Understanding Science Teachers' Professional Knowledge Growth

Michel Grangeat (Ed.)

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Edited by

Michel Grangeat
Université Grenoble Alpes, France

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Murray Bales (LL.B, B.Ec. – both University of Sydney) has been a freelance language editor ('proofreader') working with top-level academics from across Europe since 1995. He has worked on many international/EU projects (e.g. DEHEMS (2009–2012), HEGESCO (2007–2009), EMCOMSU 2015) and is or has been the in-house language editor of several academic journals in the fields of education (Education Inquiry), politics, economics, international relations, sport etc. He has edited a large number of books, such as Beyond Fragmentation: Didactics, Learning and Teaching in Europe and, recently, a large pan-Europe volume on Comenius edited by Wouter Goris, Meinert A. Meyer and Vladimír Urbánek.

Isabelle Herman Misse is a PhD student in educational science and involved in the research team of the Education Science Laboratory in Grenoble. She is also responsible for a bilingual school group in Cameroon going from nursery school to high school and which comprises about 1,800 students. She was in charge of organising the seminar Teacher Professional Knowledge that led to the writing of this present book. She took part in the proofreading and editing of chapters of this book.

MICHEL GRANGEAT AND SUZANNE KAPELARI

1. INTRODUCTION

Exploring the Growth of Science Teachers' Professional Knowledge

The world around us is changing at high speed. New technological devices or processes are being continuously proposed by companies or organisations for improving our ways to interact with the physical or social environment. They all necessitate new competencies or new adaptations of already mastered competencies. The world is facing huge challenges. Reducing climate change will require new ways to use energy to be discovered, while preserving the planet's resources and reducing carbon dioxide emissions. Overcoming these challenges will require all citizens to have a better understanding of science if they are to participate actively, responsively and responsibly in knowledge-based innovation and science-informed decision-making. To achieve these purposes, mathematics, science, and technology education have a crucial role to play (EC, 2015).

Science education has to be improved in order to become more responsive to the needs of society and particularly to the development of positive attitudes to science for all citizens. Enhanced educational strategies are called for to engage researchers and other actors in mastering the knowledge and sense of societal responsibility needed to participate actively in the future innovation process. Such an improvement depends on several factors. For instance, formal, non-formal and informal educational providers, business and civil society may collaborate to ensure the relevant and meaningful engagement of all societal actors with science. Schools may be networked with researchers, science centres or institutes for teacher education in order to create a context conducive to improving science education. In brief, the context in which teachers perform may be transformed in order to meet societal purposes: teachers will no longer only perform behind closed classroom doors. Exploring the school context appears effective, and this book takes it into account. Nevertheless, the focus is on teacher knowledge.

Teacher effectiveness is one of the crucial factors that impact learning outcomes. As stated by Hattie (2012), "teachers' beliefs and commitments are the greatest influence on student achievement over which we can have some control" (p. 25); he claims that "the differences between high-effect and low-effect teachers are primarily related to the attitudes and expectations that teachers have when they decide on the key issues of teaching" (p. 26). In other words, teacher professional

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knowledge makes a difference. This book addresses this question of the nature and development of such knowledge.

When talking about professional knowledge, three metaphors may be used to explain its development (Paavola, Lipponen, & Hakkarainen, 2004). A first and simplistic view stresses the acquisition process by considering the mind as a container and learning as the way to fill it. Learners may be seen as collectors or "as the consumers of this knowledge" (Gess-Newsome, 2015, p. 32). The crucial point resides in the transfer of knowledge from the educator's container to those of the learners. A second metaphor examines learning as a process of participation in multiple activities and groups since knowledge cannot be separated from the context in which it needs to be applied. Learners are seen as actors. Acquisition and participation metaphors often appear to be incompatible and describing two opposite ways of developing knowledge. Nevertheless, combining the two approaches is attractive. In this perspective, Paavola and his colleagues (2004) propose the knowledge-creation model of learning. Learners are co-designers. This perspective emphasises "aspects of collective knowledge creation for developing shared objects of activity" (p. 558): the focus is on how knowledge is used and developed through the collective creation or alteration of artefacts. Nevertheless, the emphasis is not on this social practice alone, but is put on the ways through which knowledge and artefacts are collectively used and transformed in relation to the alteration of the shared activity itself.

Teacher professional development is understood in this book through this third metaphor: the transformation of teacher professional knowledge is a continuous process that depends on the repertoire of actions that are available within the community, on the social context in which teaching is performed, and on the artefacts and resources that exist in the environment. Thus, teacher professional knowledge is not static but is a matter of continuous construction and deconstruction for meeting the requirements in a particular situated context in which it is applied. Teachers interact with their students in the classroom and with the 'community' (teacher groups, heads of school, parents etc.). This book will value the interactions within this system: teaching instruments, the classroom context in which teacher knowledge is enacted, and the teaching community in which it consolidates.

In addition, while crediting ideas from Polanyi (1967), Nonaka and Takeuchi (1995), Bereiter (2002), and Batatia, Hakkarainen, and Mørch (2012) emphasise the fact that knowledge creation "is not rule-governed or an algorithmic process based solely on explicit knowledge but involves non-explicit and iterative processes" (p. 18). Two levels of knowledge need to be considered since a large amount of professional knowledge is and remains tacit. This book endeavours to take account of these two types of professional knowledge.

Tacit knowledge results from individual experience and involves factors that are difficult to reach, such as personal belief, perspective and value system (Batatia et al., 2012; Paavola et al., 2004). Conversely, explicit knowledge that is easy to express formally articulates the reasons that reside behind common practices. The difference between these two types of knowledge does not reside in the classical opposition between procedural and declarative knowledge but in their more or less facility of access, and in the way it is accessed: the former is rooted in human experience; the latter is dependent on cultural and social artefacts. These models describe knowledge development as a four-level cycle (Batatia et al., 2012; Nonaka & Takeuchi, 1995). The first stage is socialisation: tacit knowledge is shared through the community, creating a common way of acting and improving trust amongst participants. The second is externalisation: this central phase in knowledge creation leads tacit knowledge to be made explicit through the analogies and concepts that are available amongst the actors. That creates a common understanding of the events the actors are facing. The third is a combination: units of knowledge are combined, synthesised and exchanged by actors in order to overcome the challenge they encounter. Finally, internalisation is a phase that leads individuals to transform the explicit knowledge of the group into individual tacit knowledge that underpins new ways of acting and thinking. Within this book, the distinction between these types of knowledge and these phases of knowledge transformation are considered as essential.

The engine of such development is a crucial issue. According to Engeström (1999), questioning and criticism of existing practices is the starting point of the process. In the same perspective, Fischer and Boreham (2004) note that new professional knowledge is needed when the reality the actors are facing is too strongly different from what is stated by instructions or theories. They show that new professional knowledge results either from collective exchanges through the work team, or from education when the programme includes professional problem-solving activities. Specific educational programmes based on collaboration may transform individual tacit knowledge into partly explicit knowledge that might be shared by the community. This set of explicit knowledge is the fundament of a renewed repertoire of actions that might underpin more efficient practices.

Within the science education domain, research meets the same results. Through a survey of 1,000 mathematics and science teachers involved in US professional development programmes, Garet, Porter, Desimone, Birman, and Yoon (2001) show that teachers' knowledge and skills are enhanced through programmes that foster coherence (between what teachers have already learned, curriculum requirements, and professional communication into school), focus on a professional problem (academic subject matter), and promote active learning ('hands-on' work). This book addresses the two sources of knowledge transformation: unexpected events occurring in the day-to-day life of schools or classrooms, and teacher education programmes based on activity analysis or on lesson iterative design.

These types of research stress the importance of seeing professional knowledge development from the point of view of the actors involved, taking the extent of their repertoire of actions and capabilities into account (Grangeat & Gray, 2007). Their activity is transformed by both the tools and artefacts that are available and the social context. This leads to emphasising the role of the concrete context and of the community on professional learning. A threefold question then arises of the role of the curriculum, of the school environment and leadership, and of the teacher community's beliefs, orientations and habits. Addressing this question, this book considers professional development as a combination of individual and situated learning: each teacher finally learns in an individual way, but cannot learn without relying on colleagues and other partners, even if the social environment in which a teacher is acting may also limit teachers' development.

Within the science education domain, mainstream models used to explain teacher knowledge following the distinctions initiated by Shulman (1987) who initially understood teacher professional knowledge as combination of three categories of knowledge: content (CK), pedagogical (PK) and pedagogical content knowledge (PCK). This model has been refined in order to better specify these categories or adapt them to a specific content – see an example for mathematics in Lindmeier (2011). In a recent review of the question, H. Fischer, Borowski, and Tepner (2012) state that most of the literature addresses PCK and there is a lack of studies exploring either the nature of PK or the linkage between CK, PCK and PK in a way that allows teachers to face students' difficulties. According to these authors, PK can be seen as a necessary but not sufficient precondition to use CK and PCK for enhancing subject-specific learning processes. This book[1] draws on these existing models so as to contribute to the collective efforts for enhancing teaching and learning in mathematics, science and technology.

The model resulting from the PCK Summit held in 2012 (Berry, Friedrichsen, & Loughran, 2015; Borowski et al., 2011) is used in this book as a basis for reflection (see Figure 1). The first stage of this model is represented by a set of teacher professional knowledge bases that consist of five types of knowledge referring to: assessment, pedagogy, content, students and curriculum. These are seen as knowledge for practices that was created by experts and used by teachers. This canonical and normative knowledge needs to be translated into topic-specific professional knowledge often coupled with a grade level. This second stage of the model consists of a set of expert knowledge: instructional strategies, content representations, student understandings, science practices and habits of mind. This knowledge base can be identified, measured, investigated and taught. The third stage represents classroom practices. This is not directly derived from the topic-specific professional knowledge base since a set of amplifiers and filters mediates the link between these two levels. Such an interaction creates a gap between canonical teacher knowledge and practices and depends on teachers' beliefs, orientations, knowledge and affects. Classroom practices result from the interaction between a teacher's personal professional knowledge and its enactment, and the classroom context. Such practices address two elements: planning and performing since teaching cannot be limited to direct interactions with students. This stage retroacts on the previous two: the reflection in and on practices transforms the topic-specific and general professional knowledge bases. This knowledge adopts two forms that are not equipotent: declaration and enactment. The declarative form is easy to assess, at least its explicit part. The practical form is more difficult to assess due to the crucial role of the context such as, for instance, the presence of an external assessor. Finally, the fourth stage consists of students' outcomes. Here again this is not directly transferred from classroom practices but mediated by students' set of amplifiers and filters. Once more, this stage retroacts with teachers' amplifiers and filters as well as with their professional knowledge base and content-specific knowledge. Like all scientific models, this way of understanding teacher professional development needs to be questioned. This book aims to contribute to this refinement.

Two types of questions arise from this model. First, the initial stages of the development of teachers' professional knowledge need to be investigated. This question is central to translating the research results into pre-service teacher education programmes. Second, the role of the social and teaching contexts in this development is to be highlighted. This is valuable for informing school authorities and teacher training providers.

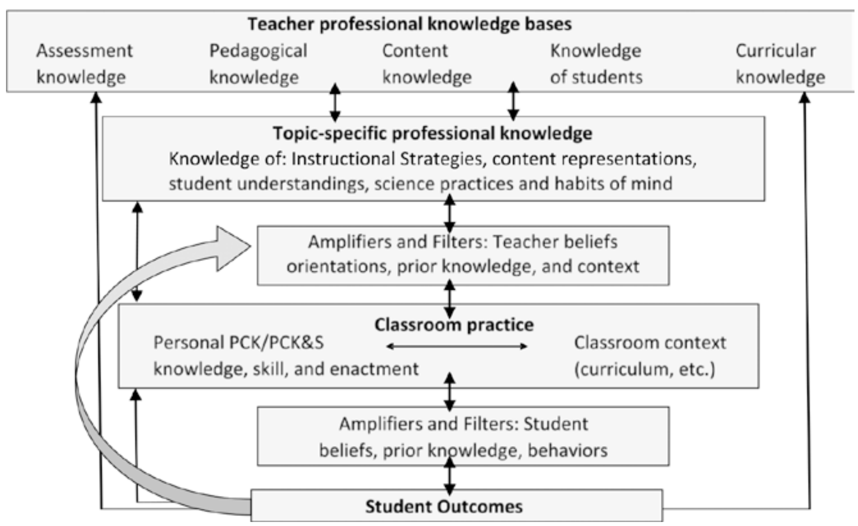

Figure 1. Model of teacher professional knowledge (Gess-Newsome, 2015, p. 31)

There is a consensus on thinking that PCK improves depending on teacher experience, but that teaching experience does not necessarily result in efficient PCK. In addition, PCK can be strengthened through teacher professional development or other interventions. This process raises an initial question about the nature of teacher professional knowledge which underpins the first stages of such an evolution. The question is: What kind of knowledge is actualised during the beginning stages of a new lesson or the use of a new technology when the set of PCK is limited?

It is obvious that subject teachers are not isolated within a school and have to share constructs and methods with their colleagues from other subjects. Thus, they may need PK as generic knowledge to help them cross the boundaries between subjects. The questions are: How can we identify the set of PK shared by teachers? To what extent might teacher collaboration underpin the development of a balanced set of PK and PCK?

The opening section of the book considers the role of the content to be taught in performing efficient teaching. It focuses on the linkage between CK and PCK, and on PCK development. The first issue is to allow teachers to develop relevant PCK even if they are more or less aware of their lack of CK. This question concentrates on the linkage between the two first stages of the PCK Summit model. It addresses the challenges that primary teachers face, or that subject teachers encounter in the case of curriculum change, or when confronted with the constant scientific breakthroughs. In her chapter, Lorraine McCormack shows how the development of a science subject knowledge base to support children's scientific thinking and interest in the subject is essential. Therefore, teachers' strong subject knowledge and their confidence in their knowledge are crucial. A second question addresses the evolution of PCK. The point is to better identify the factors that impact this development and to better understand the dynamic of such an evolution. The chapter by Alain Jameau and Jean-Marie Boilevin addresses the retroaction processes between the third and second stages of the PCK Summit model. They show that unexpected events lead to the construction of new knowledge, specifically of PCK about the students. Their longitudinal study stresses the interaction between this new knowledge and the adjustment of the lesson plan by the teacher, during the second year. A third question explores the relationship between a teacher's PCK and students' learning. The chapter by David Cross and Celine Lepareur tackles the retroactive process between the two last stages of the PCK Summit model. This relationship is often the missing point of the literature in the domain. Their chapter concerns teachers' PCK at stake in the interaction between teachers and students when the students encounter difficulties in progressing in a task. From verbalisations and analyses of actions the difficulty the students encountered and the difficulty the teacher diagnosed were identified. It ended up that the teacher did not diagnose the correct difficulty the students were facing. The results show that the fact that the teacher was anticipating a specific difficulty for the students prevented her from diagnosing the actual difficulty the students were confronted with. That specifies the crucial roles of the amplifiers and filters of the PCK Summit model. Finally, the concluding chapter of this section by Gérard Sensevy addresses the way the PCK model might be complemented by studies that explore the relationship between 'didactical contract' and 'milieu'. It is argued that TPCK 'in action' is necessarily grounded on knowledge-related generic principles and strategic rules, but needs to also take account of the (more or less) contingent features of a situation nested in a given institution.

The second section considers the role of collaborative settings in improving the balance between general and specific pedagogical knowledge. It focuses on the linkage between PCK and PK, and on the nature of PK. The first chapter by Isabelle Kermen focuses on the PCK and PK commonalities and differences between two teachers involved in the same professional development (PD) programme. The chapter sheds light on the differential impact this PD based on the co-design and co-assessment of science teaching units has on the professional knowledge of new and experienced teachers. It complements the PCK Summit model by providing indicators for differentiating PK and PCK. The second chapter addresses the respective roles of PK and PCK in the teacher professional knowledge bases of the PCK Summit model. The study by Michel Grangeat analyses the set of professional knowledge of three groups of teachers. It shows that teacher collaboration seems to be a means for balancing general and content pedagogical knowledge. The third chapter by Suzanne Kapelari considers the evolution of science centre educators during a joint project with teachers. It stresses the importance of a combination of situated and individual learning in transforming professional knowledge. It addresses the roots of the teacher professional knowledge bases of the PCK Summit model. Finally, the concluding chapter of this section by Pernilla Nilsson aims to renew the perspectives about the linkage between PK and PCK. It stresses that teacher collaboration – particularly when collaborative groups are supported by teacher educators and researchers – may underpin the development of both PK and CK.

