Chapter 7
Illustrating and Developing Science Teachers' Pedagogical Content Knowledge Through Learning Study

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Abstract Using a teacher educator's perspective to study pedagogical content knowledge (PCK) as described in the Refined Consensus Model (RCM) of PCK, this chapter explores an approach to uncover teacher thinking that is grounded in the complex work of teaching and learning about teaching. PCK is described in the RCM as the knowledge that supports science teachers' pedagogical reasoning during teaching. Stated from a teacher educator's perspective, PCK is the knowledge used and developed by science teachers in their teaching practice. The complexity of teaching, however, creates a challenge for researchers and teacher educators interested in gathering evidence to better understand and document science teachers' developing PCK. An approach to supporting science teacher learning that is embedded in the facets of teaching—planning, enacting, and reflecting—is learning study. Learning study engages teachers in cycles of describing phenomenon-based tasks, anticipating students' ideas, and analysing learning. Each of these phases in the study of learning draws on science teachers' pedagogical reasoning in ways that appear to be aligned with descriptions of collective PCK (cPCK) and distinguishes qualitative differences between individual teacher's ePCK. In the context of graduate teacher education, this chapter describes the potential of learning study to enable researchers and teacher educators to capture, unpack, and refine our ideas about the features of PCK that guide science teachers' thinking within the different facets of their teaching.

Introduction

As a construct that promises to be helpful in describing what science teachers need to learn, pedagogical content knowledge (PCK) can be an interesting idea for teacher educators. The challenge has been how to incorporate ideas about PCK into designs for science teacher education and, in turn, demonstrate teachers' learning. The work of the Second (2nd) PCK Summit was to refine our model of PCK in ways that would better illustrate the group's thinking and to explore methods of gathering data

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on science teachers' PCK. How to use this Refined Consensus Model (RCM) of PCK to frame research that identifies science teachers' PCK from empirical data is an interesting challenge for both teacher educators and researchers. The research work described in this chapter is approached from a teacher educator's perspective. The idea is to investigate how PCK, as conceptualised in the RCM, might be useful in guiding the design of experiences intended for science teachers' learning while at the same time illustrating teachers' PCK. This chapter describes how teacher-developed learning studies might be an approach to observe teachers' developing PCK in ways that can inform our thinking about how to model and research PCK.

Studying PCK in Science Teacher Education

Studying PCK from a teacher educator's perspective means thinking about PCK as a tool for describing what teachers need to learn about teaching science. Teaching is an incredibly complex and dynamic activity that takes time and effort to learn well (Lampert, 2001). It is a multifaceted activity that involves planning, enacting, and reflecting around tasks intended for student learning. To support teacher learning, teacher educators are challenged to design tasks for teachers—preservice and continuing—that will develop teachers' thinking about teaching and that document their progress (Grossman, 2005). A model for science teacher knowledge that represents the complexity of knowing about science teaching could guide teacher educators in developing teacher-educative tasks and assessing teacher learning.

The RCM of PCK described in Chap. 2 of this book is a significant step in creating a model that represents what teachers know about teaching subject matter. Based on years of thoughtful work and multiple conversations, the refined model represents the thinking of the participants in the second international summit on PCK. This model provides a framework in which to situate studies of PCK for science teaching. The predictive power of the model now needs to be tested, for its ability to be helpful in describing teachers' thinking in ways that predict outcomes for students. For teacher educators, having predictive power means being helpful in designing tasks that support and assess teachers' progress in learning about teaching subject matter. To do this work well, a set of methods for gathering evidence that describes science teachers' PCK in meaningful ways is needed.

With this goal in mind, I have been exploring a method to investigate science teachers' PCK within a framework of learning about teaching. In teacher education, PCK is conceptualised as the knowledge of teaching subject matter (in this case, science) that is used and developed within practice (Feiman-Nemser, 2008). Thus, tasks intended for teacher learning should engage teachers in the activities of teaching while learning about teaching (Hammerness et al., 2005). It is also important for teachers to engage in thinking about student learning while learning about teaching (Sykes, 1999). These outcomes require the development of teacher-educative tasks that emphasise the study of student thinking in connection with plans, enactments, and reflections. In other words, teacher-educative tasks should highlight teachers' pedagogical reasoning behind the act of science teaching. An approach that is embedded within the complex work of science teaching, with the potential to both develop and illustrate teachers' thinking, is learning study.

