents publicly held (i.e., shared) codified knowledge.

The Nature of ePCK

Consistent with its connection to practice in the RCM, we consider ePCK to be "tacit knowledge in action" (Eraut, 2000, p. 123), i.e., knowledge that science teachers draw on in the moment of action, where the action may include planning, teaching or reflecting on teaching. This interpretation has two important implications. First, ePCK exists only in action (i.e., as tacit, unarticulated knowledge). Second, ePCK is flexible and generated in the moment of action. Since action occurs in the moment, the underlying ePCK is also adaptive, created and used in that moment. Thus, we contrast ePCK with pPCK and cPCK, which are more declarative and relatively more stable (or static) forms of knowledge.[1,2]

Science teaching is responsive to students and context, so each classroom situation is (at least) slightly different from others that a teacher has experienced (or knows

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[1] This is not to say that pPCK and cPCK do not evolve over time (indeed, as detailed below, we argue that pPCK changes through the construction of ePCK). However, both pPCK and cPCK are static in the sense that it is (theoretically) possible to articulate this knowledge and, thus, to measure it, whereas ePCK is inarticulable and fleeting, existing only in the moment (before potentially being transformed into pPCK). In other words, we fully expect that all three realms of teachers' PCK will change over time, but that change in ePCK will occur at a much shorter timescale.

[2] In this contrast, i.e., a focus on knowledge that is not declarative and not static, we connect with literature that refers to "dynamic PCK" (e.g. Alonzo & Kim, 2016; Schmelzing et al., 2013) as opposed to "declarative PCK".

about). Thus, the ePCK utilised in each classroom situation is unique, and it is unlikely (and even impossible) for a science teacher to already possess the exact ePCK required to plan, enact and reflect on instruction about a particular topic for a particular group of students in a particular setting. Thus, ePCK must be constructed anew for each teaching episode. Of course, ePCK for a given classroom situation might be almost identical to that for another similar situation, but differences in terms of the context and/or students will necessitate (even very small) tweaks, resulting in unique ePCK for that setting. Therefore, new ePCK is constantly being generated for each science teacher during every act of planning, enacting and reflecting on instruction.

Therefore, we view ePCK as the knowledge in action generated during, and made visible in, science teachers' planning (ePCK_P), enactment (ePCK_T) and reflection (ePCK_R) on instruction in a particular classroom situation. As such, ePCK is the unarticulated knowledge that underlies action in each of these activities. ePCK_T is perhaps easiest to imagine, as the knowledge that underlies science teachers' in-the-moment instructional decisions. Teachers respond to students—e.g., with feedback, with explanations or demonstrations, and questions—in the midst of science instruction, without articulating (even to themselves) the reasoning behind those decisions. Similarly, when planning, teachers may propose particular instructional activities, with the intuitive sense that they will be appropriate for a given upcoming classroom situation (ePCK_P). Reflections may start with a teacher's sense that a given activity did not "go well" or that a particular student was confused about part of the lesson (ePCK_R). Such reflections, tied to specific instances and/or specific students, do not already exist as part of a teacher's ePCK—and a teacher may not have associated declarative knowledge to express the basis for his/her concerns. As discussed in the section below, these intuitive actions (planning, teaching and reflecting) are all influenced by a science teacher's pPCK; however, in the moment, they exist as ePCK.

Relationships Between ePCK and pPCK

In this section, we describe how—through the constant generation of ePCK and the interaction between ePCK and pPCK—teaching experience can lead to changes in both science teachers' ePCK and pPCK. We depict this process in Fig. 12.1, which is an expansion of the ePCK and pPCK parts of the RCM (see Chap. 2), depicting in more detail both the different forms of ePCK and the specific points at which pPCK influences ePCK and vice versa. To illustrate the fuzziness that we see between ePCK and pPCK (particularly in their tacit forms), we have blurred the line representing the interface between ePCK and pPCK.[3] As shown in Fig. 12.1, in the RCM, double-sided arrows on the interface between ePCK and pPCK indicate a bidirectional flow

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[3] Although not discussed here, we expect that similar ambiguities exist at the pPCK–cPCK interface; thus, the outside of the pPCK ring (i.e. the boundary between pPCK and cPCK) is likewise blurred in Fig. 12.1.