The third section presents two perspectives that challenge and may complement the PCK Summit model. The first contribution, by Shulamit Kapon, stresses the role of affordances that are noticed and exploited by teachers in order to integrate new instructional resources into teaching, and thus new professional knowledge into teachers' repertoire of instructional strategies. These affordances play a crucial role since the professional knowledge is put into practice only if teachers have the ability to connect their own prior knowledge with the opportunities included in the instructional resources and artefacts. This contribution stresses the role of the instrumental context because the way teachers are able to benefit from teaching resources and instruments contributes to shaping classroom practice. The second contribution, by Philippe Dessus, Franck Tanguy and André Tricot, explores a cognitive way to define teacher professional knowledge, arguing that some fundamental knowledge, which contributes to several human social abilities, may be applied as mediators in teaching. This may happen automatically or at a low cognitive load. This chapter suggests that a relationship exists between the distinction of PK and PCK and the distinction of two other types of knowledge that underpin each human activity. The latter separates implicit primary knowledge triggered by human experience and acquired through adaptation from explicit secondary human knowledge that is acquired by education. This distinction stresses the importance of improving teacher education and training by asking participants to reflect on ontological and epistemological questions regarding basic abilities such as cooperation, argumentation or project design.

Finally, a concluding section by Michel Grangeat and Brian Hudson summarises the book, provides recommendations for teacher education, and highlights further research perspectives. It particularly stresses the importance of epistemological and ontological issues. Three factors that influence science, technology and mathematics education are commonly addressed: competence in the use of scientific enquiry processes, confidence in handling the emotional and psychological states associated with the subject, and understanding the content to be taught. However, it is the last of these that provokes most attention when perhaps it is the first two that need more focus. This addresses the question of the nature of science and the importance of developing scientific thinking as opposed to the dry, procedure-driven approach that is often typical of the science classroom. In order to address these issues, the book proposes a refined model of the development of science teacher professional knowledge that draws on the current literature and might underpin further studies. This model is designed upon a teacher perspective in order to help teacher educators and teacher professional development providers design more efficient programmes. It aims to be a reference for researchers in order to better understand the transformation of science teacher professional knowledge.

This reference to these stable and shared frameworks allows the authors of the book to insert their studies as potential responses to the questions raised by the mainstream models used in science education. They aim to join their efforts with those of the international research community in order to sketch out some way of transforming the professional knowledge of 21st century science teachers.

NOTE

[1] The book results from symposia in ECER Porto 2014 and ESERA Helsinki 2015 and from a two-day seminar held in Grenoble in March 2015 at the Educational Science Laboratory (Univ. Grenoble Alpes).

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Michel Grangeat
Educational Science Laboratory
Higher School for Teaching and Education
Univ. Grenoble Alpes, France

Suzanne Kapelari
Austrian Education Competence Center Biology
University of Vienna, Austria

SECTION 1

PERFORMING EFFICIENT TEACHING: ROLE OF THE CONTENT TO BE TAUGHT

LORRAINE MCCORMACK

2. PRE-SERVICE PRIMARY SCHOOL TEACHERS' KNOWLEDGE OF SCIENCE CONCEPTS AND THE CORRELATION BETWEEN KNOWLEDGE AND CONFIDENCE IN SCIENCE

Studies of the subject knowledge of teachers, in relation to science, have highlighted the prevalence of misconceptions and the potential negative impact of this on the teaching of scientific ideas in school.

In this chapter, we examine some of the research exploring pre-service and in-service primary teachers' understanding of science and the implications for their practice. Findings from an audit of pre-service teachers' content knowledge are reported and their confidence in relation to the answers they provided is examined.

The chapter begins with a review of some of the literature about teachers' content knowledge in science and their confidence and awareness of their understanding in relation to this.

CONCEPTUAL FRAMEWORK

In the United Kingdom (UK), the importance of science is reflected in its status as a core subject, taught in primary schools from age five, alongside English and mathematics. Since its introduction as a compulsory subject in 1989, there have been concerns regarding the relationship between teachers' weak science subject knowledge and low levels of confidence on pupils' development in science. This concern has been well documented and explored in the UK and internationally.

Much of the discussion has stemmed from Shulman's work on the nature of knowledge needed for teaching, where he proposed three categories of content-related knowledge (1986, p. 9). These were: (i) subject matter content knowledge that "*refers to the amount and organisation of knowledge per se in the mind of the teachers*"; (ii) pedagogical content knowledge that "*goes beyond knowledge of subject matter per se to the dimension of subject matter knowledge for teaching*"; and (iii) curriculum knowledge which is represented by "*the full range of programmes (and materials) designed for the teaching of particular subjects and topics at a given level*". Shulman (1987) included both substantive and syntactic knowledge in his domain of teacher knowledge. The former, according to Hashweh (2005) in relation to science teachers, includes knowledge of general concepts, principles and conceptual schemes, together with the detail related to a science topic.

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Content Knowledge

Across all domains, 'good' content knowledge is widely accepted as a key feature of an effective teacher (Lederman et al., 1994). In relation to primary school, Morrisey (1981) proposed that one of the key influences on the extent to which teachers teach science is their knowledge of science and the issues involved in science teaching. Kallery and Psillos (2001) report that teachers' content knowledge influences the way in which they represent the content to students.

Many researchers believe that teachers may feel uncomfortable teaching science to children due to their lack of content and pedagogical knowledge, and this inhibits their ability and motivation to create meaningful science experiences for children (Watters et al., 2001; de Baz, 2005, cited in Fayez, Sabah, & Oliemat, 2011). Garbett (2003) and Hedges (2003) propose that the development of a science subject knowledge base to support children's scientific thinking is essential. Osborne and colleagues' (1990) work on primary pupils' thinking highlighted the lack of capacity to link phenomena together in a way that scientists would see related. Harlen and colleagues (1995) propose that, for pupils to be able to make these links between related ideas, teachers themselves must recognise the links and must possess the more general idea which links the separate ones.

Carré (1998) summarises the relationship between secure subject knowledge and effective teaching: *"The more you know about science, the more you will be able to provide a framework to help children think in scientific ways; in so doing you will also represent the subject with integrity"* (p. 103). Findings from an action research project conducted in the UK, in the mathematics context, found that early years teachers who were confident about their subject knowledge were more likely to recognise and maximise potential learning in children's integrated play experiences (Anning & Edwards, 1999).

Hedges and Cullen (2005) highlight "*the critical importance of teachers having sufficient breadth and depth of subject knowledge in order to respond meaningfully to extend children's interests and inquiries*" (p. 20). The authors (2005) claim that it is "*likely that teachers' beliefs and their lack of subject content knowledge will impact on the curriculum provided for children and on the teachers' ability to effectively construct knowledge with children*" (p. 16). Although Hedges and Cullens' focus was on science education, other researchers have echoed concerns in several different subject areas, such as numeracy (Babbington, 2005), literacy (Booth, 2005; Phillips, McNaughton, & MacDonald, 2002), visual arts (Gunn, 2000) and music (Willberg, 2001).

Studies examining the science subject knowledge of both in-service and pre-service teachers (Trundle et al., 2002; Bulunz & Jarrett, 2009) have highlighted the prevalence of teachers' misconceptions and the potential negative impact of this on their teaching of, often complex, scientific ideas in school. Kallery and Psillos (2001) report in their study of teachers of early primary pupils' responses to children's questions that only 21.9% included sufficient scientific conceptual knowledge. Garbett (2003) investigated early childhood pre-service teachers' conceptual knowledge of science and found that many student teachers had a limited understanding of science, but were unaware of this. Studies show that this lack of subject knowledge has also been identified as a concern for pre-service primary school teachers. A study in New Zealand showed that pre-service teachers' subject knowledge in science was generally poor (Garbett, 2003). In addition, it emerged that the student teachers were unaware of how little they knew. In Irish studies, Murphy and Smith (2012) and Liston (2013) found that high percentages of pre-service teachers enter the teaching profession with similarly inaccurate conceptions of science as the students they will be teaching. It has been found that, even though pre-service primary teachers often feel confident in their teaching of science, they can have poor knowledge and understanding of scientific concepts (Tekkaya et al., 2004). Studies on primary teachers' conceptual understanding in areas such as forces (Kruger, Palacio, & Summers, 1990, 1992), energy (Summers & Kruger, 1992) and changes in materials (Kruger & Summers, 1989) showed that they had incomplete understanding of the phenomena and in many cases communicated the same misconceptions as secondary school pupils.

Confidence and awareness. Teachers' confidence in their ability to teach science is a major area of interest, with lack of confidence identified as an issue for teacher development (Shallcross et al., 2002). Khwaja's (2002) work highlights that weak subject knowledge contributes to this low confidence and poor pedagogical skills.

McDairmuid, Ball, and Anderson (1989) claimed there was evidence to suggest pre-service teachers, at both primary and secondary level, do not understand their subject in depth. The implications of this, as reported by Grossman, Wilson and Shulman (1989), are that the teacher's confidence can become undermined and this can cause them to avoid teaching science, or to do so in more instructional ways (e.g., using a textbook, placing heavy reliance on kits and worksheets, avoiding practical work, depending on the assistance of external experts). A study from New Zealand reported that primary teachers identified deficiencies in their content knowledge as a concern in implementing the science curriculum (Lewthwaite, 2000; McGee et al., 2003). Primary teachers' inadequate subject knowledge and understanding of science may affect their teaching methodologies and their ability to teach science effectively (Murphy & Smith, 2012; Harlen et al., 1995; Harlen, 1997).

Pre-service teachers with little science discipline knowledge also expressed lower confidence in teaching science, particularly in the areas they know least about (Appleton, 1992). A study of elementary teachers indicated that 76% felt competent to teach reading and language arts, while only 28% felt competent to teach science (Jarrett, 1999). Studies have shown that pre-service teachers' reported confidence and competence in science is lower than in mathematics or literacy (Sharp et al., 2009), despite those reporting positively constituting a higher proportion than in a study 20 years earlier (Carré & Carter, 1990). In a study of primary teachers' confidence levels in their ability to teach the subjects, Harlen (1997) found that science was ranked eighth out of eleven subjects.

Jarett (1999) states that for prospective teachers' confidence one's own school experience is a strong predictor of both interest in science and confidence in teaching science. The effect was described by Hawkins (1990, p. 97) as a "loop in history by which some children grow to be teachers, taught science little and poorly, they teach little and poorly". This is supported by Garbett (2003) who reports that many negative attitudes among primary teachers towards science are due to their memories of science at primary school as an unpleasant experience.

It may be difficult for pre-service teachers to recognise areas of uncertainty in their own understanding of science content knowledge. Misconceptions of scientific concepts can often remain unchallenged (Murphy & Smith, 2012) and it is therefore essential that these areas are assessed and addressed in pre-service teacher education. A recent Ofsted (the official body for inspecting schools in the UK) report (2013) highlighted that teachers must recognise the limitations of their scientific knowledge and know how to address them.

In England, concerns about teachers' subject knowledge were raised by Alexander and colleagues (1992) and, in response, the curriculum for initial teacher education included a strong focus on subject knowledge. The Teachers' Standards (DfE, 2011) require that teachers (pre-service and in-service) must "*demonstrate good subject and curriculum knowledge*". It is against this background of on-going concern about subject knowledge that this auditing became a feature of initial teacher education programmes in the UK. Most initial teacher training institutions require student teachers to carry out a 'subject knowledge audit' to identify the areas where their knowledge needs improving. Approaches to this auditing vary across institutions, ranging from self-assessments and on-line assessments to formalised examinations.

In the base institute for this research, students in full-time undergraduate and postgraduate primary teacher education courses were 'audited' on their science subject knowledge by taking a multiple-choice examination. The student teachers' papers were marked by a team external to the course tutors (but within the University); the students were given their raw score and informed whether they had achieved the pass mark in the various sections. Whilst this gave a summative indication of the students' knowledge, it did not reveal the strength of their understanding or depth of their content knowledge.

To combat some of these shortcomings, a team of science tutors at the university designed and developed an on-line science knowledge audit comprising multiple-choice questions. The student teachers were also asked to identify the confidence levels they had in their answers and so, as well as choosing their answer from one of four choices, they also indicated the strength of their confidence in giving this answer in terms of low, medium or high. This relates to the work of Gardner-Medwin and Gahan (2003) who argued that knowledge depends on certainty in knowing.

This study set out to ascertain:

- The extent of pre-service teachers' subject knowledge across three topics (featured in the National Curriculum for Science).
- The confidence rating of the pre-service teachers' answers across the range of topics.
- Any relationship between knowledge and confidence overall, in particular topics and for particular questions.

Individual follow-up interviews were conducted in order to investigate any patterns emerging and deepen understanding of these phenomena.

METHODOLOGY

Study Setting and Participants

The research for this study was conducted at a UK-based university that has two full-time programmes for Initial Teacher Education (ITE), namely Bachelor of Education (B.Ed) and Postgraduate Certificate in Education (PGCE). The B.Ed is a three-year undergraduate programme and the PGCE is a nine-month postgraduate programme running from September to May. Both programmes combine school-based practice and university-based work. In England and Wales, successful completion of one of these programmes is the major route into state-funded primary school teaching. All pre-service teachers are expected to evidence a level of competence in teaching the National Curriculum (2008). As part of the National Curriculum, core subjects include English, Mathematics and Science and non-core subjects include Humanities, Religious Education, Art and ICT amongst others. All students have university-based courses on teaching and learning each of the subjects in primary school. In school placements, the student teachers are also assessed on a range of aspects of their teaching against Teachers' Standards (DfE, 2011).

The sample for this study comprised 18 self-selecting students in the B.Ed. and PGCE programmes. The students were in their first term of pre-service teacher education at the time of the study. The participants in this study undertook the on-line science audit in formal examination conditions. Ethical approval was sought and each participant signed informed consent forms prior to starting the study.

Audit

The audit comprised six main sections of knowledge (aligned with the National Curriculum for Science). These were Living processes, Forces, Materials & their properties, Light, Sound, Earth & Space, Physical Properties and Scientific Enquiry (see Table 1). In developing the questions for the audit, caution was exercised concerning the potential for "*subject knowledge [...] being elevated as the only* *important aspect of science*" (Stephenson et al., 1999) by including questions relating specifically to aspects of pedagogy, namely investigative science.

Upon completion, students received immediate feedback on their total score for each of the six sections and explanations about the answers for each of the questions answered incorrectly. It is understood that 'auditing' the students' subject knowledge formally can lead to anxiety as the gaps in their knowledge come to the surface (Shallcross et al., 2002); this study therefore also aims to help in the search for a way to support students in developing science subject knowledge without compromising their teaching confidence.

Table 1. Sections of the developed science knowledge audit, and the number of questions

Section	*Number of questions*
Living processes	25
Forces	17
Materials & their properties	19
Light, Sound & Earth & Space	13
Physical processes	8
Scientific enquiry	19

For the purpose of this study, the participants completed three sections of the on-line science knowledge audit. These sections were Living processes, Forces and Materials & their properties.

The audit required the pre-service teachers to: read the question (see the example in Appendix 1, select the answer that matches their knowledge and rate their confidence in answering that question). After completing each section, they were given a report on the questions and correct answers and reasoning if they answered a question incorrectly (see the example in Appendix 2).

Interviews

Five of the sample participated in individual follow-up interviews in order to investigate any patterns emerging and deepen understanding of these phenomena and to reflect on their confidence in teaching science.

RESULTS

On-line audit

The total numbers of correct and incorrect answers for each section are shown in Table 2. As can be seen for all three sections, the majority of questions were answered correctly. However, the Forces section had the lowest number of correct answers, with 36.6% of the questions being answered incorrectly by the participants. Pearson's correlation value for the overall result (number of correct answers) with the confidence levels had a value of 0.333 ($p< 0.01$), indicating a moderate, positive correlation.

Table 2. Section and percentage of questions answered correctly and incorrectly

Section	*Correct (%)*	*Incorrect (%)*
Living processes	81.1	18.9
Forces	63.4	36.6
Materials & their properties	74.3	25.7

When this was explored further, it emerged that there was a distribution in the level of confidence in answering each question with respect to the questions answered both correctly and incorrectly. As Table 3 shows, when the sample answered the questions correctly the distribution of confidence levels was as follows: 15.4% rated as low confidence; 33.9% rated as medium confidence; and 50.7% rated as high confidence. When the sample answered the questions incorrectly, the distribution of confidence levels was as follows: 43.2% rated as low confidence; 37.2% rated as medium confidence; and 19.6% rated as high confidence.

Table 3. Confidence levels for questions when answered correctly and incorrectly (all sections)

	Low (%)	*Medium (%)*	*High (%)*
Answered 'correctly'	15.4	33.9	50.7
Answered 'incorrectly'	43.2	37.2	19.6

When the confidence distribution for answered 'correctly' and 'incorrectly' is explored, it can be seen that they are indirectly proportional. The highest level of confidence was for the questions answered correctly and the lowest level was for the questions answered incorrectly. This indicates some awareness of the participants' knowledge of their understanding or lack of understanding in relation to some questions. Table 4 shows that there was a significant, positive correlation between the result for each section and the confidence level. This was the highest for the Living processes section (0.359) and the lowest for the Forces section (0.236).