Learning Study to Support Teacher Learning

Learning study is a recent proposal for supporting teacher learning that builds upon the well-known lesson study approach to professional development (Cheng & Ling, 2013; Tan & Nashon, 2013). In contrast to lesson study, learning study is not focused on lesson plans per se, but rather on plans for engaging and uncovering students' thinking in order to learn about learning (Wood, 2015). It is important to note that planning is a complex activity of teaching that requires sophisticated thinking across multiple timeframes from within a class period to across weeks (Calderhead, 1996). In learning study, teachers focus on the complexity of understanding subject matter and how students express their thinking. Teachers are asked to select an object of learning. In other words, teachers select a phenomenon for students to investigate and develop explanations around. A well-chosen object will lead to explanations that require and develop subject matter thinking. Learning study requires teachers to construct complex tasks that will enable students to illustrate their thinking in multiple ways. Teachers anticipate and then analyse students' thinking while students develop and revise the products of their work (e.g., investigation plans or reports, annotated diagrams or models, written explanations, and oral presentation of reasoning). In this way, learning study illustrates what teachers know and are learning about their students' interactions with subject matter ideas. By embedding the study of PCK within tasks for science teacher learning, researchers can get closer to uncovering the reasoning that illustrates teachers' developing PCK.

Learning Study and PCK for Science Teaching

Learning study and PCK are approaches to understanding the development of teacher knowledge and skills that are both squarely situated with the practice of teaching. It is reasonable to think that by engaging in the structured study of science learning, science teachers will use and develop PCK. And like teaching science, the processes of studying learning and developing PCK are both dynamic and complex. The RCM attempts to untangle this complexity for PCK by describing three realms of PCK from the professional knowledge of a community of science teachers and educators, to that of an individual teacher, to the ideas used to inform and the actions taken in an instance of teaching (see Chap. 2). In a parallel fashion, learning study is framed by the professional community's knowledge of teaching and aims to develop each teacher's ideas in ways that will enable him or her to skilfully teach in specific cases. The RCM also describes the interplay of levels of PCK in ways that align with the dynamic work of studying learning. Teachers necessarily engage in planning, enacting, and reflecting with a particular setting, student(s), and learning goals in mind in order to add to their own understanding, which can in turn contribute to the community's understanding of science learning and teaching. The next step in this line of thinking is to unpack how the RCM can guide the design of a learning study assignment and how the assignment artefacts can inform the RCM.

From a teacher educator's perspective, the design of a learning study as a task for teacher learning should be framed by the broader ideas about teaching science while being situated in a specific case of teaching science. Although teacher learning about teaching is considered to be embedded in specific instances of planning, enacting, and reflecting, teachers will need the knowledge and skills to reason about many instances of teaching science. Teacher educators are charged with preparing science teachers for multiple settings and sets of learning goals for students at different stages. The RCM identifies this broader or community-based knowledge as collective PCK (cPCK). Similarly, enacted PCK (ePCK) is described as the knowledge and skills used by a science teacher when they are engaged in the practice of teaching in a particular setting with a particular learning goal for particular student(s). Situating the work of science teacher education within the RCM implies using the realm of cPCK to frame the design of tasks for teacher learning while using ePCK to frame the analysis of a teachers' work within these tasks.

Studying science teachers' ideas about learning and teaching subject matter within the context of a learning study is a twofold, intertwined task of developing and analysing science teachers' PCK. One phase of the work is to integrate ideas about PCK in order to develop and describe the experience for teachers and in turn support their learning. Another phase is to use ideas about PCK to analyse teachers' responses in ways that enable the qualitative features of their thinking to be described and documented. Framed by the RCM, one phase requires the broader framework of cPCK, while the other phase illustrates instances of ePCK. Thus, the questions guiding this exploration into how PCK might be studied in teacher education could be framed as:

One: In what way can cPCK guide the design of learning study as a task for science teacher learning?
Two: In what ways do teacher-developed learning studies illustrate science teachers' ePCK?

As a teacher educator, my examination of an approach to use and study PCK is embedded within tasks developed for teacher learning. In this case, a learning study approach was used to design an assignment to serve two purposes. One was to support teachers in learning about teaching science, while the other was to explore how the assignment could uncover teachers' developing ideas about teaching science. Developing the assignment and examining teachers' work was an iterative process across several semesters of a graduate course in curriculum and instruction. For clarity, this work is presented here as two phases—designing the learning study and illustrating teachers' ideas—and uses examples from one cohort.

Designing the Learning Study Assignment

The learning study was developed as an assignment in a graduate course in curriculum and instruction. This course is a regular offering that is not necessary for teachers only, but since it is a core course in curriculum and instruction, most students who enrol are licensed teachers. The course topics include subject matter for teaching (Grossman, Schoenfeld, & Lee, 2005), learning progressions where students' thinking about science becomes more sophisticated over broad spans of time (Corcoran, Mosher, & Rogat, 2009), and ambitious teaching that considers inquiry and discourse essential to developing all students' scientific thinking (Windschitl, 2008, 2013). As a course assignment, the graduate students' study of learning is informed by reading and discussion around each of these perspectives for thinking about learning and teaching science.

Learning Study Plans

The learning study assignment in this course is focused on the planning phase of a learning study. The process of planning in learning study generally includes selecting subject matter, identifying an object of learning, and considering patterns of variation (Wood, 2015). Translated to an assignment, graduate students select and justify a subject matter idea for learning, identify and describe a cognitive task centred on a phenomenon, and create an "anticipation guide" describing on-target and off-target student thinking. Since the learning study is not a lesson plan, details about materials and student activities are not emphasised. It is also important to point out that learning study goes beyond planning to include the examination of student work using the anticipation guides. Then, based on their students' work, teachers refine their ideas about student thinking and plan future instructional tasks. This second phase of learning study is part of a subsequent graduate course for teachers.