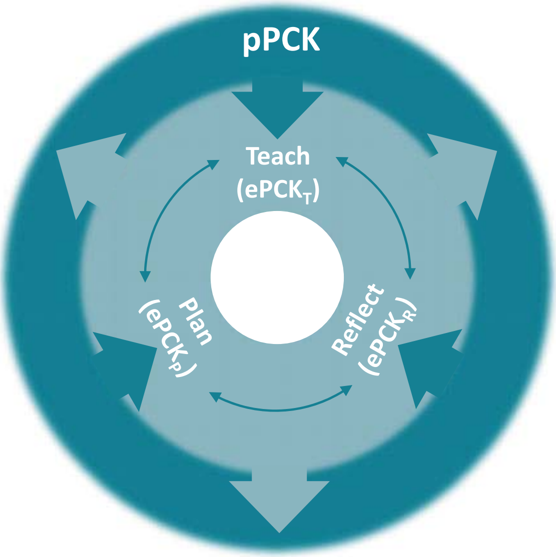

Fig. 12.1 Relationships among ePCK stages and between ePCK and pPCK

between these two realms of PCK, representing how pPCK influences ePCK and vice versa.

First, pPCK provides the basis for ePCK at each step of the plan-teach-reflect cycle. In other words, ePCK is generated in the moment, but not out of thin air. All of a science teacher's knowledge, from past teaching and learning experiences, including classroom situations that are similar to the current one, serve as resources. The three dark blue arrows pointed inwards in Fig. 12.1 represent this sourcing of extant knowledge. Second, ePCK is transformed into pPCK, i.e., part of the store of knowledge available for future planning, teaching and reflecting. Consistent with the composition of pPCK as including both explicit and tacit knowledge, ePCK may be transformed into pPCK in either of these forms. The three light blue arrows pointed outwards in Fig. 12.1, following each stage of the plan-teach-reflect cycle, represent the transformation of ePCK into both explicit and tacit forms of pPCK. A conscious process may transform ePCK into pPCK in a form that can be articulated by the teacher. This transformation happens primarily through reflection in, or on, a science teaching episode as intuition and experiences become part of future knowledge that can be explicitly drawn upon in planning, teaching and reflection. For example, a teacher may recognise a student learning difficulty during class and later explicitly draw on this experience to inform future teaching. In a subconscious process, ePCK may also be transformed directly into pPCK without the teacher's conscious awareness.[4] In this case, a science teaching episode (e.g., recognising a student difficulty)

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[4] While repeated encounters with similar situations may eventually lead to tacit knowledge becoming explicit, the opposite may also be true, i.e. explicit knowledge may become tacit, for instance, through the routinisation of certain instructional moves over time, as is the case with highly expert

becomes subconsciously incorporated into memory that forms part of a tacit knowledge base that may be activated to inform future action (tacit pPCK). Transformation of ePCK into pPCK includes instances of planning and reflecting as well as teaching.

Before unpacking these mechanisms for each stage of the plan-teach-reflect cycle, we note that this cycle occurs on two timescales: a “macro” one focused on a unit of instruction (e.g. a lesson) and a “micro” one focused in-the-moment during a unit of instruction (i.e. many such moments in a lesson). At the lesson level, a teacher plans the lesson, teaches the lesson and then reflects on learning and instruction during the lesson. The teaching of the lesson includes all of the instructional moves that the science teacher makes (whether planned or unplanned). When reflections at the “macro” level are made explicit, ePCK is transformed into pPCK as articulable knowledge.