The confidence levels for the three sections for the questions answered correctly are shown in Table 5. It can be seen that the students rated themselves as highly confident for 61.4% of the Living Processes section, 43.3% for the Forces section and 40.9% for the Materials and properties section. It can be seen that, although the questions were answered correctly, less than half of the participants rated themselves as highly confident in their answers to these questions. For the Living Processes section, 30.7% were rated as medium and 7.9% as low confidence. For the Forces section, 36.6% were rated as medium and 20.1% as low confidence. For the Materials and properties section, 36.6% were rated as medium and 22.4% as low confidence. The Forces and Materials & their properties sections had comparable proportions of participants with low and medium confidence, when answered correctly.

Table 4. Relationship between confidence and result for each section

	Pearson correlation value	*p value*
Living processes	0.359	0.01
Forces	0.236	0.01
Materials & properties	0.346	0.01

Table 5. Confidence for each section when answered correctly

	Low (%)	*Medium(%)*	*High (%)*
Living processes	7.9	30.7	61.4
Forces	20.1	36.6	43.3
Materials & properties	22.4	36.6	40.9

Table 6. Confidence for each section when answered incorrectly

	Low (%)	*Medium(%)*	*High (%)*
Living processes	35.3	41.2	23.5
Forces	37.5	40.2	22.3
Materials & properties	58	29.5	12.5

Table 6 shows the confidence levels for the three sections for those questions answered incorrectly. It can be seen that the students rated themselves as highly confident for 23.5% for the Living Processes section, 22.3% for the Forces section and 12.5% for the Materials and properties section. It is evident that, although the questions were answered incorrectly, a significant proportion rated themselves as highly confident that they were selecting the correct answer.

DISCUSSION

This study sought to measure the extent of pre-service teachers' subject knowledge across three topic areas. The findings suggest that the sampled pre-service primary teachers who participated in this study are not fully consolidated in their knowledge of three areas of the National Curriculum for science. The poorest area of response was Forces, with 36.6% of questions answered incorrectly. This was followed by Materials & their properties section, with 26% answered incorrectly. These findings further support the work of Kruger and colleagues (1990, 1992) in relation to primary teachers' misconceptions regarding forces and changes in materials (Kruger & Summers, 1989).

In relation to the pre-service teachers' confidence rating regarding their responses in the three sections, two findings warrant further discussion, namely the high confidence levels when questions were answered incorrectly and the low-medium confidence levels when questions were answered correctly. Across all sections, when questions were answered correctly only for 50% of the questions did students mark themselves as highly confident, and 15.4% were noted as being of low confidence when answered correctly. On the contrary, when the questions were answered incorrectly, almost 20% of them were rated with high confidence and 37.2% with medium confidence.

To address the first case, where confidence levels were high when questions were answered incorrectly, it is important to note the link between confidence and competence. In Garbett's study (2003) on student teachers' confidence and competence, it was reported that many student teachers had a limited understanding of science concepts and also that they did not know what they did not know. Most of the student teachers' perceptions of their competence in science were inaccurate (discovered when asked to predict scores in a test). Garbett found there was little correlation between their perceived competence and the actual competence as measured by the test. The student teachers in the study seemed confused and ignorant of their own understanding and/or misunderstanding of science (2003). Similarly, in Sanders and Morris' (2000) study in the area of mathematics they found that pre-service teachers either disbelieved the test result or placed a lower priority on the subject knowledge in a similar situation. The findings from this study support these perspectives and particularly Garbett's findings (2003) where it was noted that pre-service primary teachers were unaware of how little they knew. These findings highlight the necessity of the role of teacher educators to facilitate the opportunity for pre-service teachers to explore their subject knowledge and their confidence in that knowledge. One could argue that this should form the starting point of any course aiming to support pre-service teachers in their teaching of science.

The other contrary finding – when confidence in the answers was low, but the answers were correct – also holds some implications for initial teacher educators. The effects of low confidence in one's knowledge base may have a damaging effect in terms of avoidance of teaching science and/or poorer quality teaching.

These results reveal that the confidence levels vary across the three sections assessed in this study. The implications of these findings are stark. For the initial teacher educator provider, it is important to promote an ethos where pre-service teachers acknowledge responsibility for their own professional development and to establish a positive environment in which they feel confident to explore and construct their own knowledge. In the follow-up interviews, all student teachers mentioned the valuable impact of rating the confidence in their answers. Some reflections were: "It was helpful in getting me to think about my own thinking"; "Good for reflection… sometimes you feel more confident or less confident and it helps me think why".

In relation to initial teacher education, Sanders and Morris (2000) highlight the need for three elements to be incorporated into programmes. These are the need to support students as they come to terms with their lack of knowledge and the need to provide appropriate strategies for them to address deficits. Yet the critical element for ITE providers as they see it is the need to challenge students to accept that they have gaps in their skills and knowledge, and this is difficult, as ITE institutions have traditionally provided a non-confrontational and very supportive approach to such deficits.

CONCLUSION

The findings from this study, albeit preliminary, highlight the importance of pre-service teachers acknowledging responsibility for their own learning and content knowledge. In addition, it is important for teacher educators to provide a positive environment for pre-service teachers to construct their science content knowledge and develop confidence in their understanding or challenge their current level of confidence. Without this being challenged, pre-service teachers may be unaware of the implications their lack of knowledge could have for their pupils' futures, and the cyclical effect.

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Lorraine McCormack
Department of Education
Brunel University London, UK

APPENDIX 1

Selection of Questions and Multiple-Choice Answers

Question 11 of 17:
The mass of an object is:

- How heavy it is for its size
- The amount of matter in it
- The amount of space that it occupies
- None of the above Rate your confidence in this answer: Low Medium High

Question 12 of 17:
Which of the following statements is true, in relation to the mass of a block on earth and on the moon?

- The block is heavier on earth than on the moon
- The block has the same mass on earth and on the moon
- The block is lighter on earth than on the moon
- None of the above

Rate your confidence in this answer: Low Medium High

APPENDIX 2

Sample of Feedback after Each Section

You got 4 questions correct out of 17.
Here are the questions you answered incorrectly:
Question 1: Transfer of energy is important in which of the following combinations?
You answered “Physical processes only”, the correct answer is “Biological, chemical and physical processes”.
Question 3: Which condition will allow the car to move away more easily?
You answered “Car on a dry road with narrow tyres”, the correct answer is “Car on a dry road with wide tyres”.

ALAIN JAMEAU AND JEAN-MARIE BOILEVIN

3. THE DOUBLE LOOP OF SCIENCE TEACHERS' PROFESSIONAL KNOWLEDGE ACQUISITION

The study of teachers' professional knowledge has already been addressed in numerous educational research studies at the international level, both in general and with a focus on science teachers. These research studies often refer to the concept of Pedagogical Content Knowledge or PCK (Shulman, 1986, 1987), which is specific knowledge for teaching that is enriched, in part, by content knowledge (Sensevy & Amade-Escot, 2007). As shown by Abell (2007), most international studies have sought to identify teachers' knowledge based on what they say about their knowledge and their practice. In France, some groups have implemented methodologies that identify PCK based on teachers' actions (Bécu-Robinault, 2007; Kermen & Méheut, 2008; Cross, 2010; Jameau, 2014). Some of these methods emphasise the need to focus on a smaller scale in order to better conceptualise PCK (Cross, 2010; Morge, 2008). In all cases, the original model is rarely discussed because it is either redefined in each study or another theoretical framework is proposed (Abell, 2007).

Further, in recent years a reflection at the international level about the role of experimental activities in science teaching along with an evolution of the purposes of science education have allowed the development of new curricula, accompanied by new teaching practices, such as Inquiry-Based Science Education (IBSE) (Boilevin, 2013a, 2013b; Venturini & Tiberghien, 2012). The different curricula around the world (AAAS, 1989; NRC, 1996; Eurydice, 2006) describe this teaching approach in more or less the same form, but there is no real consensus on the definition of IBSE. The challenge is to renew teaching practices in science and technology (and sometimes in mathematics) by trying to make learning more active and more motivating and by providing more open tasks for the students, which give them greater autonomy (Boilevin, 2013; Calmettes, 2012). Thus, we move from activities focused on laboratory work or on conceptual learning, organised into stereotypical approaches, to education based on open investigations including the elaboration of questions and of hypotheses etc.

In this chapter, we present a model for science teachers' professional knowledge acquisition and compare it with an empirical study based on the implementation of a science course based on an investigation in the French curricula context.[1] IBSE is indeed promising if we assume that its implementation incites teachers to change their practices so as to meet the new requirements. Before we describe the model we

M. Grangeat (Ed.), Understanding Science Teachers' Professional Knowledge Growth, 27–45.

have constructed in detail, and demonstrate its interest, we present the conceptual framework to which we refer.

RESEARCH QUESTION AND THEORETICAL FRAMEWORKS

Our study led us to explore different theoretical frameworks, which we present here. First, we discuss our references on professional didactics for the analysis of the organisation of teacher activity and its accompanying regulation mechanisms. Then, we examine the studies about the PCK concept before presenting the Magnusson, Krajcik and Borko (1999) model, which we used in our analysis. Finally, we present some research concerning the concept of unexpected events.

Teacher Activity/Action

According to Sensevy (2007), the meaning of the word "action" in the phrase "didactic action" refers to acting "whether this is manifest or intellectual, and the general meaning that we give it when talking about philosophy of action" (our translation, p. 5), which Bronckart (2005) calls "any form of oriented intervention from one or more humans in the world" (p. 81). Schubauer-Leoni et al. (2007) emphasised the utility of retaining the elements of articulation between activity and action as they were proposed by Leontiev (1975) and, subsequently, by Bronckart. The latter defined activity as an interpretation of acting at the level of an organised collective and action at the level of a single person. The collective dimension of the activity is driven by *goals*, while the individual dimension of the action is driven by *intentions* and *motivations* that are specific to the reasons for acting. Leontiev (1975) considers realised actions as essential components of human activities. They are subordinate to activities. Activities are carried out through actions and actions respond to conscious goals. These goals are part of the task that he defines as a specific goal in defined conditions (Leontiev, 1975). Actions are realised by operations determined by the conditions of the activity and activities are oriented by a motive, which is a material or conceptual objective satisfying a need (Venturini, 2012).

It is important to differentiate what is related to the task from what is related to the activity in order to study the tasks required of students. The work of Leplat (2004) connects these two elements while showing precisely what differentiates them. He states:

> the task is what there is to do: the goal to be achieved under certain conditions (…), the activity depends on the task and the characteristics of the subject, of the individual, but it can contribute (in return) to the definition of the task and to the transformation of the subject. (p. 14)

Consequently, the activity cannot be studied independently of the task (Vinatier, 2009).

Retroactive Activity Regulation Loops

Leplat (2006) notes that the concept of regulation is often used in texts devoted to the study of activity in work situations. In addition, according to Coulet (2011):

> It is, indeed, difficult to account for activity without insisting on the regulation mechanisms that accompany it. (p. 15)

Consequently, Leplat (2006) proposes a definition and a model that allows him to show how a model of regulation can highlight some aspects of the activity. He mentions a few of the main types of regulations that he classifies as retroactive and proactive regulations: the first type is based on results, the second on anticipation. Coulet (2010) adds that:

> The function of proactive regulations is the adjustment of a scheme with regard to the specificity of the situation through the variability of the actions performed, while retroactive regulations show the reorganization of the activity as a result of the feedback of the action taken into account by the subject. (p. 5)

In the context of his research on the learning of nuclear power plant operations using simulators, Pastré (1999) shows that there are two types of strategies, both qualified as "retroactive and partial". The novice teacher cannot have an overview of the whole operation; his strategy called a short loop is procedural by nature. The result of the simulator training led Pastré to qualify the second strategy as a long loop; it is analytic by nature. In other words, the novice modifies his activity gradually, using a procedure that may be described as trial and error, where each mistake is associated with a rule for action. The short loop represents an "active coordination" regulation (Piaget, 1974), mainly oriented towards success. Concerning the long loop, the operator implements a form of "conceptual coordination" (Piaget, 1974) through a global approach. Moreover, in problem-solving situations, another form of retroactive activity regulation is seen: one that reorients the subject towards other forms of activities, towards other schemes, which would be better adapted to the properties of the situation and the task. According to Coulet (2010), these represent "scheme change" regulations.

Pedagogical Content Knowledge

The Shulman model can be used to understand the specific knowledge involved in the teaching of subject-related knowledge in order to distinguish a teacher from a specialist in a subject. He first defined three types of "content understanding" and studied their impact in the classroom: "Subject Matter Knowledge" (SMK), "Pedagogical Content Knowledge" (PCK) and "Curricular Knowledge" (CK). Later, Grossman (1990) proposed developing the Shulman model by defining four domains: general pedagogical knowledge (PK), disciplinary knowledge (SMK), pedagogical content knowledge (PCK), and knowledge of context (KofC).

Magnusson, Krajcik, and Borko (1999) defined the components of PCK separately (see Figure 1). According to these authors, there are four components: knowledge of teaching strategies, knowledge of programmes, knowledge of assessment, and knowledge of students. These four components of PCK are also divided into subcategories that interact with each other. In addition, a fifth component shapes the others: the "orientation to teaching science" component.

In our study, this model is useful in order to categorise the knowledge involved in teacher practice. It is composed of categories and subcategories that make a fine distinction between knowledge at the level of the teacher, which he uses in relation to the content to be taught (weight and mass in our study), and knowledge at the student level that is specific to the teaching of this content.

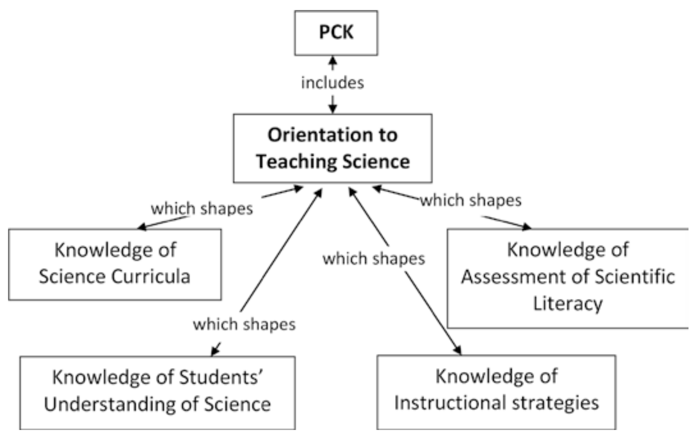

Figure 1. Examining pedagogical content knowledge (Gess-Newsome & Lederman, 1999)

The Concept of Unexpected Events

In some studies, the unexpected is considered as a tool while, in other works, it is seen as an object or as "a structuring object integrated in a method or as a training element" (Jean, 2008, p. 25). Unexpected incidents are sometimes synonymous with disruptive incidents (Woods, 1990) or misunderstandings (Broussal, 2006), linked to teaching described as "vague work" by Tardif and Lessard (1999). Yinger (1986) refers to improvisation to describe the work of expert teachers.

Huber and Chautard (2001) consider the unexpected as a particular type of event defined as disruptive, which leads the teacher to look for "a new balance" either immediately or later. This implies that the unexpected should be considered as a regulation system for learning. We find this relationship between the unexpected and regulation in the work of Broussal (2006). He demonstrates a relationship between the identification of misunderstandings and the expertise of teachers who use the misunderstandings as "pertinent indicators" that have an impact on their interventions. Perrenoud (1999) also uses the concept of event, but adds the qualifier "unexpected". He distinguishes the case of the predictable event whose occurrence is not planned, and the unpredictable event for which only an improvised response is possible.

A THEORETICAL MODEL FOR PROFESSIONAL KNOWLEDGE ACQUISITION

Our study of the gap between the planned and the realised entails identifying unexpected events in the class. Based on the work of Huber and Chautard, as well as that of Perrenoud, we define the unexpected as a disruptive event that occurs in the classroom and is not planned by the teacher. We consider the particular case where the unexpected event is perceived by the teacher and generates a regulation. These unexpected events can lead to the construction of new teacher knowledge.

From a methodological point of view, we identify the unexpected events during self-confrontation interviews (Clot, Faïta, Fernandez, & Scheller, 2001) (see the methodology section). Then, we note the goal changes that are characteristic of retroactive regulations of activity with reference to the work of Leontiev.