Defining cPCK for the Learning Study Assignment

To inform the design of the learning study assignment, components of PCK were identified by reviewing the literature on science teacher PCK and through empirical work with science teachers (Park & Oliver, 2008; Schneider, 2015). The five components of cPCK used as a guide for this assignment are described below.

- *Orientations* to teaching science. Teachers' ideas about: (a) *nature of learning and teaching* science, (b) *goals* of teaching science, and (c) *purpose* of teaching science.
- *Science curriculum* prepared for teacher and student thinking. Teachers' ideas about: (a) *scope* of science ideas that are important and worth learning, (b) *stan-*

dards as guides for planning and assessing, and (c) *sequence* of science ideas organised for learning.
- *Frameworks* for science teaching. Teachers' ideas about: (a) *inquiry* science learning environments that characterise science and (b) *discourse* in science, both oral and written.
- *Student thinking* about science. Teachers' ideas about: (a) students' *initial* science ideas and experiences, (b) *development* of students' science ideas, (c) how students *express* science ideas, (d) *challenging* science ideas for students, including why the ideas are challenging, and (e) appropriate *level* of science understanding.
- *Instructional strategies* for science topics. Teachers' ideas about: (a) *natural phenomena* experiences and (b) *assessment* of science learning.

Aligning Learning Study and cPCK

The first question for this work asks in what way can cPCK guide the design of learning study as a task for science teacher learning? To answer this question, the development of the learning study assignment was informed by both the components of learning study and the components of cPCK. The task of developing a learning study as an assignment involved creating clear and helpful directions for how, exactly, teachers should plan a learning study. To uncover teachers' pedagogical reasoning, the assignment was designed to prompt their reasoning about teaching science. In addition, the framework of the learning study needed to be consistent with the work of planning and the directions to prompt teachers' pedagogical reasoning had to fit with the purpose of the pedagogical task.

Thinking about cPCK did indeed improve the description of this assignment by supporting the addition of descriptive details for the directions (see Appendix 1). For example, rather than ask teachers to simply identify a target science idea (i.e., learning objective), the directions guide teachers in how to identify a "big idea" and then support their decision. Informed by thinking about specific cPCK components of purpose, scope, and goals, the directions were refined to have teachers select a high impact idea that is worthwhile and meaningful for students and appropriate for students across multiple grade levels. Based on the cPCK concept of sequence (see part c of the Science Curriculum component above), the "big idea" is one where students can develop increasingly more sophisticated thinking over broad spans of time. Similarly, directions for identifying a phenomenon and describing a task were refined when thinking about inquiry, discourse, and expressing ideas, while directions for anticipating student thinking were refined by thinking about initial and challenging ideas for students. The complete alignment between the components of the learning study assignment and cPCK is outlined in Table 7.1.

Table 7.1 Alignment of learning study and collective PCK components

Aspects of learning study assignment	Aspects of collective PCK
High impact idea: teachers select a science idea for student learning that will have a high pay-off for students in understanding science and is appropriate for students across multiple grade levels	*Orientations*: *purpose* of teaching science *Science curriculum*: *standards* as guides for planning and assessing
Sophisticated idea: teachers describe how students can develop increasingly more sophisticated thinking regarding this science idea over broad spans of time	*Science curriculum*: *sequence* of science ideas organising for learning
Worthwhile: teachers describe how the science idea is of value to *science*	*Science curriculum*: *scope* of science ideas that are important and worth learning
Meaningful: teachers describe how the science idea is of value for students *outside* of academic tasks	*Orientations*: *goals* of teaching science
Cognitive task: teachers describe what students will be asked to think about and do that is complex and cognitively demanding	*Instructional strategies*: *natural phenomena* experiences *Frameworks*: *inquiry* science learning environments
Artefact: teachers describe the artefact students will create (write, draw, present, etc.) while engaged in the task *Frameworks*: *discourse* in science both oral and written including argumentation and technical writing	*Instructional strategies*: *assessment* of science learning
Student thinking: teachers describe how this task and artefact will make student thinking visible	*Student thinking*: how students *express* science ideas
Target-level artefact: teacher creates an example of an on-target artefact to illustrate goal for student performance	*Student thinking*: appropriate *level* of science understanding
Describing on-target ideas: teachers describe, list, or illustrate what they anticipate that student will say or do or draw that unpacks complex or sophisticated thinking. Teacher creates a checklist or other method that makes sense for the task	*Student thinking*: *development* of students' science ideas *Student thinking*: how students *express* science ideas
Not on-target ideas: teachers describe, list, or illustrate what they anticipate that student will say or do or draw that illustrate initial or challenges. Teacher creates a checklist or other method that makes sense for the task	*Student thinking*: students' *initial* science ideas and experiences *Student thinking*: *challenging* science ideas and why the ideas are challenging
Role of the teacher: teachers describe their role during this task. What they will do, pay attention to, record, examine, interpret, and revise	*Frameworks*: *inquiry* science learning environments *Frameworks*: *discourse* in science