As illustrated in Fig. 12.2, we can also “zoom in” to investigate how the teaching of the science lesson (as a series of instructional moves) arises. At this level, we see a reflect-plan-teach cycle associated with each instructional move in the “macro” cycle. Here, instruction (“teach” in the macrocycle) comprises a series of instructional moves (“teach” in the microcycle). In contrast, the planning and reflection that occur as part of the microcycle happen during “teach” in the macrocycle (i.e. distinct from the planning and reflection that occur before and after a lesson, respectively). In a microcycle, a particular instance (e.g. an interaction with a student) prompts reflection (i.e., noticing and identifying the significance of a student’s question or contribution to a class discussion), a plan for how to respond and the instruction (i.e., the response, such as a follow-up question to the student or a revision to the instructional plan). As this entire cycle takes place in one instance, in the moment between the student’s contribution and the teacher’s response, the ePCK generated is likely to remain tacit and, thus, unless included in reflection as part of the “macro” cycle, more likely to be transformed into pPCK in tacit form.

As described above, since each student and each classroom context is a little bit different, most teaching situations will present science teachers with some similarity to past teaching situations and/or teachers’ prior knowledge, but also some uniqueness—such that existing pPCK is relevant and useful, but ePCK must be generated for a particular situation. Thus, when planning instruction, science teachers draw on their existing pPCK, using knowledge of common ways students interact with the content and instructional strategies that can be used to address that content in order to identify a particular set and sequence of learning activities. As teachers tailor instruction to a particular classroom context and group of students, they may propose learning sequences and/or instructional moves without explicitly articulating the underlying reasoning (e.g., knowledge of common student learning difficulties, knowledge of the conditions under which a particular instructional strategy is most beneficial)—or even being aware of it themselves. Through this process, science teachers generate their ePCK$_P$.

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teachers. Thus, ePCK that is transformed into pPCK in tacit form may eventually become explicit pPCK, and ePCK that is transformed into pPCK in explicit form may eventually become tacit pPCK.

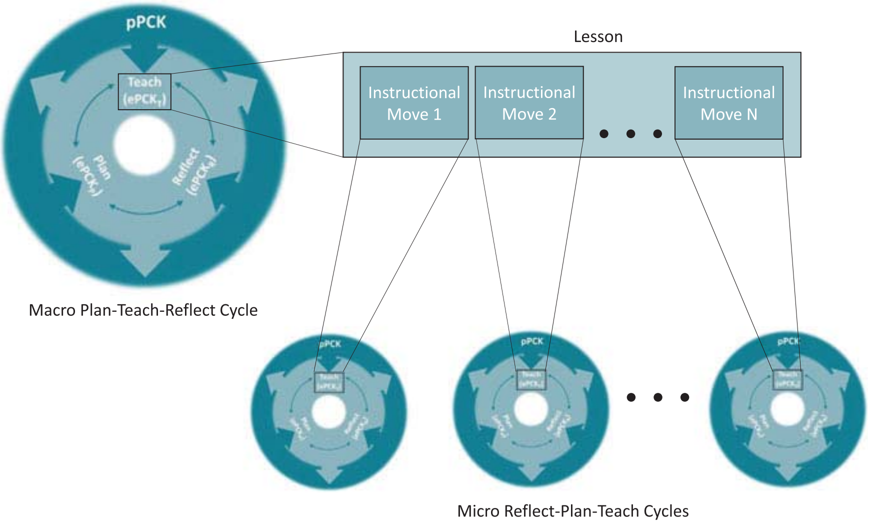

Fig. 12.2 Macro- and microplan-teach-reflect cycles

Science teaching is complex and uncertain, requiring continuous in-the-moment responses to students' learning needs and features of the classroom context. While teachers' pPCK may include a range of instructional strategies associated with particular classroom conditions, teachers are unlikely to find themselves in those precise conditions in any given teaching situation. Therefore, to support student learning, they must generate responses appropriate for the moment. Through this process, science teachers generate their ePCK$_{\mathrm{T}}$.