We propose a theoretical model (see Figure 2) that expresses the acquisition of new knowledge from the in-class activity and, at the same time, shows the impact of this new knowledge on the organisation of the teacher's activity. This impact can be measured by in-class and out-of-class work. It reflects the fact that the activity has a constructive factor and a productive factor (Samurcay & Rabardel, 2004). We consider that this model allows us to differentiate between the teacher activity

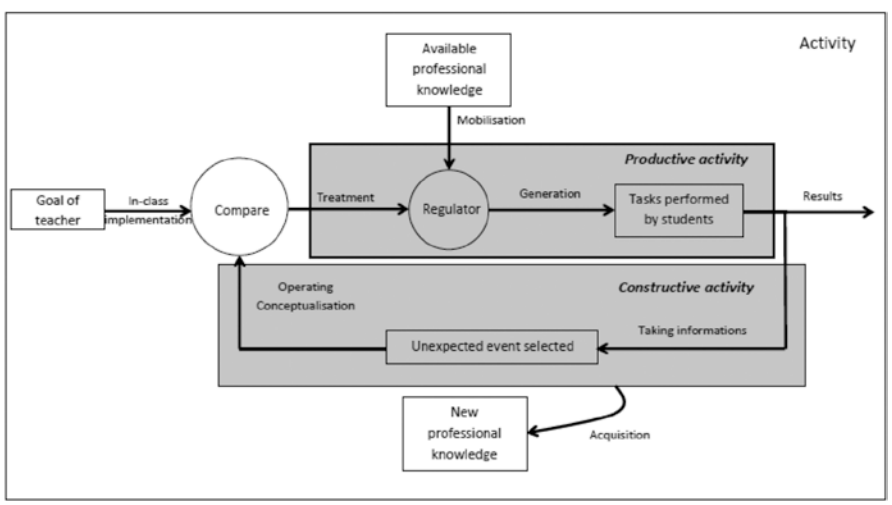

Figure 2. Theoretical model of a short-term loop

constructed during the preparation on one hand, and the evolutions of the activity as a result of the new knowledge gained in the class action on the other hand.

Our model covers two different situations. The first corresponds to an unexpected event that is perceived and selected by the teacher. He operates a short regulation loop that allows him to achieve her/his goal by operating step by step (Pastré, 1997). Then, she/he resumes the planned course of the lesson. During this regulation, new professional knowledge is acquired.

In the model, the circles represent actions of information treatment from several sources. The rectangles represent states. The regulator function aims to represent the fact that the activity of a subject position is never automatic, i.e., without checks and taken information. Here, it is either for the teacher to achieve its goal in relation with what is planned, or it comes to treating a gap between what is planned and what is realised. In the first case, we refer for example to the different modes we can characterise from the abstraction hierarchy of Rasmussen et al. (1994). In the second case, we focus on the treatment by the teacher in the class action that allows her/him to achieve her/his goal by working step by step (Pastre, 1997).

The second situation describes the consequences of the new knowledge acquisition on the result of the short regulation loop, as previously described. This allows the teacher to achieve her/his goal, but not in a way that is always satisfactory. Consequently, she/he performs a long regulation loop at a time scale that exceeds that of the class session. The result is generally more appropriate for the class, i.e., the responses given are more accurate and more efficient from the point of view of student learning (see Figure 3).

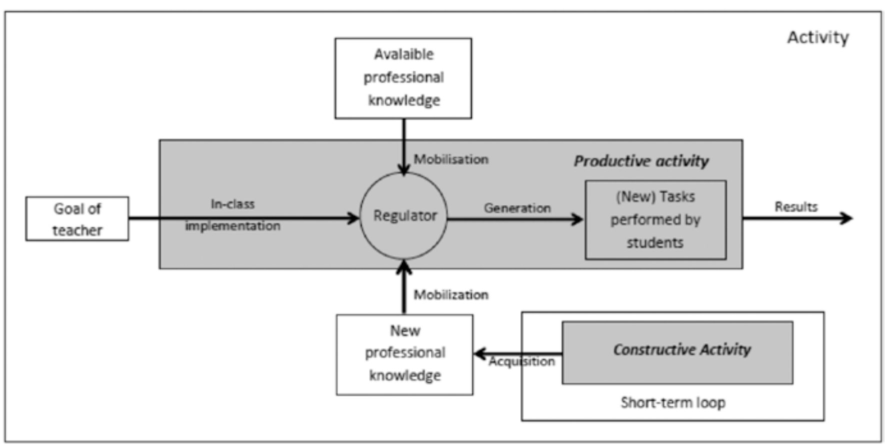

Figure 3. Theoretical model of a long-term loop

We will now compare this model with an empirical study to test its ability to account for the acquisition of professional knowledge by science teachers, as well as its evolutions. We first present our research methodology and then describe our results.

METHODOLOGY

In this paragraph, we describe the data collection and processing tools with respect to the context of the study.

Context of the Study

We implemented this methodology during two consecutive years. It consists of monitoring two experienced teachers in French secondary schools who are specialists in physics-chemistry teaching. We will call them Henri and Florence. The case study we present here involves a mechanics course for 14-year-old students. We chose Henri and Florence because they are neither novice teachers nor expert teachers. Indeed, studying novice teachers and the problems inherent to the early career stage may have obscured the objectives of our study. On the other hand, expert teachers who have been teaching at the same level for years, and among whom we might observe succinct preparations and installed routines, would have made the changes that interest us less obvious.

The chosen topic concerns the concepts of 'weight and mass'. It is treated by each of the teachers in three one-hour sessions. The advancements were coordinated so that this chapter was taught at the same time of the year to allow everyone to discuss teaching situations that had been experienced recently.

Finally, we note that the practice of these two teachers was performed within the French curricular context, where IBSE has been one of the requirements since 2005, following on from elementary school.[2]

Tools for Data Collection

The corpus we collected includes audio and video recordings of class sequences and interviews with each of the teachers, as well as data from a diary filled in by the two teachers for the duration of the study. The latter provides a trace of their class preparation and their analysis of the previous session. It allows us to address their out-of-class work. It is an essential tool in the reflexive investigation methodology in the sense that it encourages reflexivity on the activities (Power, 2008; Gueudet & Trouche, 2010).

The total duration of the video recording was approximately 38 hours. Two cameras were installed: one at the back of the class, which was focused on the blackboard, and a second mobile one, filming the interactions between the teacher and the students. The teacher was equipped with a lavalier microphone and two 'ambiance' microphones were placed in the class. The video recording was then digitised.

We conducted different types of interviews with the teachers: interviews at the beginning and at the end of the sequence, as well as self-confrontation interviews (Clot & Faïta, 2000; Clot, Faïta, Fernandez, & Scheller, 2001). The topic studied during the sequence was decided in advance by the teachers and the researcher together. It was the basis for the two interviews, in which the teachers performed a self-analysis of their action, watching the video recordings of the sessions, according to methods that are similar to simple and cross self-confrontation. Self-analysis is envisaged here as a method for collecting empirical data and analysing verbal protocols in relation to the action. Simple self-analysis consists of an interview between the researcher and each teacher. They are asked to describe and then analyse their actions, verbalising what they did, thought or took into account, and avoiding any interpretations or generalities. The cross self-analysis involved the two teachers and the researcher in a common analysis of the same video recording. It was used to analyse the unexpected events identified in the simple self-analysis. Therefore, we chose to monitor the two teachers simultaneously in order to organise these talks.

Tools for Data Processing

Our analysis was sometimes done at a very fine scale, at the statement level, to allow us to perceive the adjustments made by the teachers in the class action, which led us to proceed according to the methodology of the case study, with two levels of analysis.

At the first level, we produced a synopsis (Sensevy & Mercier, 2007) of the sessions, based on an initial video analysis. From a methodological point of view, the session synopsis corresponds to a reduction of the corpus, allowing an overview of the complete session studied. In order to prepare the simple self-analysis interview, we provided each teacher with the videos of their own practice in class, together with the synopsis. Then, we asked them to indicate all the situations that they would like to discuss with their colleague, in particular noting all the unexpected events that occurred during the class. During this interview, the unexpected events identified by the teacher were compared to those identified by the researcher, and then discussed. Those that were judged relevant to our study were kept for discussion in the cross interview. We then provided each teacher with the videos of their colleague's courses, as well as the session synopses. They had to do an initial analysis of the courses and note the subjects for discussion with their colleague. This could be related to the progress, the planning, a situation etc. This corpus represented the basis for the cross self-analysis interview. At the second level, we made transcripts of the situations that were discussed in the interviews. They concerned notably the unexpected events that were defined. We also made transcripts of the interviews related to these situations. We inferred the knowledge of the teachers by triangulating all of the data from the videos and transcripts.[3]

RESULTS

We now present some results of our research. We focus on one teacher and choose excerpts that we consider as representative. We analyse a topic taught by Florence during two consecutive years and present the unexpected events that gave rise to retroactive regulations of activity. We analyse a short loop and a long loop. Then, we discuss our results.

Analysis of an Entry Situation Implemented by Florence

Year 1: A short-term loop. In the first year, Florence starts the sequence by asking the students the following question: "So if I just say weight or mass what does that make you think of?". She explains that they will then classify their propositions in a table with respect to weight or with respect to mass. The students respond by mentioning "kilogram", "gram", which they put in the mass column or in the weight column. She validates these responses as she punctuates each proposition from a student with "ok" or "yes". Then, we observe a rupture in the planned lesson when a student (S_1) proposes to classify "volume" in the weight column. In fact, Florence nods for a few seconds. She seems surprised! The proposition "heavy, light" is made by student S_2, and is repeated by Florence. Then, she decides to respond to the "volume" proposition. Consequently, at this moment in the session, her goal is no longer to collect propositions from the students concerning weight and mass in order to classify them, but to 'correct the error' of student S_1 (see Table 1).

Table 1. Translation of session transcript: Confusion between mass and volume. The case of Florence

Speakers	*Verbal productions*
S_1	Volume
F (Florence)	Volume? ((the teacher nods her head))
S_2	Heavy, light
F	Heavy, light! So volume there is a small distinction between mass and volume ok? So volume, then this is more the capacity so heavy light no? Can you think of anything else?

We note that Florence's intervention is brief and hesitant because it is punctuated by pauses of at least 2 seconds each. We observe the teacher mobilising the class on this confusion, by formulating the first element of her response that she finishes with "ok", looking at the entire class, followed by a pause of about 4 seconds. Then, she says that volume is related to a capacity, before returning to the planned course of the lesson by asking the question: "can you think of anything else?". Florence says in the interview that she "eliminated" this proposition because density is not in the secondary school programme and "it can quickly become very complicated". We note this unexpected 'confusion between mass and volume'. In our opinion, she performed a regulation that we model with a short loop during which she made a correction to the confusion between mass and volume to avoid letting wrong ideas pass which could constitute "an obstacle later".

We observe that the teacher activity is organised around three goals during the short regulation loop. Her first goal is to mobilise the class on the proposition of student S_1. The second is to correct the confusion by saying that volume is associated with capacity. The teacher's third goal is to return to the initial goal, which was to find out the students' initial conceptions of weight and mass. Indeed, the teacher tells us her objective: "is precisely to classify everything related to weight on one side, and everything related to mass on the other, but already to try to clean up their knowledge a little before starting". According to her, it is by classifying the propositions in the table that the students express their initial conceptions on the subject. She expects certain answers: "kilogram I thought that was pretty sure I knew that kilogram would be in weight, it's classic! Light heavy I had had it in a class in sm[4] but not in the other one for some words. I knew they were going to come out but not in the right place not in the right class after". In contrast, Florence is not expecting "volume" as a characteristic of mass.

During this regulation, the teacher mobilises professional knowledge. We identify PK of class management, SMK of the concepts of weight, mass, volume and density. We also find PCK of the programmes that we note "density is not in the secondary school programme" and two PCK of the students "I need to eliminate the 'volume' proposition because I know that it can become very complicated"[5] and "I need to distinguish between volume and mass". The first belongs to the subcategory "Specific knowledge of the programme" and the other two to the subcategory "Knowledge of domains where students have difficulties".

Year 2: A long regulation loop. In the following school year, Florence is in class, in the same situation as described previously, but we observe her giving a different answer. She refers to the eighth grade programme where volume and mass are defined: "the volume is the space occupied by an object and it is measured in litres or dm^3". In the interviews, Florence justifies this change by the fact that she had expected this response, which she had already heard the previous year. The unexpected event of the first year actually turned into a predictable event in the second year. However, her preparation remained identical. For us, this change is characteristic of a long retroactive regulation loop.

The new PCK about the students, "Volume can be associated with mass", is the basis for this regulation that we model with a long loop. It was constructed during the first year by the teacher. We observe that the response provided by Florence in the second year is more structured and clearer than the one she formulated in the first year. To do this, she mobilised the PCK of the students "volume is defined in

8th grade" and knowledge that we could not situate in the model of Magnusson et al. We called it "Knowledge of what students learned in previous years" because, according to us, it goes beyond knowledge of students' prerequisites and of science curricula. It concerns the content of the response given by the teacher, which is precisely what she asked students to learn two years earlier. According to her, this ensures a better understanding on the part of the students of the difference between mass and volume. This teacher knowledge is constructed from the common history she has with the students because she is the only teacher of physics and chemistry in the school. We observe that this type of knowledge can influence her practice. In our opinion, it is PCK of the students because it is linked to specific content.

We observe that the teacher has learned merely by acting in a situation. She acquires the PCK of the students who make her plan a more appropriate response to this confusion, which she constructs in another context. Indeed, it is by giving the course on the measurement of volume in eighth grade, a month later, that Florence tells us that she elaborated it.

DISCUSSION

We now discuss the elements of the analysis presented in this study. We develop our proposals further based on the case of Henri. We start with the professional knowledge mobilised by the teachers. We compare our results with the model of Magnusson et al. (1999) and mention certain limits. Then, we present the evolution of professional knowledge through mechanisms of new knowledge acquisition. We analyse the consequences of the reorganisation of teacher activity. Finally, we discuss our model for professional knowledge acquisition by science teachers.

The Professional Knowledge of the Teachers

The model of Magnusson et al. allows us to identify the professional knowledge mobilised by the teachers during the implementation of a course based on investigation. Let us return to the two moments we analysed in the previous part: the introductory situation of the sequence and the experimental investigation constructed by the two teachers.

We previously showed that Florence has two goals: on one hand, she wants the students to propose characteristics of weight and mass and to classify them in a table and, on the other, she wants to find out their conceptions of these two quantities. In order to build and implement this introductory situation, the teacher mobilises not only CK, but also PCK. This includes CK of the concepts of weight, mass and gravity applied to the Earth. We observe different categories of PCK: of the students, the programmes and the strategies (see Table 2).

The question posed at the start concerning "what do you know about…" seems fairly common to us when it comes to understanding the students' conceptions. It is not specific to the teaching of weight and mass. It is a strategic approach as there

Table 2. Categories of PCK mobilised by Florence in the entry situation

PCK categories	*Subcategories*	*Formulation*
PCK of the students	Knowledge of the domains where students have difficulties	I know that kilogram will be in weight. I know that the word scale will not necessarily go with mass. I know that the students mix up weight and mass.
PCK of the programmes	Knowledge of the goals and objectives in the official instruction	I know that I have to find out the students' initial conceptions at the start of the sequence in order to construct the subsequent learning
PCK of the strategies	More general knowledge of strategies (for multiple topics)	Start the sequence by asking the whole class a question in order to identify the confusion between weight and mass

is a question and the answers are put in a table. We classify this PCK as "general knowledge of strategy". It is linked, in our opinion, to the fact that the teacher already understands a certain number of conceptions that we have classified in the sub-category "domains for which students have difficulties". She knows that the students' conceptions will emerge when the propositions are classified in the table.

Florence refers to the programmes and, more specifically, to the investigation approach when she says "find out the students' initial conceptions at the start of the sequence in order to construct the subsequent learning". Indeed, this moment of the session corresponds to the problem that aims, notably, at "identifying the conceptions or representations of the students, as well as the persistent difficulties (analysis of cognitive obstacles and errors)".[6] This approach allows the students to carry out investigations where "the search for explanations or justifications leads to acquisition of knowledge, of methodological skills and the development of technical know-how" (ibid.). We classify this knowledge as belonging to the sub-category of the goals and objectives in the official instructions.

We observed Henri starting the sequence on "weight and mass" with the study of a comic strip of the adventures of Tintin from the album "Explorers on the moon". This strip shows one of the heroes, Dupont, on the moon, jumping over a crevasse and falling much further than expected. The teacher tells us in the interview that he has two goals: to interest the students to ensure their adherence to this new chapter and to give a definition of the weight of an object. He gives us two reasons for choosing a comic as the start situation. The first reason is strategic: "Everyone knows Tintin, so it speaks for itself if you like (…) so we get caught up in it, it's easy". His goal is to attract each student, to gain their interest from the start of the lesson, to ensure they will stick with it as long as possible. The second reason is linked to the programmes that advocate teaching by IBSE for some subjects. According to him, implementation of this kind of teaching requires "asking open questions to break down erroneous representations, to make them evolve". Therefore, it involves choosing a topic that can be associated with a "concrete" problem situation and allows him to pose a problem that is "understandable" by the students. During the discussion, for Florence, the term "concrete" means "referring to the students' daily life". The problem situation constructed from the comic strip, described above, thus appears relevant for the two teachers: "Everyone knows Tintin, so it speaks for itself if you like (…) so we get caught up in it, it's easy".