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Table 7.1 (continued)

Aspects of learning study assignment	Aspects of collective PCK
Rationale: teachers describe how their plan is an illustration of how they frame their thinking about teaching and learning science	*Frameworks*: *inquiry* science learning environments *Frameworks*: *discourse* in science
Teacher learning: teachers describe what they are learning about teaching and learning	*Orientations*: *nature of learning and teaching* science

Illustrating Teachers' ePCK

This particular learning study assignment was part of an introductory graduate-level course in curriculum and instruction. Ohio science teachers enrolled in the course as part of a programme to prepare current high school teachers to teach introductory-level college content in their high school classrooms. The study group included 19 high school chemistry teachers across multiple course sections in the same semester, and as Ohio teachers, all were using the same state-provided content standards for chemistry. These teachers developed learning study plans as part of the course.

In order to investigate possible differences in their enacted PCK (ePCK), teachers were identified as new (1–3 years of experience), some experience (4–10 years), or much experience (11 or more years). Their content knowledge background was described as excellent (content major with high grades in area), good (content major with lower grades or non-major with high grades in area), or developing (non-major with modest grades area). The examples presented here were selected from three chemistry teachers who focused their work on atomic models. This selection of the same teaching topic meant qualitative differences in ePCK could be highlighted. Teacher A was a new teacher with a good background in chemistry, while Teacher B also had a good background in chemistry but more teaching experience (some). Teacher C was a new teacher but had an excellent background in chemistry. With different levels of experience and chemistry background, the work of these three teachers tests the learning study as a task to uncover differences in teachers' ePCK.

Describing ePCK

The second question for this work asks in what ways do teacher-developed learning studies illustrate teachers' ePCK? To answer this question, teachers' responses to components of the assignment were examined in relation to the corresponding components of cPCK. In other words, the cPCK component determined to be most aligned with each component of the learning study (Table 7.1) was used to guide the review of that aspect of a teacher's response. The intention was to develop qualitative descriptions of teachers' ideas. For example, when a teacher describes how the subject matter idea they have selected is meaningful for students outside of academic tasks, his/her response is examined for ideas about goals of teaching science. To explore whether the learning study responses were helpful in illustrating differences in teachers' ePCK, responses from teachers with different levels of experience were compared. To determine whether this task was illustrating ePCK separately from content knowledge, teachers with different levels of chemistry background were compared. Tables 7.2, 7.3 and 7.4 include sample responses selected from these three teachers' learning studies in order to demonstrate how ePCK is illustrated.

To illustrate ePCK for teachers with different levels of teaching experience, responses from Teacher A (new teacher with a good background in chemistry) and Teacher B (some teaching experience with a good background in chemistry) were compared (see Table 7.2). For example, Teacher A describes the selected subject matter idea (atomic model) as meaningful for students because all matter is made of atoms. In comparison, Teacher B does not directly describe how this idea is meaningful but does mention the need to understand the viewpoint of students. Both responses begin to illustrate the teachers' ideas about goals for teaching science. Although it is premature to suggest one response is more advanced or correct than the other, differences based on experience with students are suggested.

Comparing responses from Teacher B (some experience with a good background in chemistry) and Teacher C (new teacher with an excellent background in chemistry) explores possible differences in ePCK based on teaching experience for teachers who also have different levels of content background (Table 7.3). In one example, Teacher B describes student thinking by stating that students will use arrows to represent movement, but it is not clear why these ideas are challenging for students. On the other hand, Teacher C describes student thinking by stating that students' drawings will show their thinking, but it is more specific in describing how students will misunderstand ideas about models and elements. Again, these responses illustrate differences that might begin to uncover ePCK.

A third set of comparisons highlights two new teachers with different levels of content background and limited teaching experience. Teacher A (new teacher with a good background in chemistry) and Teacher C (new teacher with excellent background in chemistry) are both novice teachers, but one has more chemistry background (Table 7.4). In this case, both teachers describe the role of the teacher in an inquiry and discourse environment as encouraging students to investigate or collaborate, but do not have specific ideas about how to do so. This response is reasonable for new teachers. Their responses also differ in that Teacher A mentions feedback, while Teacher C is more specific about the chemistry ideas students will explain. These responses might be indicating similar ePCK, but differences in content knowledge.