During and after instruction, teachers may reflect on their planned instruction (ePCK$_{\mathrm{P}}$), their in-the-moment adaptations (ePCK$_{\mathrm{T}}$) and/or the foundational knowledge (pPCK) underlying both. When reflecting on the outcome of enacting a strategy in the unique situation of a particular set of interacting factors in a particular classroom context, science teachers generate ePCK$_{\mathrm{R}}$. While drawing on pPCK (e.g., knowledge of common student difficulties or common student expressions of content understanding) that is applicable across classroom situations, teachers engage in in-the-moment reflections specific to the particular incident under consideration. For example, a teacher may identify that a particular moment was key to the success (or difficulty) that students experienced in a lesson, or he/she may recognise a particular student's contribution as indicative of a preconception that she had not encountered before. When this ePCK$_{\mathrm{R}}$ is articulated and/or stored as knowledge that, while contextualised in the teacher's classroom, exists for use beyond the specific students and classroom conditions under which it was generated, it becomes part of a science teachers' pPCK. In this way, insights gained from the specific situation may contribute to new knowledge that can be applied in other situations.

Thus, whether coming up with instructional strategies appropriate for a given classroom situation (ePCK$_P$), recognising new evidence of student thinking (ePCK$_T$), or reflecting on the outcome of instructional strategies or a response to evidence of student thinking (ePCK$_R$), science teachers build on existing pPCK and generate new ePCK. When articulated, the new ePCK can be incorporated into a teacher's pPCK. In this way, the interplay between these different realms of PCK operates in both directions: ePCK informs and is informed by pPCK.

To illustrate how these different forms of ePCK play out in a science teaching episode, consider the following example. Recalling how her students have struggled to understand natural selection (pPCK), a biology teacher designs an activity to address common learning difficulties (ePCK$_P$). While teaching the lesson, a student expresses an understanding of natural selection that the teacher was not expecting. On the spot, she decides to use Darwin's Galapagos finches to respond to the student (ePCK$_T$). After school, the teacher thinks about how the student may have come up with his idea (ePCK$_R$). She remembers the student idea and her explanation so that she can anticipate this response when she teaches natural selection again (pPCK). Considering just the teacher's instructional response in the lesson, we can zoom in further to see how ePCK plays out at the level of the microcycle described above. While some evidence of student thinking may be presented in ways that match perfectly with teachers' prior knowledge (i.e., pPCK), most classroom situations require teachers to recognise/notice something they have never encountered before—whether a particular student's way of expressing a known pattern of student thinking or evidence of truly novel student thinking. Thus, when the student expresses her understanding of natural selection, the teacher must immediately make sense of the student idea (i.e., what it indicates about student understanding, what the student does and does not understand; generating ePCK$_R$). Still acting in the moment, the teacher must then make a decision about how to respond, (i.e., plan an instructional move; generating ePCK$_P$) and enact the planned response (generating ePCK$_T$). In these in-the-moment instances, ePCK is likely to be transformed into pPCK only tacitly, but this decision is also available for reflection in the macrocycle and, thus, could contribute to the development of more explicit pPCK.

Illuminating the Complexity of Science Teachers' PCK in Action: Empirical Examples

In the sections above, we laid out a conceptualisation of ePCK and its relationship to pPCK in order to unpack how these realms of PCK are brought to bear in the moment of planning, teaching and reflecting. In this section, we provide examples from empirical work on PCK that help to both illustrate our conceptualisation and illuminate the complexity of the knowledge in action that we seek to understand by articulating ePCK and pPCK. We start with an example of the processes by which pPCK is transformed into ePCK and then ePCK is transformed into pPCK, both through pedagogical reasoning. This example helps to make concrete specific features of ePCK and pPCK described above and provides further elaboration of the pedagogical reasoning inherent in the transformation from ePCK into pPCK.

Since ePCK is tacit knowledge, the best efforts to capture ePCK may still only result in approximations of this realm of science teachers' PCK. The next two examples in this section represent different approaches to making such approximations, both seeking to understand the ePCK that is utilised in the moment of instruction (i.e., in microcycles of plan-teach-reflect). These examples serve to illustrate the complexity of capturing ePCK, pointing out where reasonable approximations can and cannot be made.