As in the case of Florence, Henri mobilises knowledge of the CK and PCK types to formulate his objective in line with the level of the class and his answers to questions that are appropriate from the point of view of the concepts and vocabulary used.

Evolution of the Teachers' Professional Knowledge: The Case of Unexpected Events that Do Not Generate Regulation

In the two cases we studied, the acquisition of PCK led to regulations operated by the teachers. It included PCK of the students in the sub-categories "Prerequisites necessary for learning a concept" and "Knowledge of domains where students have difficulties", respectively, and PCK of the strategies in the sub-category "more general knowledge about strategies (for multiple topics)". But unexpected events can be perceived by the teacher and do not necessarily generate a regulation loop. In other words, they are not the subjects of short or long regulation loops. In this case, they represent an event for the teacher but not necessarily for the student. Indeed, the teacher did not always have the answer to an event in action, as with the case of Florence when she saw that the question asked in the introductory situation "aimed at finding out the characteristics of weight and mass to better differentiate between them was not precise enough". But this new knowledge acquired by the teacher is saved in the sense that it can create a system with other new knowledge elements acquired at different moments of the session or the teaching sequence and participate to activity reorganisation.

We observe Florence modifying the organisation of the introductory situation of the first session in the second year. Indeed, she uses part of Henri's student material.[7] She shows an animated film and distributes the cartoon strip associated with the part she wants to study. Hergé's characters are found on the moon, jumping from place to place. The teacher builds on the students' description of the film, by asking: "why do the characters jump so high?".

The teacher says in the interview that she was not satisfied with her introductory situation in the sequence during the first year. She thinks that her questions and the students' answers were not "precise" enough. She says that the articulation with the previous course on gravity did not occur, resulting in difficulties in defining the notion of weight. She observes that she lost a lot of time in discussions. In our opinion at the end of this analysis, the teacher had constructed three new pieces of PCK: "The students do not re-use the concept of gravity to define the weight; the student knowledge is not sufficient at the beginning of the sequence to distinguish between the two concepts; the question asked the previous year aimed at finding out the characteristics of weight and mass to better differentiate between them was not precise enough". The first two items of knowledge are the PCK of the students, in the sub-categories "Prerequisites necessary for learning a concept" and "Knowledge of domains in which students have difficulties", respectively. The third statement corresponds to a piece of PCK of the strategies, in the subcategory "more general knowledge about strategies (for multiple topics)". All of these pieces of PCK lead to the changes we have described above.

In our opinion, Florence can change her introductory situation in the sequence because all pieces of the PCK are related to each other and constructed from elements of her in-class activity. We say that the knowledge elements create a system and participate in this type of regulation performed by the teacher. They are acquired on the time scale of the sequence or the activity. That is what we call "saving new knowledge". Nevertheless, some questions arise: on what time scale is each new piece of knowledge acquired? Is it only the new knowledge formulated by the teachers that creates a system? In the case we analysed, the new PCK is related to the activities carried out in the first session and also concerns the learning achieved in the previous sequence (the gravitational interaction). However, we think that elements from other activities at other, possibly later, moments in the sequence, the assessment results for example, can participate in the acquisition of new pieces of knowledge that create a system with the formulated ones and participate in the teacher's decision to reorganise their activity.

For us, these changes are characteristic of a long retroactive regulation loop. It would appear that the teacher's goal changes, as well as the students' task, at the level of the activity. Indeed, Florence's goal is different from that in the first year. Here, it is to define weight with the students based on their previous knowledge, notably about gravity depending on the planet. The students' task is to explain why Hergé's characters jump so high and so far. The acquisition of the new PCK actually leads to an organisational change in the teacher's activity. It is particularly characterised by a change in the teacher's goal and in the students' tasks. Here, Florence partly rewrites her preparation.

Limits of Our Analysis Framework

Our analysis framework allows us to identify the four types of knowledge in the model of Magnusson et al. (1999). In this study, we show how the CK and PK of class management or of strategy (Florence deciding to dismiss the student S_1's proposition) is mixed with PCK in the organisation of the teacher's activity. However, our results raise several questions concerning the definition and characterisation of PCK.

We now go back to Florence's response to the confusion of a student between mass and volume in the second year of our study. We have shown that she uses knowledge that we could not situate in the model of Magnusson et al. We called it "Knowledge of what students have learned in previous years". This teacher knowledge of the history of these students' learning is specific to the context in which Florence teaches because she is the only teacher of physics-chemistry in this French school. Consequently, not only does she know exactly what the students have learned in previous classes in physics or in chemistry, but she also makes planning choices on the scale of several years. For example, Florence says during the second year interview that she did not ask the students to plot their measurements because she had already insisted on this the year before (in eighth grade). She gives this task based on an exercise in the students' textbook. This category does not appear in the model of Magnusson et al. and is, for us, a new type of knowledge.

Another outcome of our study questions the analysis framework of PCK. It concerns the nature of the teaching approach, which can be described as inductive or deductive depending on what the teacher can anticipate about the students' difficulties. For example, when the two teachers want the students to find the mathematical relationship between weight and mass ($Fg = mg$) they either ask them to find a "mathematical relationship" or a "link" between these two quantities, or they give them the scientific law and ask the students to prove it by measurements. The teachers mobilise a system of the PCK of the students which allows them to better adapt the approach to formulate a law. However, we noticed that the two teachers were not aware that the nature of the educational approach changed between the two years. They thought they were still implementing an inductive approach because "in theory in physics we obtain laws from experiments, so it's not math!". Yet our study shows that the reality is different. We see from this that the epistemology of academic teaching subjects is an important element in the teachers' decision-making, although we do not know if, in this case, the mobilised knowledge is CK or another category of knowledge linked to a 'practical epistemology'.

Our study raises a new question: What is strategic for a teacher? Is it the implementation of a plan such as a lesson experiment, or starting a session with a question, or the choice of a medium such as a comic strip or is it the approach that is associated with it? This question comes as a result of the difficulties we had distinguishing between two subcategories of the PCK of the strategies or distinguishing it from the PCK of the programmes or the students. We can consider the following example: when Florence reformulates the task the students have to complete in order to find the law $Fg = mg$, she changes the instructions during the lesson. Indeed, she rephrases the sentence given at the start "show that there is a link or that there is no link" so as to make the students "find a mathematical relationship". During this regulation, does the teacher mobilise the PCK of the strategies or the PCK of the students? In contrast, when a teacher uses an analogy, we can say that he uses the PCK of the strategies. It is an approach with knowledge involved that aims to help the students understand one or more phenomena or to conceptualise ideas.

If we consider that it is the plan or the type of media that is strategic, we are in the presence of pedagogical knowledge because a plan or a medium is not specific to a topic.

CONCLUSION

The theoretical and methodological approaches used in this research allow us to illustrate our model for science teachers' professional knowledge acquisition. This model gives a macroscopic view of the modes of professional knowledge acquisition. We organise it within the PCK framework, which allows us to specify the type of knowledge acquired. In fact, we believe that our model and the PCK analysis framework are complementary.

Our study shows that the teachers mobilise other types of knowledge in addition to the knowledge of their academic subject: knowledge of students, knowledge of the programmes, and knowledge of the teaching strategies. The knowledge depends on the content to be taught, and corresponds to the PCK categories. It is combined (Shulman, 1986) notably with discipline knowledge (CK) of a level higher than that being taught, and pedagogical knowledge (PK). All these categories are included in the teacher's professional knowledge base. They allow the teacher to make the study topic more understandable for the students. In this study, we raised a theoretical question. In accordance with other research results, we encountered difficulties in identifying the PCK of the strategies. What is strategic in the teacher action? Is it the plan used, regardless of the content or is it everything? What can be used to differentiate the PK of the strategies from PCK? We also asked a question about the discipline epistemology that is involved in the teachers' decision-making, although we do not know if the mobilised knowledge in this case is CK or another category of knowledge linked to a 'practical epistemology'.

We believe that our study results in the identification of some elements concerning the teachers' experience acquisition. Indeed, the unexpected events lead to the construction of new PCK for the students. They sometimes generate retroactive activity regulation loops, which show how this knowledge participates in the teacher's adaptation of the teaching for the class over a more or less long time scale. In fact, the mechanisms that could model, in part, the professional experience acquisition are the acquisition of new PCK and the constitution of predictable events that we identified in the action and which were constructed previously. Nevertheless, this study should be continued, particularly by positioning it with respect to the work on teachers' professional development.

The empirical study presented here shows that the model we have constructed is suitable for representing and explaining the acquisition of professional knowledge by science teachers based on IBSE. But is it predictive? It should be tested in other cases and especially in other science teaching situations because IBSE has specific characteristics. Further, with its specific epistemology is this model suitable for academic subjects other than physics-chemistry? Again, it should be tested in other academic subjects.

In addition, other questions arise concerning our model of professional knowledge acquisition by science teachers. Is it adapted to more general or 'versatile' teachers, such as primary school teachers? Indeed, teachers can mobilise different kinds of PCK and PK, notably concerning the learning of French (syntax, phonology, spelling etc.) at the service of science learning, or about the role of writing in science learning (Jameau, 2015). Is PK not used more often when the PCK and CK are limited?

All of these questions indicate the work we still have to do to better understand teacher activity and its evolutions from the point of view of professional knowledge. We believe a research programme should be elaborated based on our model in order to test its heuristic power and possibly use it as a baseline for research in the context of science teacher training.

NOTES

1. BO N°5, 25 August 2005, Special Edition.
2. BOEN N°1, 14 February 2002, Special Edition.
3. We use "transcript" to refer to the tables of transcripts of verbal productions of classroom situations, and the interviews, together with some brief descriptions from the researcher.
4. sm is the other secondary school where Florence teaches.
5. Our underlining.
6. MEN. Les programmes du collège (Secondary school programmes). BO Special edition N°6, 28 August 2008.
7. Florence considered it more effective to enter into the sequence with the character of Tintin, as Henri did, rather than as she did in the first year. But she adapts the situation to her own objectives. This is a consequence of the self-confrontation interviews methodology. The reflexive collective activity on his own work transforms the participants, and the situation (Clot et al., 2001).

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Alain Jameau
Université Européenne de Bretagne
Ecole Supérieure du Professorat et de l'Éducation
CREAD EA 3875, France

Jean-Marie Boilevin
Université Européenne de Bretagne
Ecole Supérieure du Professorat et de l'Éducation
CREAD EA 3875 , France

DAVID CROSS AND CELINE LEPAREUR

4. PCK AT STAKE IN TEACHER–STUDENT INTERACTION IN RELATION TO STUDENTS' DIFFICULTIES

PCK has been a very successful concept in science education for the last 30 years. Many research studies have used this construct to study teachers' development, teacher initial training and teachers' practice. Although PCK has been very fruitful in providing a framework to identify what could be important knowledge for teaching, very little, if anything at all, is known about the link between PCK and student learning. One of the few studies to attempt to examine this link in science education is the one published by Alonzo et al. (2012) who looked at the PCK of two teachers teaching the same topic in relation to the students' outcome: knowledge and interest. This study not only provides empirical evidence of a link between PCK and student achievement but also offers reasoned speculations about how PCK may actually influence student achievement and motivation. We assume that students' learning relies mainly on their action in the classroom; therefore to understand how PCK enacted in the classroom can influence students' learning we need to understand how PCK can influence students' action. One way of characterising students' action in the classroom is to refer to self-regulation theory (Carver & Scheier, 1998). Indeed, self-regulated learning is a central process to many learning theories and many studies show that this process is positively connected to academic achievement. As far as we know, such a question has not yet been addressed.

CONCEPTUAL FRAMEWORK

We are interested in PCK enacted in the classroom. Although PCK was conceptualised as practical knowledge from the very beginning, the relationship between PCK and action in the classroom is not very clear. We will therefore start by presenting what PCK is before discussing a model of PCK in action.

Teachers' Pedagogical Content Knowledge

In his seminal paper from 1986, Shulman states that one category of knowledge is central for teaching – Pedagogical Content Knowledge (PCK). This category of knowledge is defined as "going beyond knowledge of subject matter per se to the dimension of subject matter knowledge for teaching" (Shulman, 1986, p. 9).

M. Grangeat (Ed.), Understanding Science Teachers' Professional Knowledge Growth, 47–61.

This category of knowledge is linked to other categories of knowledge, defining a knowledge base that a teacher needs in order to teach. Grossman (1990) developed Shulman's model to incorporate this category of knowledge amongst three other categories: general pedagogical knowledge, knowledge of educational context and content knowledge.

As shown by the important number of research studies on PCK over the last 30 years, the idea of a category of knowledge that is specific to teachers, and that links content knowledge with pedagogical knowledge, has been very enthusiastically embraced by education researchers. However, what exactly PCK is does not seem to have reached a consensus (van Driel et al., 1998). Nevertheless, in science education, one model of PCK developed by Magnusson et al. (1999) has been used by many researchers (Friedrichsen et al., 2011). Different components of PCK are described in this model (see Figure 1): 1) orientations towards science teaching; 2) knowledge and beliefs about the science curriculum; 3) knowledge and beliefs about student's understanding of specific science topics; 4) knowledge and beliefs about assessment in science; and 5) knowledge and beliefs about instructional strategies for teaching science. The Orientation component is central and shapes the other components.

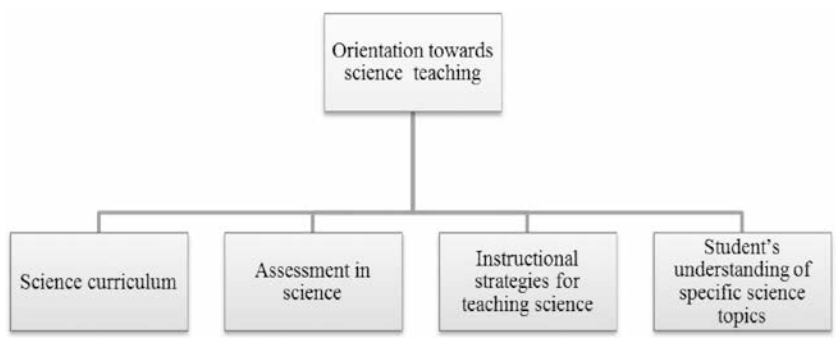

Figure 1. PCK components from the Magnusson et al. model (1999)

In their paper, Magnusson et al. (1999) point out that nine orientations can be defined by providing the goal of teaching science and the characteristics of instruction for each orientation. However, Friedrichsen et al. (2011) have shown that the orientation component lacks empirical and theoretical grounding. Moreover, although the orientation component is described as central in the PCK model, few studies have investigated the ways in which it relates to other components. In the conclusion of their paper, Friedrichsen et al. (2011) argue that the orientation component should be conceptualised as comprising three different elements:

- knowledge and beliefs about the goals and purposes of science teaching;
- knowledge and beliefs about science teaching; and
- knowledge and beliefs about the nature of science.

Another issue about PCK is the way to study it. Based on questionnaires and interviews, the early PCK studies focused on knowledge on action rather than knowledge in action. Since the late 1990s, the research methods show a variety of data and of ways of portraying PCK. For example, the CoRE and Paper method elaborated by Loughran et al. (2004) focus on what teachers are able to say about the teaching of a topic when talking in a group with some colleagues. Another example is given by Park and Oliver (2008) who collected classroom observations, semi-structured interviews, lesson plans, teachers' written reflections, students' work samples, and the researchers' field notes in order to study PCK. These examples show the shift from a knowledge on action towards a knowledge in action point of view that research on PCK has adopted to the extent that some researchers focus mainly on the action of the teacher and the students in the classroom rather than on what the teacher can say about his/her teaching (Cross, 2010; Alonzo et al., 2012).

PCK in Action

We believe that the variety of methods of different models of PCK and action in the classroom for studying PCK is significant. One of the limitations often pointed out when studying PCK from observational data (mainly video data) is that it cannot provide a complete portrayal of PCK (Baxter & Lederman, 1999; Loughran et al., 2004). As video data will show only a small portion of a teacher's activity, Baxter and Lederman (1999) advocate that "When attempting to study a teacher's knowledge of 'best examples', we cannot rely exclusively on observational data as a teacher may use only a small portion of his/her accumulated store of examples during a particular teaching episode. We, as observers, would never see the examples that the teacher decided not to use. In addition, an observation would not reveal why the teacher chose to use some examples while avoiding others" (p. 148). We can see from this quotation that PCK is understood, amongst other things, as teachers' knowledge of "best examples" and the reasons a teacher would decide to use this example rather than another one. Research about PCK should therefore be about having the greatest understanding possible of a teacher's knowledge. Another limitation that is sometimes attributed to observational data is that "[…] myriad factors influence classroom instruction and student understanding. Consequently, the level of consistency between teacher's observed behaviour and their knowledge and beliefs is highly variable" (Baxter & Lederman, 1999, p. 158). In other words, the classroom context might play a role in the action in the classroom, making it difficult to attribute the implementation of a given PCK to a given action.