Discussion

Using the RCM (i.e. cPCK, pPCK, and ePCK) as a guide, this chapter describes how a learning study was designed and teachers' responses were examined. It makes sense that PCK, as a construct that is intended to describe what teachers know about

Table 7.2 Teacher A and Teacher B: responses to components of the learning study assignment and ePCK illustrated

Teacher A	Teacher B
Orientations, *purpose*: to prepare students for the next level of schooling in chemistry	*Orientations*, *purpose*: to prepare students to understand further chemistry
Science curriculum, *standards*: clear linking of standards across grades	*Science curriculum*, *standards*: not focused on standards
High impact idea: the big idea I have selected for my learning study is the atomic model. The atomic model is a big idea that is built upon throughout students' education. In the Ohio model curriculum, the idea that all matter is composed of atoms is presented in the elementary grades. Later, in middle school, they are to understand that these atoms are made up of subatomic particles and a model of this atom can be created based on current scientific evidence. At the high school level, different models of the atom are presented	*High impact idea*: this learning plan deals with the formation of ions in order to increase atomic stability. This idea builds on the knowledge of atomic structure and leads to understanding the formation of bonds and chemical reactions
Science curriculum, *sequence*: focused on components of the atomic model, mentions these are useful (more below)	*Science curriculum*, *sequence*: focused on how the model explains bonds and reactions
Sophisticated idea: the atomic model is a big idea that is built upon throughout students' education. In the Ohio model curriculum, the idea that all matter is composed of atoms is presented in the elementary grades. Later, in middle school, they are to understand that these atoms are made up of subatomic particles and a model of this atom can be created based on current scientific evidence. At the high school level, different models of the atom are presented. The two most useful models include the Bohr model and the quantum mechanical model	*Sophisticated idea*: this idea builds on the knowledge of atomic structure and leads to understanding the formation of bonds and chemical reactions…. after we have learned the structure of atoms and their stability and have begun to work with ionisation
Science curriculum, *scope*: describes detail about how this idea will help students think about chemistry	*Science curriculum*, *scope*: describe that structure relates to function
Worthwhile: knowing the atomic model is worthwhile because having a deep understanding of the atomic structure is a key to all topics covered in chemistry. For example, the trends seen in the periodic table can be explained by understanding how the protons and electrons within an atom are arranged. The more advanced quantum mechanical model helps to describe exactly how the electrons are arranged, which gives rise to the properties of elements and compounds. Chemical bonding also relies on the atomic orbitals becoming hybridized, and this gives rise to molecular geometry, molecular polarity, and many other concepts	*Worthwhile*: this idea builds on the knowledge of atomic structure and leads to understanding the formation of bonds and chemical reactions (did not give a distinct response for worthwhile)

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Table 7.2 (continued)

Teacher A	Teacher B
Orientations, *goals*: to help students think about properties and models, closer to classroom than outside of the classroom	*Orientations*, *goals*: to match students' perspective, no details yet on what that is
Meaningful: this idea is meaningful because all matter is made of atoms. If one is able to understand the structure of the atom, one can begin to make sense of the physical and chemical properties of the materials they encounter in their everyday experiences. This idea is also meaningful because it exemplifies the use of a model in science. Models can be used to show things at the very macroscopic and very microscopic levels and are used to visualizse abstract ideas	*Meaningful*: by analysis of the results, I would hope to better understand the viewpoint of my children (did not have a response for meaningful)

teaching subject matter, would be helpful in designing tasks for teacher learning. It also makes sense that evidence collected from artefacts of teaching (in this case, planning), would make teachers' ideas visible in ways that can illustration their personal PCK (pPCK). Descriptions of whether and in what ways this is, indeed, the case are needed. The descriptions provided here are from a teacher educator's perspective, exploring this potential approach as a means of illustrating teachers' ideas while supporting teachers in learning about teaching.

Designing Tasks for Teacher Education

The RCM identifies three realms of PCK, each of which describes PCK at a different level from a community's knowledge, to an individual teacher, to a subset of ideas and actions used in a particular instance of teaching. It turns out, quite reasonably, that the different realms of the RCM were useful for thinking about PCK in different situations. To design a task for teacher learning, cPCK was a helpful framework for thinking about what ideas should frame a teaching-based task. The RCM, in and of itself, did not have the detail needed to guide the design of the learning study as a planning task. However, thinking about cPCK as a community-based knowledge is consistent with existing thinking about a collective understanding of the components of PCK. The science education research community, for example, has been describing and researching ideas to identify a set of PCK components for some time (Schneider & Plasman, 2011). The RCM helps to clarify how to use the components of PCK most often described in the literature. In this work, the components of cPCK were helpful in developing the learning study as an assignment for teachers. The specific components were a guide in adding specific details and directions to guide teachers in thinking deeply about learning that otherwise might

Table 7.3 Teacher B and Teacher C: responses to components of the learning study assignment and ePCK illustrated