All three examples highlight tools and approaches that have been developed to capture and/or support science teachers' PCK in action. While standardised instruments can be used to evaluate whether teachers have acquired particular cPCK, the contextualised nature of pPCK and ePCK requires different kinds of tools and approaches. Below, we describe the use of some of these tools and approaches and the extent to which they can be used to gain insights into science teachers' ePCK and/or pPCK and the interaction between them both.

Pedagogical Reasoning: Transformations Between ePCK and pPCK in Macro- and Microcycles of Plan-Teach-Reflect

For the purpose of stimulating science teachers' reflections and developing their PCK, Content Representations (CoRes) have been shown to be a useful pedagogical tool (Hume & Berry, 2011; Loughran, Berry, & Mulhall, 2006; Nilsson & Loughran, 2012). Further, in her review on PCK, Kind (2009) argued that the CoRe tool offers the most useful technique devised to date in science education research for eliciting and capturing PCK directly from teachers. Constructing a CoRe requires the teacher(s) to reflect upon how to teach a specific topic in order to promote students' learning. It prompts the teacher(s) to articulate what is called "big ideas" and address queries that include: what students should learn about each big idea; why it is important for students to know these ideas; students' possible difficulties with learning the ideas; and how these ideas fit in with the knowledge the teacher holds about that content. In this way, working with the CoRe as a reflective tool has the potential for transforming science teachers' tacit pPCK into explicit pPCK but also, when implemented into teaching practice, informing teachers' ePCK for planning ($\mathrm{ePCK_P}$), teaching ($\mathrm{ePCK_T}$) and reflecting ($\mathrm{ePCK_R}$). CoRes may also be used to represent the collective views of a group of science teachers for teaching a specific topic, so that a CoRe also represents a form of cPCK for that teacher group.

In Nilsson and Karlsson´s (2018) research, the CoRe was introduced to student science teachers as a tool to stimulate their thinking about links between the content, teaching and student learning as they individually planned and tailored science instruction to a particular secondary classroom context and group of students. As such, each student teacher's individual CoRe was used to stimulate the transformation of pPCK into ePCK (for planning, teaching and reflecting). During the planning process, the student teachers were also encouraged to use resources such as curriculum materials and educational research, thus supporting the process of transforming cPCK into pPCK. The student teachers then taught a science lesson based on their constructed CoRes. Following their teaching, the student teachers viewed their video-recorded lessons and were encouraged to reflect upon their teaching performance to identify unexpected moments (expressed as critical incidents) in relation to their CoRes. Each student teacher chose two science teaching episodes, each about 4–8 min in length, representing: (1) a critical incident where she/he had succeeded in accordance with the big ideas in the CoRe and (2) a critical incident where she/he had experienced difficulties in fulfilling ambitions as expressed in the CoRe. The student teachers made annotations in the videos pinpointing these two critical incidents and providing reasoning as to why they felt they had succeeded or not in achieving their aims as expressed in the CoRes. In this way, the student teachers' video-recorded lessons were used to scaffold and structure their articulation of their in-the-moment pedagogical reasoning, transforming their $\mathrm{ePCK_T}$ and their $\mathrm{ePCK_R}$ into pPCK.

The outcomes of this research indicate that CoRe design prior to teaching episodes raises student science teachers' awareness of teaching issues around certain science content and engages them in reflection and decision-making that they enact in classrooms. As such, the research supports the notion that reasoning about specific instances of practice can help student teachers develop different aspects of their pPCK (e.g. knowledge of content and knowledge of students' understanding) as well as their ePCK (i.e., knowledge that teachers draw on in the moment of action, where the action may include planning, teaching or reflecting on teaching). The use of the CoRe as a tool for planning the science lesson illustrates the macrocycle of the unit of instruction. At the same time, the use of video annotations highlighting critical incidents illustrates the microcycle. Such a way of organising student teachers' reflective work during their practicum implies a transformation from pPCK to ePCK to more sophisticated form of pPCK through the process of pedagogical reasoning, from both a macro- and a microlevel perspective. As such, the CoRe, together with the video annotation tool, proved to be successful in scaffolding, structuring and even transforming student teachers' reflections, and consequently contributed to their pPCK development.