Concerning the first limitation, we follow Alonzo et al. (2012) when they say that looking at PCK from video data enables us to study PCK when it matters most, that is to say when teachers are interacting with students. Consequently, the aim of the research is not to portray as fully as possible a teacher's PCK, but to understand the role of PCK in the teaching-learning process. It is therefore important to keep in mind that the methods for studying PCK should be consistent with the research questions. Studying PCK from interviews or other self-reported data may be the best way to have a broad understanding and a complete portrayal of a teacher's PCK in order to conceive a teacher training programme. But it would not be sufficient for understanding the role of PCK in teacher-student interactions. We believe that this second limitation is a crucial issue. If the level of consistency between PCK and the action in the classroom is variable, we need to understand what can explain the variability of this level of consistency. One possible assumption is that the context may influence the action, as noted by Baxter & Lederman, but it could also influence PCK itself. Indeed, PCK literature highlights the context-dependant aspect of PCK (Cochran et al., 1993). This assumption is at stake in the model of PCK originating from the PCK summit held in 2012 (see Figure 2).

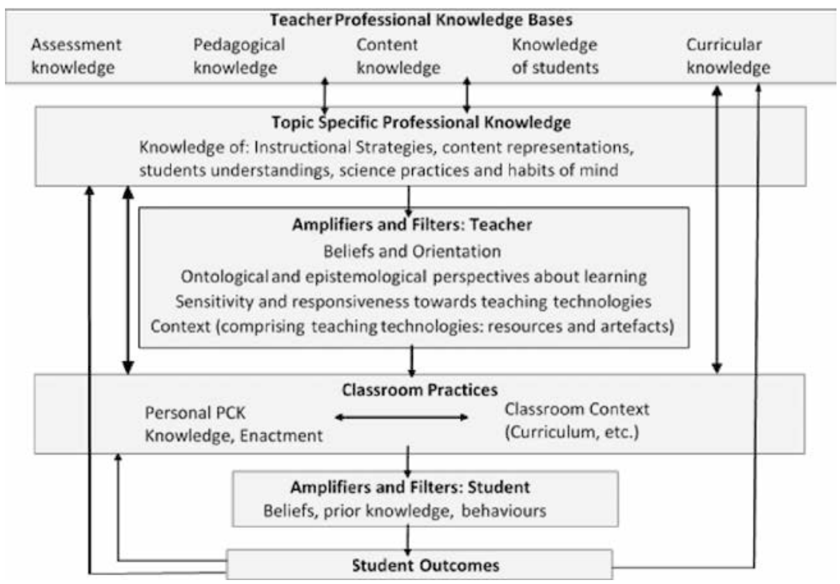

Figure 2. Consensus Model for PCK (after Kind, 2015)

Indeed, in this model the context influences personal PCK, and personal PCK influences the context. The context is also an amplifier and filter of topic-specific professional knowledge. Although we agree with this view about PCK and context, we assume that it is important to clearly distinguish action from knowledge. We would therefore have a different category for enactment rather than having it in the personal PCK category. Another problematic aspect of the PCK summit model is the knowledge category named Personal Professional Knowledge which comprises knowledge of: instructional strategies, content representations, students' understandings, science practices and habits of mind. It is unclear for us how this category is distinct from PCK as many of the components of PCK can be found in the Personal Professional Knowledge category. Thus, we propose a model that takes account of the above discussion and inputs from the PCK summit model:

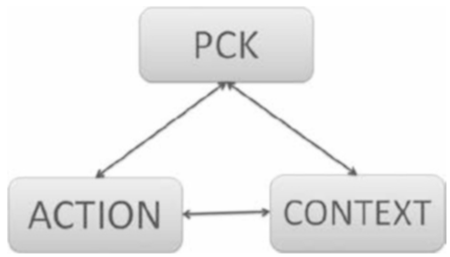

Figure 3. Relationship between PCK, Action and Context

In this model, PCK influences the action in the classroom, but the action also influences the PCK. This is supported by the idea that PCK is practical knowledge, as noted by van Driel et al. (1998, p. 675):

> PCK implies a transformation of subject matter knowledge, so that it can be used effectively and flexibly in the communication process between teachers and learners during classroom practice. Thus, teachers may derive PCK from their own teaching practice (e.g., analysing specific learning difficulties) as well as from schooling activities (e.g., an in-service course on student conceptions). More important, when dealing with subject matter, teachers' actions will be determined to a large extent by their PCK […].

Of course, action will influence context and vice versa. The term "PCK in action" supports the idea that PCK is dependent on a context and is closely related to the action in class.

The Link Between PCK and Students' Outcomes

Alonzo et al. (2012) studied PCK from the interactions between the teacher and students in the classroom. By linking what the students say in relation to what the teacher says, this research opens an important field in PCK research. Indeed, as van Driel et al. (2014) stress, research about the link between PCK and students' achievement is only starting in science education. Most of the research undertaken for the moment uses statistical approaches, and fails to find clear results (Baumert et al., 2010). Maybe this lack of clear results can be explained by considering the model of PCK presented above. Indeed, in this model, students' outcomes are not related directly to PCK but to the teacher's action in the classroom in a given context. Therefore, the question might not be to investigate teachers' PCK as thoroughly as possible by asking questions about a teacher's PCK whatever the context, but to understand how the teacher's action, the context, PCK and students' actions relate to each other. Accordingly, in addition to quantitative approaches that aim to study the impact of PCK on students' learning, a qualitative approach is needed in order to understand how the implementation of PCK can, or cannot, foster students' learning.

Research Questions

Our research questions relate to the above-mentioned model of PCK. We aim to explore the three dimensions of this model: the teacher's action, the context, and PCK. Our research questions rely on two assumptions:

First, that PCK which plays a major role in students' outcomes is PCK enacted in the classroom rather than PCK that a teacher can have but does not enact in the classroom. In other words, we do not focus on PCK as a personal construct (Baxter & Lederman, 1999), but on the teachers' action which will be described as the enactment of a specific type of knowledge, e.g. PCK. We therefore do not attempt to portray all of the PCK that a teacher can have, but only the PCK at stake in a given situation.

Second, to understand in detail how the enactment of PCK in the classroom can play a role in students' outcomes, we need to understand to what extent PCK enacted in the classroom is congruent with the students' action in the classroom, assuming that students' learning relies mainly on their action in the classroom.

Our first question is about the way to describe the action and the context in order to infer PCK. Our second question is about the relations among PCK, the teacher's action, the context and the students' outcomes.

METHODS

Data

Our data consist of a video recording of a physics lesson in grade 8 with an experienced teacher (with more than 15 years of teaching). One camera was pointing to a group of two students, and another one to the teacher, enabling us to grasp the context of the classroom. The teacher was also interviewed after the lesson. The aim of this interview was to clarify the learning objectives and the difficulties encountered. The whole video data and the interview were transcribed.

The aim of the lesson was for the students to make an electric circuit and to do some tension measures of the different components of the circuit. From these measures they had to identify the characteristics of each component. These components are a lamp, a switch, a resistor, a generator and a multimeter. The teacher is used to distributing the equipment needed for the activity in a basin. Not all of the elements in this blue basin are useful for making the circuit. The students make the circuit by using their activity sheet that contains a list of components and their description, but also an electric diagram.

Process

Our analysis consists of several steps:

First Step: Analysing the Students' Activity and Selecting Privileged Moments

Analysing the students' activity. From the field of psychology of learning, the concept of self-regulated learning (SRL) is an important theoretical development which relates the way in which independent learning skills help students to learn (Whitebread & Grau Cárdenas, 2012). As many research studies show that this process is positively connected to academic achievement, we have chosen to analyse the students' activity within this framework. According to the self-regulation theory, highlighting the cybernetic control approach introduced by Carver and Scheier (1998), behaviour is organised around goals and the subjects have expectations regarding the possibility of achieving these goals. According to their expectancies and their perception of where they are according to the goal, subjects will measure (comparator function) the discrepancy between their current state and the goal to be achieved. Subjects will therefore act towards a given goal and implement a set of strategies to reduce this gap. These actions will have effects on the environment. These returns of the environment will constitute the feedback. They are crucial because they provide information on the discrepancy vis-à-vis the goal, the effectiveness of the actions and what remains to be done.

First, the whole video data were coded using keywords corresponding to the students' actions, especially the 'feedback loop' when they implement self-regulated learning strategies. These keywords refer to: (1) the goal and sub-goals to be achieved; (2) the assessment of their current state (related to their progress in the task and their level of understanding); and (3) the set of strategies implemented to reduce the gap. This enabled us to identify when students are engaged in the activity and when they encounter difficulties in progressing in the task. This can be observed when there are little or no solving strategies implemented by students. Second, the teacher's actions are encoded according to the feedback (verbalisation or behaviour) given to the students:

- does it refer to the goal to be achieved?
- does it refer to progress in the task?
- does it refer to the strategies implemented by the students?

Finally, we encode if the provided feedback corresponds to a student's question or if it is initiated by the teacher himself.

Selecting a privileged moment. Since video data have the particularity of presenting a lot of information due to the density and length of this type of data (Tiberghien & Sensevy, 2012), we need to select a moment of the video in order to analyse it deeply. We assume that a possible rich moment of the classroom for implementing PCK would be when students encounter difficulties.

The analysis of the students' activity enabled us to select such a moment, where the students are:

- waiting for feedback from the teacher
- questioning themselves about their understanding
- not implementing solving strategies
- showing signs of demotivation

Second Step: Inferring PCK From the Teacher's Action and the Context

Analysis of the context. The first step in analysing the context is to understand what the difficulty was for the students. For this, we analysed the whole video of the students. It appears that the students plugged in the voltmeter in a series and did not plug a generator into their circuit. From the video, what can be understood is that one of the students believes that the voltmeter is a generator. The following excerpt illustrates this confusion:

> Student 2: I don't know what we are doing wrong, anyway it's written here, look we need a table generator, this, wires. *(Student 2 points to the voltmeter as he says "a table generator")*

How can this confusion be explained, knowing that the students had already used the voltmeters and made this type of circuit? All of the equipment necessary for the activity had been distributed at the beginning of the lesson by the teacher in the basin, except for the generator. The generators the students had to use were 'table generators', which means they are built into the table, and are therefore not directly visible to the students. Besides, the students were used to working with batteries with this teacher, even in previous years. This assumption is evidenced by the students' questions to the teacher while she is handing out the equipment at the start of the session:

Table 1. Excerpt number 1

S3	Miss, but where is the battery?
T	so we're going to use the table generators
S4	and where are the table generators
T	thus if you do a circuit you wait for me to plug it in
S2	there is no battery in the…
S5	and where are the table generators?

Therefore, we believe that the students used the voltmeter as a generator by default as they did not see a battery or a generator in the basin. This confusion of the students can be modelled by the didactical contract (Brousseau, 1997; Caillot, 2007). The didactical contract refers to a system of expectations between the student and the teacher, which gathers the current habits (rules, norms, capacities) relating to the knowledge at stake, and which constitutes the students' current strategies. The strategy implemented here by the students could be formulated as: "Use what's in the basin to make the circuit". This strategy relies on an element of the didactic contract rooted in the teacher's habit of handing out the experimental device in the basin at the beginning of each laboratory work session.

Analysis of the teacher's action. The teacher's action is analysed in relation to the context, based on three moments. The first one corresponds to excerpt 1 (see Table 1), when the teacher is handing out the experimental device to the students. The second one (excerpt 2, see Table 2) is an interaction between the teacher and the group of students which is being filmed. During this episode, the students ask the teacher to validate their circuit. The teacher points out to the students that there is a problem with the voltmeter, and asks them to think about it. The third moment (see Table 3) corresponds to the moment when the teacher comes back to the students. Meanwhile, the students have spent nearly 10 minutes trying to solve the problem.

We point out that the teacher does not explain to the whole class where to find the table generators (excerpt 1). From excerpts 2 and 3 we notice that the teacher focuses on the voltmeter but does not focus on the generator until the problem with the voltmeter is solved. It seems that she only notices the fact that there is no generator in the students' circuit once she has plugged the voltmeter in correctly.

Finally, we can highlight that the teacher asks the students how a voltmeter should be plugged in (theoretically) and then plugs the voltmeter in for the students while thinking out loud (excerpt 3). This last point is important for understanding the task from the point of view of the teacher, which can be understood as:

- (1) students have to make a circuit which has already been made by the students;
- (2) students have to plug a circuit in by applying knowledge about the elements (a voltmeter is plugged in parallel).

Table 2. Excerpt number 2

S2	Miss can we start?
T	are you sure about what you've done?
S1	no
T	come on think about it, first what do you want to do with that?
S1	well we are looking for
T	what do you want to measure?
S2	volts
T	measure volts, how is your device plugged in? Now try to rectify it

Table 3. Excerpt number 3

T	OK your turn
S1	but it's tension so we plug in V and COM
T	yeah it's V and COM theoretically you plug it in?
S1	ah yeah in
S2	series parallel
T	in parallel so here you haven't plugged the device in parallel so it cannot work and if your circuit is to work haven't you forgotten an important element?
S1	the generator
T	OK
S1	see I told you
T	so let's go back to the circuit here I plug there the circuit there you see now we know we're going to plug it in parallel OK and now we're going to see if so there what are you doing go on plug it I'll look where are you going to put it?

Inferring PCK. PCK is inferred on the basis of the analysis of the action, the context and the task and by taking into account Magnusson's categories of the components of PCK (orientations towards science teaching, knowledge and beliefs about science curriculum, knowledge and beliefs about the student's understanding of specific science topics, knowledge and beliefs about assessment in science and knowledge and beliefs about instructional strategies for teaching science). Part of this construction of PCK components is to ask ourselves what the teacher could have done differently, which allows us to take into account the fact that the situation may have guided the teachers' action rather than her PCK. Finally, we look for some evidence of the validity of the construction of the components of PCK in the video data (both the students' and teacher's video). In other words, it is a way to go back to the video data with the lens of the constructed PCK components. This whole process was undertaken jointly by the two authors. Each proposed PCK component was discussed and argued using evidence from the data.

RESULTS

PCK Inferred

From the analysis of the privileged moments two PCK were inferred:

- Students have difficulties plugging in the voltmeter; instead of plugging it in parallel, they plug it in in a series.
- Students do not have problems using a table generator (they know where to find or what a table generator looks like).

These two PCK are from the “knowledge of students’ difficulties” category from the Magnuson et al. model.

The first PCK is inferred regarding the teacher’s action and the task from the teacher’s point of view. Concerning the teacher’s action, the fact that the teacher focuses on the voltmeter but does not focus on the generator until the problem with the voltmeter is solved leads us to assume that she does not make a connection between the lack of a generator in the students’ circuit and the plugging in of the voltmeter. Moreover, the teacher could have asked the students to explain what they had done, and to describe their circuit. The task that is at stake also contributes to the inference of this PCK. The fact that the teacher asks the students to plug a circuit in that they have already made in a previous lesson by applying knowledge about the elements could be interpreted as an opportunity for addressing a specific difficulty encountered by these students.

The second PCK is inferred based on several aspects; first, on some elements of the context. Students are not used to working with table generators but with batteries. However, the teacher does not first explain to the students what a table generator is or where to find one. She also does not answer the whole class when a student, in a group, asks her where to find the table generator. The teacher could have anticipated the question about the table generators when distributing the experimental device or answered to the whole class about where to find the table generators. These two PCK components are closely linked to each other through the teacher’s action. The teacher focuses on the voltmeter and not on the generator as she believes that the main difficulty for the students is to correctly plug the voltmeter in and not to recognise or find a table generator.

Description of the Context

The description of the context is based on the habits of the class, what they had done before, and what these habits enable the students to do; in other words, what are the possible strategies to progress in the task. This description was useful in order to understand the students’ actions and their difficulty. We can also include in the context the task from the point of view of the teacher, which was for the students to plug a circuit in by applying knowledge about the elements of the circuit. Thus, the description of the context takes account of the situation from the point of view of the teacher and the students. We think that it is an important feature of our analysis, which we will discuss in the discussion section of this paper.

Description of the Action

Describing the action of an actor of the classroom requires certain decisions from the researcher. Indeed, some choices must be made to select what is relevant in accordance with the research question. We have chosen in this study to focus on the teacher's action in relation to the students' actual difficulty. For this, we concentrated on what the teacher is doing in relation to the voltmeter and the generator. We also focused on what she is doing in relation to the students' strategy to use what is in the basin to make the circuit. In other words, we looked at the teacher's action in relation to the students' action, even though the students' action was not analysed per se but was taken into account in the context by means of the didactic contract.