Teacher B	Teacher C
Instructional strategies, *phenomena*: focused on one model to connect to bonding, link to phenomenon not implied	*Instructional strategies*, *phenomena*: focused on two specific atoms to compare using the model and to connect to bonding, link to phenomenon explicit
Frameworks, *inquiry environments*: one guiding question	*Frameworks*, *inquiry environments*: several guiding questions
Cognitive task: students will look at the Bohr model of a standard atom and determine how it will become stable. "Would this cause these two atoms to bond?"	*Cognitive task*: the student will have to draw the Bohr model for a francium atom and a fluorine atom and describe why they believe each element to be either reactive or unreactive and why. They will be asked to think about what happens to the size of things when you continually add more to it and to consider the charges of all types of the particles
Instructional strategies, *assessment*: students use model to begin to predict. Students draw and label, but do not describe what the drawing represents	*Instructional strategies*, *assessment*: students draw, label, and describe what the drawing represents
Frameworks, *discourse*: focus on representation and notation only	*Frameworks*, *discourse*: focus on representation and description in their own words about their ideas
Artefact: draw a second Bohr model showing the resulting atom/ion. Indicate the atomic number, mass number, and ionic charge for each model. Finally, use arrow to show how electrons move from one atom to another	*Artefact*: students will illustrate the atomic structure (Bohr model) for a francium and fluorine atom and describe why you believe each element to be reactive or unreactive. (Number of energy levels and electrons not necessary but shown on the artefact.)
Student thinking, *express* science ideas: students draw and use notation to represent thinking	*Student thinking*, *express* science ideas: students' descriptions and aspects of their drawings illustrate their thinking
Student thinking: the task involves having students determine electron stability and drawing a model of the ion that is formed. This artefact will show common misconceptions such as how many electrons and atom tends to gain or lose	*Student thinking*: through their descriptions of the reactivity of the atom, I can determine what they understand about how electrons are gained and lost through attractive forces of the nucleus and how that impacts the reactivity of the atom. I would be able to determine if the students understand that similar charges repel, where like charges attract. I would also be able to determine how they understand the changes in electrical attraction or repulsion as the distances between the particles changes and how that distance affects the reactivity of the element and its ability to form an ion

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Table 7.3 (continued)

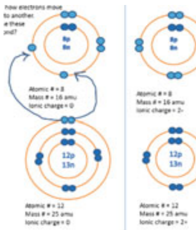
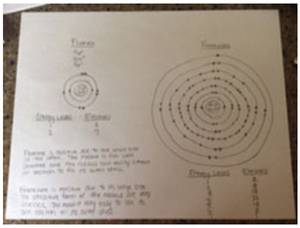
Teacher B	Teacher C
Student thinking, appropriate *level*: using diagram to represent simple bonding, using arrows to represent movement	*Student thinking*, appropriate *level*: using model to contrast elements on several dimensions
Target-level artefact: 	*Target-level artefact*: 
Student thinking: *development* of science ideas—students learn the components	*Student thinking*: *development* of science ideas—students learn by contrasting features
Student thinking: *express* science ideas—students draw the components	*Student thinking*: *express* science ideas—student model the components and explain in their words
Describing on-target ideas	*Describing on-target ideas*
Concepts: • Outer shell is full (8) • Atomic number (protons) does not change • Mass number does not change • Number of neutrons does not change • Electrons form pairs • Only outer shell is affected • Ionic charge = number of protons − number of electrons • Electrons transfer from one atom to another into appropriate places	Model (excerpt) Correct ratio in scale size (francium larger, fluorine smaller). Due to the addition of energy levels (and electrons), it will continue to make the atom larger Description (excerpt) ____Francium is larger in size due to its number of energy levels and electrons ____Fluorine is smaller in size due to the limited number of energy levels. This means the attractive forces can pull in and hold the electrons very easily
Student thinking: *initial* science ideas and experiences—student do not know the components	*Student thinking*: *initial* science ideas and experiences—students misunderstand the interactions
Student thinking: *challenging* science ideas— superficial ideas about what is challenging	*Student thinking*: *challenging* science ideas—students misunderstand the connections such as size or forces
Not on-target ideas	*Not on-target ideas*

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Table 7.3 (continued)

Teacher B	Teacher C
Misconcepts: • Outer shell is not full • Number of protons changes • Number of neutrons changes • Mass number changes • Electrons added/removed from inner shells • Gaining electrons instead of losing electrons or vice versa • Ionic charge is incorrect • Electrons are not transferred	Models (excerpt) ____: Models drawn the same size or fluorine drawn bigger Used to seeing computer pictures of the Bohr models and thinks they are all the same size. Does not understand the pull of the positively charged nucleus or that adding more energy levels increases the diameter of the atom Description ____Describes the elements as unreactive for various reasons ____Size is not used in the explanation for either element or is not used correctly ____The attractive forces of the nucleus to the electrons are not mentioned in the descriptions correctly

have been overlooked. Because the assumptions underlying the RCM of PCK and the ideas about teacher learning were based on the same fundamental ideas about teaching and learning, it was possible to align each of the components of cPCK with a corresponding component of the learning study task.