Approximating ePCK in Microcycles of Plan-Teach-Reflect

The tacit nature of ePCK presents a clear challenge for researchers seeking to capture this realm of PCK. Even when connected to a particular instance of science instruction, artefacts such as lesson plans or annotated videos capture pPCK (expressed when teachers' reasoning is made explicit as part of macroprocesses of planning or reflecting), rather than ePCK. Because ePCK is transformed into pPCK as it is made explicit, we argue that it is impossible to capture the true nature of ePCK.

An alternative approach is to try to infer ePCK through evidence of the planning, teaching and reflecting that occurs in association with a single instructional move in science teaching (i.e., a microplan-teach-reflect cycle). In this section, we describe two examples of this approach.

Cognitive science research suggests that, even a short time after a given activity, people are unable to recall exactly what they were thinking when engaged in that activity (e.g., Ericsson and Simon, 1993; Leighton, 2004). Therefore, there is reason to believe that inferring the ePCK associated with a given instructional move would require teachers to "think aloud" (Ericsson and Simon, 1993) while teaching (i.e., to articulate pedagogical reasoning associated with the planning, enacting and reflection on that instructional move).[5] "Thinking aloud" would allow inferences of $\mathrm{ePCK_T}$ to be made directly from the observed instructional move, but also provide opportunities (a) to elicit pPCK associated with planning and reflecting (as a proxy for $\mathrm{ePCK_P}$ and $\mathrm{ePCK_R}$) and (b) to elicit pPCK associated with teaching (to check inferences about $\mathrm{ePCK_T}$ made directly from teaching actions). Unfortunately, this ideal is clearly not feasible in real classroom settings. Thus, researchers turn to work with science teachers outside of the classroom context to try to recapture or to simulate aspects of the plan-teach-reflect cycle that happen in-the-moment during instruction. We describe a method of each type in the sections below.

Documenting Evidence of ePCK and Associated pPCK

Pedagogical and Professional-experience Repertoires (PaP-eRs) (Loughran, Milroy, Berry, Mulhall, & Gunstone, 2001) offer one means of representing science teachers' in-the-moment instructional decisions and actions. PaP-eRs are short (1–2 pages) vignettes intended to represent the thoughts and actions of a knowledgeable science teacher in teaching a specific aspect of the content to students in a particular context. PaP-eRs include information about the classroom context, the teacher's thinking about the content, examples of students' responses, and what it is about the content that shapes the approach to teaching and learning and why. PaP-eRs are constructed by researchers in consultation with teachers from data gained while observing a particular science teacher's classroom and/or through interviewing a teacher about an instance of practice where he/she came to understand the content differently as a consequence of teaching it. Through making explicit these components of classroom practice and associated teacher reasoning, PaP-eRs capture aspects of a teacher's $\mathrm{ePCK_P}$, $\mathrm{ePCK_T}$ and $\mathrm{ePCK_{R,}}$ within the microcycles of instructional moves occurring in the lesson, and since PaP-eRs are constructed post-lesson, their $\mathrm{ePCK_R}$ in the

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[5] While acknowledging that video stimulated recall is often used to elicit teachers' recollections of in-the-moment reasoning (e.g., Akerson, Flick, & Lederman, 2000; Nilsson, 2008), following Ericsson and Simon (1993), it seems that such efforts may be accessing existing pPCK (i.e., the way a teacher has made sense of a given classroom event after the fact), rather than pPCK that is being transformed directly from ePCK during the stimulated recall (i.e., pPCK that could serve as a direct proxy for ePCK).

macrocycle of instruction, as teachers think back on their planned instruction and its subsequent student outcomes.