DISCUSSION

Our results show that 'having' PCK does not mean that the teacher will give effective feedback to the students. In fact, it is a common student mistake to plug a voltmeter in in a series as the ammeter (which must be plugged in a series) is also introduced in the same grade in France. Moreover, the correct use of a voltmeter forms part of the French curriculum. It is therefore an important piece of knowledge for French teachers to know that students have difficulties using a voltmeter. However, in the case we analysed, having this PCK leads the teacher to a false interpretation of the students' difficulty. This result has several implications. First, this means that the relationship between PCK and the students' outcomes is not a linear relationship. Studies trying to relate the amount of PCK a teacher holds to students' outcomes may well never succeed in showing that the more a teacher has PCK the better the students' outcomes. If such a relationship is evidenced, its interpretation should be carefully discussed. Second, in a theoretical point of view, this shows how PCK needs to be understood in its relationship to the context. The situation studied here could be interpreted as if the teacher does not take into account the students' possible strategy to use whatever is in the basin to accomplish the task. This didactic contract aspect of teaching and learning is difficult to account for in the Magnusson et al. model. It could perhaps be included in the orientation towards science teaching category as defined by Friedrichsen et al. (2011) in relation to the sub-category "knowledge and beliefs about science teaching". This brings us to notice that we have only inferred PCK from the "knowledge of students' difficulties" component. We assume that this arises from the fact that we are using a model of PCK that was built more for "PCK on action" than "PCK in action". For example, the category "Knowledge and beliefs on strategies" relates to what the teacher knows about a strategy. But observational data can only inform on what strategy is implemented in a given context. Therefore, this category may not be adapted to study PCK in action. Another reason we did not infer other types of PCK stems from a methodological issue. We have chosen to analyse only one lesson from this teacher. To infer some PCK from the "instructional strategy for teaching science" component, we would need to study this teacher's activity over a longer period in order to spot some regularity in her teaching strategies in relation to the context. We believe that this question of the length of the data is crucial to studying some of a teacher's PCK, especially for the orientations towards science teaching category. In our case, we would need to look at other situations where the teacher does not take into account the effects of the didactic contract to infer that it is part of the orientation component of her PCK.

The use of the didactic contract to understand the situation brings us to include this modelling of the teaching-learning process as part of a teacher's PCK. This point is central to understanding what PCK actually is. As far as we know, the PCK concept is not based on a model of teaching and learning, or at least not on a model that is made explicit or discussed. This may explain why so many definitions of PCK and what exactly comprises PCK can be found in the literature. In our research, we based our analysis on some elements of the Joint Action Theory in Didactics (Sensevy, 2011), which sees the teaching-learning process mainly as a communicative process of a certain kind. In fact, due to the instructional goal given by society to the school, knowledge is at the core of this communicative process. This theory aims to link teaching and learning by postulating that one cannot understand learning practices without understanding the related teaching practices. One of this theory's central features is to consider that the communicational process at the core of the teaching-learning process can be described using the concept of didactic contract. If we postulate that the didactic contract is central in the teaching-learning process, we would need to understand how it can be taken into account in the PCK model. One example of the way a teaching-learning model may influence the conceptualisation of PCK is given in the study by Alonzo et al. (2012). In this paper, the researchers aim to study PCK in action in relation to students' outcomes based on video data. They do not discuss the teaching-learning model they follow to analyse the video data, but the analysis shows they focused on the verbal interactions between the teacher and the students as a describer of the action in the classroom. The researchers came up with three categories of action: flexible use of content, rich use of content and learner-centred use of content. In their discussion, the authors try to relate the description of the action following these three categories to some components of PCK: flexible use of content to knowledge of student learning difficulties, rich use of content to knowledge of instructional representations, and learner-centredness of teachers' use of content to both of the previous components and suggesting that it could be an example of the interplay between these categories. The focus on verbal interaction in the classroom as an important part of teaching and learning in this paper has led the authors to interpret PCK from their categories of description of the action in the classroom. This shows that studying PCK from the action can never be a 'neutral' operation: the theoretical framework used to analyse the teaching-learning process will shape the PCK inferred.

To conclude about the relationship between PCK and student achievement, our research shows that the implementation of PCK can lead, through some filters and amplifiers yet to be studied, the teacher to a wrong understanding of the students' production, entailing feedback that does not allow the students to understand their mistake. We therefore call for some further research about PCK and students' outcomes, especially about which knowledge of a teacher plays a role in the implementation of PCK in a given situation.

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David Cross
LIRDEF
University of Montpellier, France

Céline Lepareur
Educational Science Laboratory
Univ. Grenoble Alpes, France

GÉRARD SENSEVY

5. ANALYSING TEACHERS' PEDAGOGICAL CONTENT KNOWLEDGE FROM THE PERSPECTIVE OF THE JOINT ACTION THEORY IN DIDACTICS

In this paper, I argue that teachers' pedagogical content knowledge needs to be acknowledged and analysed through an accurate system of description. Such a system can be seen as a generic system of strategies that a teacher is able to manage and to specify to the knowledge at stake. That is to say that, in order to provide such a description, one has to inquire into the nature of the didactic activity, and delineate its theoretical structure as a theory of practice (Bourdieu, 1990). A teacher's pedagogical content knowledge may be considered as a "practical sense", a "feel for the game" (Bourdieu, 1990a, 1990b) in which the teacher embodies this theory.

In this contribution, I first describe a theoretical framework that one may use as a theory of didactic practice, the joint action theory in didactics (Sensevy, 2012, 2014; Ligozat, 2011; Tiberghien & Malkoun, 2009; Venturini & Amade-Escot, 2013). Within this framework, 'didactic' means 'which refers to the teaching-learning process'. Then I focus on the structure and dynamics of the teacher's pedagogical content knowledge, as it can be understood through this theory. I propose to analyse and explore the teacher's strategic system by using the notion of counterfactual strategies, and to acknowledge and describe the teacher's pedagogical content knowledge as a practical awareness of a counterfactual system attached to a given practice, that one may conceptualise according to the categories of the theory. Such a counterfactual system is first described based on a system of previously exposed theoretical categories. It is then concretely used through an example I consider as emblematic. In the last part of the paper, I provide some elements of synthesis and discuss some issues related to this way of analysing the teacher's pedagogical content knowledge.

DESCRIBING THE TEACHER'S ACTION

In this part, I present the main elements of a theoretical framework – the Joint Action Theory in Didactics – that one may considerer as a way of building dynamic "thick" descriptors (Ryle, 2009) of the teachers and students' knowledge-based joint activity. Particularly, I focus on a system of notions that may provide such descriptors: the didactic game, which depicts the teaching-learning activity as a teacher's game on the student's game, and reciprocally; the dialectics of telling-showing (expression)

M. Grangeat (Ed.), Understanding Science Teachers' Professional Knowledge Growth, 63–85.

and being tacit-hiding (reticence); the dialectics of what is previously known (the contract) and what is to be known through the problem to solve (the milieu); the entanglement of these two dialectics; the genesis triplet (which refers to the way knowledge is concretely processed through the teacher-student transactions).

The Didactic Activity and the Model of the Game

I argue that it is fruitful to consider the teacher and student's action as a joint game. This first means that we include this action in the general paradigm of joint action (Mead, 1967; Bruner, 1977, 1983; Clark, 1996; Eilan et al., 2005; Sebanz et al., 2006, Tomasello, 2014; Csibra & Gergely, 2011), in which human development and praxis are ontologically thought of as a joint activity. In order to describe this activity, one may use the concept of game to account for the way the social world is continuously constructed and perceived (Bourdieu, 1990a, 1990b; Elias, 2012; Bruner, 1983; Goffman, 1970; Wittgenstein, 1997). Through the concept of game, it is possible to see joint action as a particular kind of cooperative game in which players share a common goal.

One may include within this general paradigm the teacher and student's action, which we describe as a didactic game. In this game, the teacher wins if and only if the student wins, i.e. becomes capable of a particular behaviour that is recognised by the teacher as the right one. This simple description helps understand some of the fundamental features of the didactic activity. In this activity, the teacher's action success is determined by the student's behaviour, but the teacher is the one who acknowledges this behaviour as relevant. Namely, the teacher plays a very complex normative game on the student's game.

On the basis of this model, one may infer some prominent characteristics of joint didactic action that we would like to highlight in this paper.

The Reticence-Expression Dialectics

First, this model entails that the teacher does not tell the student in a direct way what kind of behaviour she has to be capable of. The student's behaviour has to be enacted by the student on her own, not as a kind of mimetic gesture, but as a comprehensive activity, which ensures the teacher that the student will be able to act accurately in an autonomous way. Accordingly, the teacher has to hide some meanings, she has to be tacit about some of the components of the piece of knowledge she is trying to teach. At the same time, she has to directly show some meanings, she has to be explicit about some other components of this piece of knowledge. We call this fundamental characteristic of the didactic action the reticence-expression dialectics. When a teacher teaches, she has to be reticent (to be tacit, to hide) about some meanings, and has to express (to make explicit, to show) other ones. This behavioural structure is a dialectical one in that reticence and expression are opposite and complementary. Indeed, as we will see below, it is possible to show that being reticent about a meaning implies making explicit some related meanings, and reciprocally. This dialectical peculiarity is related both to the nature of language through its relation to reference (Quine, 1960) and to the very nature of the didactic communication.

The Milieu-Contract Dialectics

In order to learn, a student has to solve a problem, with this term being employed in a very general meaning. The student enters this problem through a specific state of knowledge related to the problem. In a didactic setting, this state of knowledge can be analysed as the 'previously known' about the piece of knowledge at stake.

It is worth noticing the specificity of this knowledge, which is the fruit of the previous didactic action. In that way, one may contend that the student's state of knowledge has been shaped within the previous didactic joint action. Following the didactic tradition (Brousseau, 1997), we term this previous knowledge system "didactic contract". The didactic contract can be seen as a system of meanings that one may analyse according to different descriptions. Each meaning of the didactic contract can at the same time be seen as a norm, a rule, a habit, a capacity, and an attribution of expectation. For example, when a student solves an arithmetical word problem he tries to find the 'good' arithmetical operation needed to solve the problem. The 'finding the good operation' part may be described at the same time as a norm, a rule of action, a habit, a capacity, an attribution of expectation (from the student to the teacher). As a 'previously known' piece of knowledge, shaped in the previous didactic joint activity between the teacher and the student, it belongs to the didactic contract, to the common background knowledge the students are able to use to solve the problem at stake.

This problem can be considered as a set of meanings (think, for example, of a word problem, or a text that has to be understood, or a picture that has to be interpreted), which puzzles the student. In its more general meaning, problem-solving, i.e., inquiry, can be seen as the search for a way of uniting within a meaningful whole various components of a situation that are not related together (Dewey, 1938).[1] One may say that the student has to transform a *set* of meanings in a *system* of meanings in the meaning-making process by achieving a unified whole. What we call milieu can be seen as a set of meanings that the student has to unify in order to solve the problem. In a nutshell, we can define the milieu as the symbolic structure of the problem the student (and the teacher, in the joint didactic game) has to deal with.

The milieu and the contract have to be seen as the components of an essential relation. When a student tries to solve a problem, he confronts a given symbolic structure (milieu) on the basis of previous background knowledge (contract). This relation is dialectical. Indeed, what has to be known (the milieu) is both the opposite of and complementary with the previously known (contract). It is complementary in that the new meaning cannot be apprehended without background knowledge that enables the student to orient herself through this new meaning. It is opposite, as the new is the opposite of the ancient.

The Entanglement of the Reticence-Expression Dialectics and the Milieu-Contract Dialectics in the Joint Didactic Game

As we have seen, we model the didactic activity as a joint game in which the teacher plays on the student's game, and reciprocally. How is it possible to describe such a joint game? We argue that a primitive description of the didactic game can be enacted as follows. The teacher's work consists of orienting the student's work. She can do that in two different ways: 1) she can provide information about the previously known knowledge (contract); or 2) she can provide information about the nature of the symbolic structure of the problem which is to be solved (milieu). For example, she can tell the students "remember the last time we did such a problem" (acting on the previously known, i.e., acting on the contract) or "try to cautiously read the last sentence of the wording" (acting on the to be known, i.e., on the milieu). When providing such information, the teacher can be reticent (she can hide or be tacit on some meanings), or she can be expressive (she can show or be explicit on some meanings). More exactly, her utterances can be characterised through a certain amount of reticence, and a certain amount of expression. In our example above, the utterance "remember the last time we did this problem" is more reticent (less expressive) than "remember the last time we did a problem of subtraction", and the utterance "try to cautiously read the last sentence of the wording" is more expressive (less reticent) than "try to read the wording". Accordingly, the general structure of the joint didactic game (from the teacher's viewpoint) can be presented in Table 1.

Table 1. The entanglement of the reticence-expression dialectics and the milieu-contract dialectics in the joint didactic game

Teacher's action			
Teacher's action on the students' relationship to what is known (contract)		Teacher's action on the students' relationship to what is to be known (milieu)	
Reticence on what is known (contract reticence)	Expression of what is known (contract expression)	Reticence on what is to be known (milieu reticence)	Expression of what is to be known (milieu expression)

The Genesis Triplet

The last descriptor we present in this chapter is the genesis triplet, which refers to the way knowledge is concretely processed through the teacher-student transactions in the joint didactic game.

The first descriptor is topogenesis: the making (genesis) of the epistemic place in the game, relating to the knowledge at stake. A topogenetic analysis of a given didactic transaction consists of analysing what is the respective responsibility of the teacher and the student toward the knowledge at stake. For example, when working out the solution to a problem the teacher can ask the students questions which contain the knowledge to be acquainted with, and the students have only to answer "yes" or "no". From a topogenetic viewpoint, we describe such a transaction as giving a prominent place to the teacher's relation to the knowledge, and an ancillary place to the student's relation to the knowledge. A good way to characterise this sharing of epistemic responsibility is to acknowledge that the teacher enacts thick epistemic utterances, which contain the heart of the subject matter to be known. On the other hand, we can think of the same kind of transactions within another division of epistemic labour in which the teacher asks only very general questions, or makes only some orienting remarks, while the students take a deep responsibility to work out the knowledge at stake. In this case, students will produce behaviours that one may recognise as thick epistemic utterances. Their topogenetic stance will be considered as a high one.

The second descriptor is chronogenesis: the making (genesis) of the knowledge time in the joint didactic game. A chronogenetic analysis of a given didactic transaction consists of analysing how the didactic time is moving forward. For example, one can think of a didactic literature activity in which the students need to identify who is the text's narrator in order to grasp some hidden meanings of the text. In analysing the didactic game, one may focus on the student's move (or teacher's move), which enables one to identify the narrator (i.e. to make the didactic time moving forward). Such moves will be termed chronogenetic moves in that they move the inquiry forward.

It is obvious that the two descriptors of topogenesis and chronogenesis are strongly related. For instance, a chronogenetic move, if it is acknowledged by the teacher, gives a high topogenetic stance to the student who has made his move. In this respect, the researcher may analyse the topogenetic structure of the chronogenesis by attempting to answer the question "Who is responsible for moving the didactic time forward?".

The third descriptor is mesogenesis: the making (genesis) of the milieu. Of course, this descriptor is strongly related to the contract-milieu dialectics. The goal of a mesogenetic description is to account for the way a set of unrelated meanings that the students have to deal with is transformed into a system of meanings that unify the initial symbolic structure of the problem they have encountered. One may say that this initial symbolic structure is a fuzzy one, whose various elements cannot be apprehended as a whole system resting on the knowledge at stake. The mesogenetic description makes understand dynamically how a united epistemic whole is to be achieved, to paraphrase John Dewey.

A good paradigmatic example of such a process can be found in the understanding process through a reading experience. The reader may confront a set of meanings she is able to understand one by one, but she does not succeed in identifying the general meaning of the text, which can be achieved by putting some of these 'primitive' meanings in a distinctive relationship, like a detective does when she fulfils an inquiry grounded in a set of unrelated clues she is able to connect into a coherent whole, which gives her the solution to the enigma.

Of course, the genesis triplet (and not only the mesogenesis descriptor) may be related to the dialectics entanglement we have delineated above. We will see this in the following part.

PCK IN THE TEACHER'S ACTION

PCK as a System of Counterfactual Strategies Related to a Specific System of Knowledge

I argue that the teacher's pedagogical content knowledge (TPCK) framework can be described against the background of the notions previously outlined.

In order to show this, I have to introduce the notion of counterfactual strategies. The term 'counterfactual strategies' can be seen as various virtual ways of acting that an analysis can propose as alternatives to a given actual practice.[2] The main end of using such a notion lies in enabling the researcher to focus on the concrete teaching-learning praxis, and to explore it, in order to bring about a kind *of ascent from the abstract to the concrete* (Marx, 2012; Kosik, 1976; Illenkov, 1982; Engeström, 2012).

Table 2 summarises our previous argumentation (CF holds for counterfactual).