The design of the learning study assignment described here suggests that cPCK can be a useful guide for designing educative tasks for teachers. In this way, the RCM of PCK can be helpful in strengthening the education of teachers. Teacher education is frequently the focus of critique with some reformers recommending more robust programmes with stronger links to classroom-based experiences, while others advocate for reducing formal teacher education (Darling-Hammond, Holtzman, Gatlin, & Heilig, 2005). The learning study assignment is a carefully designed task that is anchored in well-thought-out ideas about teacher knowledge that supports teachers in thinking about their own students. If more assignments in teacher education were carefully constructed based on ideas about what and how teachers learn, this practice would not only make these experiences more powerful, it may also aid teacher educators in describing the importance of teacher education in ways that could inform policy for teacher education.

Observing ePCK

Learning study does appear to be a useful approach to illustrate teachers' ePCK for planning. The learning study assignment is consistent with the work of planning and is closely linked to teachers' pedagogical reasoning around specific subject matter for specific students. The examples above suggest that teachers with similar content

Table 7.4 Teacher A and Teacher C: responses to components of the learning study assignment and ePCK illustrated

Teacher A	Teacher C
Frameworks, *inquiry* environments: low inquiry environment, unclear about experiences	*Frameworks*, *inquiry* environments: students gather information and collaborate, draw conclusions, reasoning with explanation
Frameworks, *discourse*: visual representations, teachers provide feedback	*Frameworks*, *discourse*: students collaborate and discuss ideas, explain ideas
Role of the teacher: the teacher must investigate what knowledge the students have in order to determine where to begin. … then they can provide students with experience that will build upon their prior knowledge. In this task, the prior knowledge would be the Bohr model. Once students are engaged in their learning, the teacher must observe and monitor how students are incorporating the new material by having them create visual representation s of their understanding during the learning process. Once students have shown how they understand the new material, the teacher must examine their work and provide them with constructive feedback letting them know how successful they were with the task	*Role of the teacher*: I will allow the students to investigate and draw conclusions on their own. I will encourage the students to use their periodic table as a guide and investigate the subatomic particles themselves to determine where they should be located. Proper materials will also be provided so if a student wants to use a compass to make uniform circles so they can accurately represent the size of the atoms, it will be possible. I will encourage cooperative learning amongst students and student discussion of ideas. I will pay attention to how they draw their conclusions about reactivity of each of the elements and if they used the size and valence electrons in their reasoning. I will not just be looking for if they know it is reactive or not, but their ability to be able to explain why it is reactive
Frameworks, *inquiry* environments: translating from a simpler model to a more sophisticated model, visual, teacher feedback	*Frameworks*, *inquiry* environments: ideas build on previous ideas; student create and explain; use extremes examples first
Frameworks, *discourse*: NA	*Frameworks*, *discourse*: NA
Rationale: this plan builds upon the less sophisticated atomic model, the Bohr model, to help students understand the more sophisticated quantum model. Students find the Bohr model easy to create, while the quantum model tends to be more challenging to understand. I believe by relating the two, students will more clearly see the relationship from one model to the next. The artefact created by student during this task also allows the teacher to visually determine a student's understanding of the quantum model. The teacher can then more easily provide feedback to students to help them with their learning, as well as determine the success of the instruction based on student learning	*Rationale*: this plan illustrates subject matter knowledge for teaching as it builds on previous background knowledge the students have and provides a chance to reinforce that material along with building upon it. This gives the students an opportunity to create something to explain their thinking. I have also used the smallest halogen and largest alkali metal as they are two of the most reactive elements on the periodic table. If students understand these elements, then we could explore deeper into the other elements and use those same principles to discuss the reactivity of more complex elements
Orientations, *nature of learning and teaching* science: teachers need to monitor learning, students need to think about their own understanding, ideas develop in sophistication	*Orientations*, *nature of learning and teaching* science: learning requires verbal communication; question identify areas to work on and misconceptions; students learn differently

(continued)

Table 7.4 (continued)

Teacher A	Teacher C
Teacher learning: I learned that monitoring students learning by making their thinking visual could be a powerful tool to help the teacher guide their students to the desired learning outcome and to give students the opportunity to think about their own understanding. I also learned that the path to learning could be aided by building upon prior, less sophisticated knowledge to develop a more sophisticated way of thinking	*Teacher learning*: this artefact will support my learning about learning as I will be able to identify the students' thought processes, not only through the artefact itself, but also through verbal communication. The questions students will ask can help me identify the areas of weakness in the material and allow me to determine if it is an individual weakness or a class weakness. If it is a class weakness, and they all have the same misconception, there may be an experience in previous learning that created that misconception. I could then communicate with previous teachers to help sort out that misconception for future students. Through the students' ideas, I may also be able to determine how to best present the information initially, to give them a more solid understanding of the information. Each student learns a bit differently, so over time I may be able to compile an assortment of methods and allow the students to pick how they would like to learn a topic

preparation may illustrate different types of ePCK. This finding needs to be explored in more depth, but initial indications are that learning study may be illustrating more than content knowledge. The nature of the differences observed for the chemistry teachers appears to reflect differences related to teaching experience separately from differences related to chemistry background. Although not included in the samples provided in this chapter, learning studies from teachers working outside of their expertise (e.g., biology teachers planning for physical science) indicated that these teachers struggled to a greater degree with this planning task. Although this learning study assignment was focused on only the planning aspect of teaching, ePCK ideas suggested by the teachers were representative of the components of cPCK used to design this planning task. It is reasonable to predict that when teachers collect and examine student artefacts in the next stage of the learning study, their ePCK ideas will be further illustrated. Perhaps their ideas about inquiry and discourse environments, in particular, will be better illustrated.