For example, Bertram and Loughran (2012) used CoRes in combination with PaP-eRs to investigate the development of experienced secondary science teachers' PCK over a two-year period. In this study, participating teachers ($n = 6$) individually created CoRes for a science topic they planned to teach, then reflected on the process of making the CoRe and how that process influenced their thinking about teaching and learning, and how it influenced their understanding of PCK. As Bertram and Loughran (2012) noted:

> in creating the CoRe, it forced these teachers to explicitly think about and connect with their tacit knowledge about teaching and learning. Thus, the process of working through developing a CoRe encouraged these participants to find ways of articulating that which they knew and how they developed their knowledge of practice. (p.1036)

Following their teaching of the topic, participants were then asked to develop a PaP-eR (in collaboration with the researchers) illustrating a particular classroom teaching episode in science based on their CoRe. As one participant noted:

> "So, what I feel is - that this [PaP-eR] is articulating, documenting, making explicit - that kind of process which … on reflection, is a process … that I have going on in my head all the time, in relation to teaching…". (p.1040)

Bertram and Loughran's study showed the use of the CoRe and PaP-eR tools enhanced science teachers' knowledge of practice (i.e., transformation of ePCK to pPCK) through making explicit and sharing their knowledge about teaching and helping to highlight the ways in which content and purpose are closely linked in teaching. In particular, all participants claimed that developing their PaP-eRs encouraged their self-reflection and self-evaluation of their specific contexts and teaching practices (pPCK and ePCK_R) and helped to pinpoint areas in which they could improve (e.g., connecting with particular students and their learning needs).

Stimulating Generation of ePCK Outside of the Classroom

Simulating aspects of the plan-teach-reflect cycle that happen in-the-moment during science instruction, outside of the classroom involves a trade-off between the authenticity of a real classroom situation (such as represented in the PaP-eRs) and the ability to capture approximations of ePCK that would be unfeasible in real classroom situations. While not engaging teachers with their own students in their own teaching contexts, this method often incorporates elements of real teaching situations, such as authentic prompts (e.g., video of students expressing their ideas) and authentic response formats (e.g., interacting with a live actor). To date, these methods have not captured all three types of ePCK, focusing either on teachers' articulating in-the-moment decision-making (ePCK_P and ePCK_R) or researchers making inferences on the basis of teachers' in-the-moment actions (ePCK_T).

In order to simulate a science teacher's encountering of unexpected student thinking in a classroom situation, Alonzo and Kim (2016) presented teachers with videos of students expressing ideas about force and motion. The videos, all drawn from real physics classrooms similar to those of the participating teachers, highlighted unusual student thinking—i.e., "unexpected or novel student ideas or questions" (p. 1268). Teachers were asked first to describe the student thinking in the video and then to explain how they might respond to the student. The intent was to capture teachers' in-the-moment reasoning if a student were to offer the same statement or question in their own classrooms, by asking teachers to make explicit (i.e., transform into pPCK) the ePCK_R and ePCK_P, respectively, that might underlie a classroom instructional response.

In contrast, two German research groups have devised methods to simulate science teaching situations and teachers' actual responses to students (i.e., opportunities to infer ePCK_T), but do not require teachers to describe their planning or reflecting processes and, thus, do not capture ePCK_P or ePCK_R. In the domain of mathematics education, Lindmeier and colleagues (Knievel, Lindmeier, & Heinze, 2015; Lindmeier, 2011) used videos of classroom situations highlighting student thinking; however, rather than describing potential instructional moves to an interviewer, teachers were asked to speak (to a computer) as if directly to the student. With this method, researchers capture teachers' instructional moves in response to the video and, thus, infer their underlying ePCK_T. As the video-recorded student cannot react to the teacher's instruction, this method (like the one used by Alonzo and Kim) involves a single instructional move.

The method used by Kulgemeyer and Schecker (2013) entails multiple instructional moves. In this method, teachers are given time to prepare an explanation of a particular physics problem and then are asked to provide that explanation to a "student" (a specially trained live actor). The student asks questions or provides other responses to the teacher's explanation, using a predetermined script. With this method, researchers can capture instructional moves that the science teacher makes throughout the explanation interaction and, thus, infer evidence for ePCK_T across multiple plan-teach-respond cycles.

In the above described examples, Alonzo and Kim captured ePCK_P and ePCK_R, while Lindemeir, Kulgemeyer and colleagues captured ePCK_T. In order to capture all three forms of ePCK, one might imagine a hybrid situation, in which science teachers are presented with evidence of student thinking and are then asked to (a) articulate not only a proposal for how to respond to the student thinking, but also the reflection and planning underlying the proposed instructional response (i.e., transform ePCK_R and ePCK_P into pPCK) and (b) enact that response (i.e., provide evidence from which ePCK_T might be inferred).

One advantage of all of these approaches is that they permit comparison across teachers. While it is impossible to observe multiple science teachers in the exact same "real" classroom situation, the same video can be shown over and over again, and actors can be trained to behave similarly when interacting with many different teachers. At the same time, this advantage is a limitation, in that ePCK—like the pPCK on which is it based—is specific to a teacher's own teaching context. Simulations outside of the classroom strip that context away from the enactment. Thus, it is likely that multiple approaches, in combination, will be required to fully approximate a teacher's ePCK. Methods such as PaP-eRs provide authentic contextualisation, whereas simulations outside of the classroom may capture closer approximations of ePCK.

Conclusion

To date, research on PCK in the science education field has largely focused on relatively static forms of propositional knowledge and, thus, has deepened our understanding of the composition and structure of teachers' cPCK and pPCK, i.e., the outer rings of the RCM (see Fig. 2.3, Chap. 2). Like other chapters in Part III, ours illustrates how the RCM can be used to classify different realms of PCK and, therefore, more clearly articulate the focus of a given research or teacher education effort. As shown in Figs. 12.1 and 12.2, we found it useful to identify the different types of enactment and, thus, the different types of ePCK that are entailed in enacting macro- and microplan-teach-reflect cycles. In doing so, we highlight the growing body of research that draws attention to the centre of the RCM, exploring science teachers' ePCK (i.e., PCK in action) and the relationships that exist between ePCK and pPCK. We argue that this work is essential if we are to understand not just what science teachers know, but how that knowledge is transformed into learning experiences for students.

We bring to the RCM a strong interest in and commitment to the aspects of teachers' work that take place "in action". While the RCM acknowledges this realm of PCK (i.e., ePCK), it has not yet been fully elaborated. Thus, in this chapter, we have sought to unpack ePCK and its relationship to pPCK. By considering ePCK to be tacit knowledge in action, we emphasise that teachers' knowledge is often not made explicit, especially in the midst of interacting with students. Our perspective on the relationship between ePCK and pPCK allows us to explain how pedagogical reasoning facilitates the gradual growth of pPCK in response to the experience of teaching particular content to particular students in particular contexts. This perspective also helps us to articulate why it is so difficult to capture exactly what enables a given moment of instruction. So much of what happens in the moment is tacit. While teachers make a number of instructional moves throughout a lesson—many of them unplanned and, thus, generated in the moment—it is extremely rare for the knowledge resources (e.g., knowledge, decision-making) underlying a given move to be made explicit as part of instruction. We cannot directly observe the ePCK involved in teachers' planning, teaching or reflecting and, thus, do not know exactly what motivates a given instructional move.

We put forth this interpretation of ePCK and its relationship to pPCK with the goal of enabling other researchers to utilise this critical area of the RCM. As others heed the call to focus more attention on PCK in action (e.g., Henze & van Driel, 2015), we see the constructs of ePCK and pPCK as especially valuable for clarity in communicating the aims and challenges of our research and in devising ways to capture particular aspects of PCK in action.

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