As an approach proposed to capture (i.e. assess) teachers' ideas, it is important to think about the validity of learning study as an assessment tool. Learning study can be thought of as a performance assessment, and, as such, factors of validity for performance assessments should be considered (Messick, 1994). This learning study assignment has a relative low consequence in that it will not be used to determine anything more than a single grade in a course. However, some other factors worth keeping in mind are content coverage, cognitive complexity, and meaningfulness.

The components of cPCK (notably science curriculum, frameworks, and student thinking) were represented in the components of the learning study assignment. Learning study is embedded in teachers' work of planning for their students and, thus, should be a meaningful task outside of the course assignment. This task also reflects the complexity of teaching and learning about teaching. Learning study appears to be a fruitful path to pursue with assessment design in mind.

Mapping Trajectories

As an approach to thinking about assessing ePCK in ways to infer teachers' personal PCK (pPCK), it is interesting to think about mapping trajectories to describe how teachers' learning progresses. Learning progression is a framework for thinking about how learners (in this case teachers) develop increasing more sophisticated ways of thinking over broad spans of time and in connection with instruction and assessment (Heritage, 2008). Measuring progressions is a complex task that involves construct mapping (Wilson, 2009), that is, mapping the layers of increasingly sophisticated ideas for the construct, in this case cPCK. Based on a well-thought-out construct map, artefacts illustrating teachers' thinking are analysed to suggest a trajectory or path of learning progress. Instruction and assessment become an iterative process in the uncovering of trajectories. This process matches that described here in this chapter, that is, where a construct is used to design instruction and assess learning. This type of work is a step towards describing trajectories for teachers' pPCK.

Conclusion

Overall, learning study as an approach to develop and illustrate teachers' pedagogical content knowledge shows promise. The RCM as a model for thinking about PCK in realms or layers was helpful to situate and parse the work of design and research associated with teacher education. Perhaps most interesting is the potential to begin mapping the PCK construct and teachers' learning trajectories in conjunction with learning study. Learning study is a complex and meaningful task for teachers. It is also a more efficient or concise approach than lesson planning. This quality is an important consideration for an assessment tool. Learning study, however, does require teachers to learn about learning study. While teachers are accustomed to being asked to plan lessons, learning study planning is more focused and complex and can push their thinking in new ways. These are the features, though, that make learning study valuable. This thinking is the type of work that is needed to advance our understanding of how to design and demonstrate excellence in teacher education.

Appendix 1: Learning Study Assignment Directions

Subject Matter Idea Description: Describe the big or high impact idea you have selected for your learning study. Describe how this idea(s) is meaningful (of value outside of academic tasks), worthwhile (of value to science), and of high impact for students (will make a big difference for students). Identify a core idea that will require increasingly sophisticated thinking over time. Use and revise your description of the high impact ideas that you posted for your journal.

Cognitive Task and Artefact Description: Describe the cognitive task and artefact that will help you uncover students' thinking. Describe what students will be asked to think about and do. Describe what the artefact students would create (write, draw, present, etc.). Describe how this task and artefact will make student thinking visible to you and them. Think about a task that is substantive so that students can participate and develop ideas. Create a task that is cognitively demanding, has multiple ways for students to participate (a complex task), and results in an artefact.

Sample Artefact: Mock up a sample of what you expect students to create. This should be an on-target example. It does not need to be actual student work. It can be an extract or sample of the key aspects of the artefact. This might include essays, diagrams, and illustrations.

Assignment Directions for Anticipation of Student Thinking: Describe or illustrate and list what you anticipate that students will say or do or draw, etc., including pieces that are on target and not on target. What do you anticipate as student thinking about the target ideas? Include these ideas in a checklist or other method as makes sense for your task. For example, if the task is to draw a representation of a molecule, what features would you look for in the drawing that would tell you what they are thinking?

Reflecting on the Study of Learning: (a) *Role of the teacher as learner*: What role will a teacher (i.e. you) have that will make this a study of learning. What will you do, pay attention to, record, examine, interpret, and revise as you complete your study of learning? How will this support your learning about learning? Be specific to this learning study, the artefact, and anticipation of student thinking. (b) *Theoretical underpinnings*: How does your plan reflect theoretical frameworks for thinking about curriculum (specifically learning progressions, subject matter knowledge for teaching (teacher knowledge; PCK), and learning studies)? Be explicit in linking your plan to these ideas. (c) *Planning to learn*: What did you learn by creating this plan? How would you create another plan to study learning?

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