Table 2. The entanglement of counterfactual strategies, contract and milieu

Known (contract)		├──────┤		To be known (milieu)
CF Strategy 1	CF Strategy 2	CF Strategy 3	CF Strategy 4	CF Strategy 5
Strategy description	Strategy description	Strategy description	Strategy description	Strategy description
Dialectical structure: known–to be known (mesogenesis)/ expression–reticence	Dialectical structure: known–to be known (mesogenesis)/ expression–reticence	Dialectical structure: known–to be known (mesogenesis)/ expression–reticence	Dialectical structure: known–to be known (mesogenesis)/ expression–reticence	Dialectical structure: known–to be known (mesogenesis)/ expression–reticence
Topogenetic dynamics	Topogenetic dynamics	Topogenetic dynamics	Topogenetic dynamics	Topogenetic dynamics
Chronogenetic dynamics	Chronogenetic dynamics	Chronogenetic dynamics	Chronogenetic dynamics	Chronogenetic dynamics

In this perspective, TPCK can be seen as a particular system of skills specific to a given piece of knowledge, which relies on the repertoire of counterfactual strategies a certain teacher is able to envision relating to this system of knowledge, through the joint action she is involved in with the students. I argue that TPCK 'in action' is necessarily related to knowledge-related generic principles and strategic rules, but also needs to take into account the (more or less) contingent features of a situation nested in a given institution.

The entanglement of the two dialectics (contract-milieu and reticence-expression) of the joint didactic game, as I have described them above, is a kind of abstract formula that has to be grounded in concrete praxis in order to allow its exploration. This abstract formula is composed of *agentive* concepts which have a threefold function. First, the entangled dialectics enable the researcher (or the teacher) to account for the immanent logic of practice, its grammar; second, they allow the researcher (or the teacher) to envision other practical possibilities of the action, often by getting rid of "false necessities" (Unger, 2007) entrenched by an approximate or biased approach of practical activity; third, it provides the researcher (or the teacher) with a system of categories that may serve to describe and develop PCK.

PCK as a System of Counterfactual Strategies Related to a Specific System of Knowledge: An Example

In order to move the analysis work forward, I will focus on a practical exemplar which can be studied to both provide an emblem of the entanglement of dialectics I have presented and explore a possible structure of TPCK.

An analysis of a realised strategic system. I present a short episode in First Grade in Primary School in December, at a moment when the students ignore many phonemes and words. The session is starting.

The teacher has the students work on the following text (sentence)

> *Le père Noël va dans toutes les villes et villages*. (Santa Claus is going in all the cities and villages).

The teacher is about to continue the collective reading of the text (by unveiling its second part on the board). He asks the students if someone knows something more in the text (the sentence)[3] (see Table 3).

Table 3. An analysis of a realised strategic system in First Grade in Primary School

<table>
<tr><td>1. 10
min 20</td><td>Teacher</td><td>Does anybody know something more, maybe some little bits?</td></tr>
<tr><td>2.</td><td>Hugo</td><td>I know a little bit, me.</td></tr>
<tr><td>3.</td><td>T</td><td>Hugo?</td></tr>
<tr><td>4.</td><td>Hugo</td><td>“cadeau” (gift) Hugo goes to the board by saying “cadeau” (gift) while climbing up on the stool which enables students to work on the text directly (for example, by underlining some words).</td></tr>
<tr><td>5.</td><td>T</td><td>Wait! Before underlining, show us! Hugo shows “villes” (cities) on the text that is put up on the central board. You think that it is the word “cadeau” (gift)? Do you agree? Hugo gets off the stool and waits in front of the board.</td></tr>
<tr><td colspan="3">Hugo has made a mistake. He has read “cadeau” (gift) instead of “villes” (cities). P intervenes by asking Hugo to show “before underlining”. P knows that the word “cadeau” (gift) is not in the text. As Hugo goes to the board to underline the word (which would institutionalise the fact that the word is in the text), she asks him to show what he has ‘recognised’ as the word “cadeau” (gift) (which is actually the word “villes” (cities).
The teacher does not assess Hugo’s contention, and sends Hugo’s answer back to the class (SP 5. Do you agree?). We can see here a first bifurcation, from which other counterfactual strategies can be envisioned, as we will see.
Hugo gets off the stool and is not in an ‘utterance position’.</td></tr>
<tr><td>6.</td><td>STs</td><td>No (quite hesitating)</td></tr>
<tr><td colspan="3">The students’ hesitant answer gives us a clue about the ‘knowledge state’ of the class.
It seems that a certain number of students are in the same state as Hugo, i.e. a kind of uncertainty.</td></tr>
<tr><td>7.</td><td>T</td><td>Why Aude?</td></tr>
<tr><td colspan="3">P asks Aude, who expressed herself by raising her finger.</td></tr>
<tr><td>8.</td><td>Aude</td><td>Because there is “vi” which changes. Because with the “I” it makes “vi” and then there are two “L”, it makes “ville” (city)</td></tr>
<tr><td colspan="3">Aude shows she is perfectly able to decipher the word.</td></tr>
<tr><td>9.</td><td>T</td><td>Look, Hugo! Lou, you are not with us. I write the word...
P is going to write the word “ville” on a board to the left of the one on which the text is stabled. At the same time as the teacher, Hugo moves himself to the board on the left.</td></tr>
<tr><td colspan="3">P intervenes. In the same gesture: i) she ignores Aude’s production in a specific move we could term selective deafness. This slows the transaction time down, which we analyse as a chronogenetic move; ii) she writes the word “ville” (city) down on the board to the left, close to the studied text. While doing that, she offers a new reading object to the class. The milieu, as the symbolic structure of the problem to be solved, is changed (a mesogenetic move).
Hugo bodily follows the teacher and the institution of the new milieu on the left board.</td></tr>
</table>

<table>
<tr><td>10.</td><td>STs</td><td>Gift (cadeau)</td></tr>
<tr><td colspan="3">The fact that some students say "gift" (cadeau) shows us some kind of remaining uncertainty in the class.</td></tr>
<tr><td>11.</td><td>T</td><td>...that Hugo wanted to underline and he thought it was 'gift' (cadeau)</td></tr>
<tr><td colspan="3">By offering this new word (ville – city) to the students' reading, T expresses herself more or less directly about the fact that the word (falsely) identified by Hugo is not "cadeau" (gift).
The strategy that T manages in the Speech Turn 9-11 thus consists of:
- staying reticent relating to the word «ville» (cadeau), that she does not read to the students, but that she gives as an object of study, by writing it down on the board;
- expressing herself by creating an auxiliary milieu (writing the word "ville" down on the board), intended to build a relationship between the word written in the text (ville), that she copies on the board to the left, and the word "cadeau" (gift); and
- relaxing the reticence on the word «cadeau» (gift) that she 'disqualifies' indirectly (ST 11: "and he thought it was 'gift' (cadeau)"), yet without emphasising this 'disqualification' in the didactic work.</td></tr>
<tr><td colspan="3">This is an example of the dialectics of reticence-expression since, while keeping the reticence on the crucial knowledge at stake (the reading of the word "ville" (city)), P expresses herself by building an auxiliary milieu (the students face the text (the board on the right) and the word "ville" (the board on the left)). The building of this auxiliary milieu (that one can see as a study milieu of the main milieu) enables the reticence on "ville" (city), reticence that can be relaxed on "gift" (cadeau). From the viewpoint of the respective share taken by the agents in the transaction (topogenesis), such a strategy appears as an incentive to the agency of the students who will have to scrutinise this auxiliary milieu in order to move forward.</td></tr>
<tr><td>12.</td><td>Aude</td><td>Ville (city)</td></tr>
<tr><td colspan="3">Aude confirms her knowing.</td></tr>
<tr><td>13.</td><td>I</td><td>And well, we know the first letter. T writes down the word "vélo" (bike) in a column under the word "ville" (city).</td></tr>
<tr><td colspan="3">Aude's emphasis continues to be ignored by the teacher, who uses of the same 'selective deafness' I previously described. P continues to build the auxiliary milieu, which takes the form of an analogical comparison between the unknown word (ville) and another word (vélo). It is interesting to note that the teacher indirectly reminds the students that they know the word "vélo" (ST 1: And well, we know the first letter), which belongs to a class reference. Here is a representation of the board status.
<table>
<tr><td>v</td><td>i</td><td>L</td><td>l</td><td>e</td><td>Unknown word, being worked on</td></tr>
<tr><td>v</td><td>é</td><td>L</td><td>o</td><td></td><td>Known word, reference</td></tr>
</table></td></tr>
<tr><td>14.</td><td>Sts</td><td>It's "city" (ville)</td></tr>
<tr><td colspan="3">Some students have deciphered the unknown word (and/or they have heard Aude).</td></tr>
</table>

(*Continued*)

<table>
<tr><td>15.</td><td>T</td><td>Wait! (T laughs).</td></tr>
<tr><td colspan="3">T practices a light form of ‘selective deafness’ since she does not confirm that the word written on the board is “ville”, relating to those students who have already deciphered the word. She thus continues to slow the didactic pace down (a chronogenetic move).</td></tr>
<tr><td>16.</td><td>Sts</td><td>Bike (vélo)</td></tr>
<tr><td colspan="3">Some students have recognised «vélo» (bike)</td></tr>
<tr><td>17.</td><td>T</td><td>This one, we know it.</td></tr>
<tr><td colspan="3">The recognising of “vélo” (bike) is confirmed by the teacher, who does not read it aloud yet. A micro counterfactual strategy could have been “yes, it is ‘bike’”. In the class, the certainty state is strong about this word as shown by the students’ agreement in the next ST (18) and the teacher’s reaction (19).</td></tr>
<tr><td>18.</td><td>Sts</td><td>Yes</td></tr>
<tr><td>19.</td><td>T</td><td>It is one of the first words we have learnt. What is the same in the word, in this one (pointing to “ville”) and in the second word (pointing to “vélo”)? T addresses both Hugo, who remains beside the board, and the whole class.</td></tr>
<tr><td colspan="3">P confirms anew the class’ ‘already-there’ knowledge about the word “vélo” (ST 19: It is one of the first words we have learnt), without uttering the word “vélo”. This is a ‘contract reminder’ move in which T reminds the students of the ‘old’ knowledge. Such a move is crucial to ensure that the students can engage in the work on the auxiliary milieu that is constituted by the ‘two words’ table. This move can be described as a micro-example emblematic of the expression-reticence dialectics on the already-there (contract). T expresses herself (ST 19: It is one of the first words we have learnt), while remaining reticent on this word (she does not say that it is “vélo” (bike)).

In doing that, she gives the student the epistemic responsibility of a recognition effort. While saying “It is one of the first words we have learnt”, T organises the comparison (ST 19, What is the same in the word?), without specifying it, in order to trigger the deciphering of the word “ville” (city).
The teacher’s management of the two words table (ville/vélo) may be described within the dialectics known (contract)-to be known (milieu) since the analogical orientation through the table (the identification of a meaningful relationship in the milieu) depends on the already-there knowledge of the word “vélo” (that one can see as a background meaning of the contract). This known (contract)-to be known (milieu) dialectics is entangled with the reticence-expression dialectics because the teacher expresses herself in the building of the analogical milieu (the table that I called “auxiliary milieu”), relaxes the reticence on the word “vélo” (bike), maintains the reticence on the word “ville” (city). The expression-reticence dialectics may also be understood at a finer scale of analysis. Indeed, when the teacher organises the comparison (ST 19, What is the same in the word?), she expresses herself (her utterance could be paraphrased as “compare the two words!”), but this expression makes (didactic) sense only through the reticence it implies at the same time (the reticence could have been relaxed, for example, by asking the students to compare the two words letter by letter (e.g., the teacher could have told them: “look at the first letter of each word, what can we say”?)).</td></tr>
</table>

<table>
<tr><td colspan="3">It is worth noticing that T, from the beginning of the session, includes Hugo in the transactions, even though he does not speak publicly. Hugo holds a 'special place' since he proposed the word "cadeau" and occupies a particular proxemic position in the classroom (beside the board and close to the teacher), while being 'one among others' in the "trilogue"[4] of the class.</td></tr>
<tr><td>20.</td><td>Sts</td><td>The V</td></tr>
<tr><td>21.</td><td>Sts</td><td>The first letter</td></tr>
<tr><td colspan="3">The students perform the correct analogy (the "v" of "ville" matches the "v" of "vélo").</td></tr>
<tr><td>22.</td><td>Hugo</td><td>Hugo, from his position beside the board, raised his hand to ask for the floor for a while, and speaks without T's invitation. There is a V and an L in both words.</td></tr>
<tr><td colspan="3">The fact that Hugo, as he is beside the board, raises his hand to ask for the floor is emblematic of his status of 'one among others' in the class. Even though the whole studied episode has its roots in the management of his error, Hugo has not played any specific role in this management until now. The teacher's work consisted of organising the collective study of one particular student's mistake.</td></tr>
<tr><td>23.</td><td>S</td><td>Well, right! This letter, how is it called? T addresses Hugo.</td></tr>
<tr><td colspan="3">As time goes by, Hugo does the analogical and deciphering work for himself. Thus P gives him the floor. In doing that, she enables him to tell the class what he has understood by asking him a question (This letter, how is it called?). Here, one can grasp the impact of the didactic time on the teacher's strategies. Some seconds before, the expression–reticence index would have been truly different. It is because the epistemic state of the class (as has been inferred from the teacher) – and consequently of Hugo too – has evolved and because the distance between the knowledge to be built and this epistemic state has been reduced, that the question can be asked in a fruitful way.</td></tr>
<tr><td>24.</td><td>Hugo</td><td>Vé (the first letter of "ville" is "v", which is pronounced "vé")</td></tr>
<tr><td>25.</td><td>T</td><td>And when it sings, what does it make? P addresses the whole class and Hugo</td></tr>
<tr><td colspan="3">T 'gathers' the class as a whole, including Hugo, by checking/strengthening the 'already-there' knowledge (the phoneme "V").</td></tr>
<tr><td>26.</td><td>Stds</td><td>Vvvvvvvvvv….</td></tr>
<tr><td>27.</td><td>P</td><td>I am going to circle another little word, and I am sure that you can read it (to Hugo). What is it? T circles together the two letters "i" and "l" in the word "ville", thereby making the word "il", which means "he" in French, and which is already known in the class.</td></tr>
</table>

(*Continued*)

<table>
<tr><td colspan="3">P relies on already-there knowledge (the pronoun “il” (he) which belongs to the repertoire of words in the class). The semiotic system the teacher produces (while circling the word “il” in the word “ville”, in ST 27) enables the students to distinguish the known in the less known (“il” in “ville”) and the teacher to organise the deciphering process. In addition to this semiotic system, T utters an assertion whose effects may be thought of as both epistemic and affective (TST 27: “I am sure that you can read it”). We raise the hypothesis that this assertion enables Hugo to gain confidence, a kind of confidence that is both epistemic (Hugo knows that he knows) and affective (Hugo is recognised as capable of participating fruitfully in the classroom work). From the strategic viewpoint we are trying to delineate in this chapter, one may notice the dialectical relationship in the teacher’s move. The teacher’s form of expression (the circling of the word-syllable “il” (he)) may be described as a form of reticence. For example, T could have directly shown Hugo a poster in the classroom on which “il” (he) is present. In this example, one may find a very general dialectical feature of the didactic relationship: when a teacher expresses something, she is reticent about some other things related to the one she is expressing. In a way, to say or show something means to be tacit about or to hide a lot of things that could have been said or shown[5].</td></tr>
<tr><td>28.</td><td>Hugo</td><td>«Il»</td></tr>
<tr><td colspan="3">The pronoun “he” is recognised by Hugo.</td></tr>
<tr><td>29.</td><td>T</td><td>And what does it make?</td></tr>
<tr><td colspan="3">T encourages Hugo to make the synthesis «v» + «il».
Here one may again see how T’s expression (St 29) could be both less direct and more reticent (she could stay silent conspicuously or wait), or more direct and less reticent (for example, she might connect on the board with the ruler or her finger the “v” and the “il”).</td></tr>
<tr><td>30.</td><td>Hugo</td><td>Ville</td></tr>
<tr><td>31.</td><td>Sts + Hugo</td><td>It makes “ville”</td></tr>
<tr><td colspan="3">Hugo, then Hugo and some students, decipher “ville” correctly. One may note that during the last part of the comparison, in which Hugo played the ‘first role’, the class continued to be present, and systematically called upon by the teacher, in a trilogue with Hugo. One may speak now of a ‘concertante’ didactic form in which the solo instrument production (Hugo) is accompanied by the orchestra (the class), with ‘the solo instrument’ remaining silent for most of the episode.</td></tr>
<tr><td>32.</td><td>T</td><td>So we have found it, but we cannot read it. Therefore, in what colour are we going to underline it?</td></tr>
<tr><td colspan="3">Here, the teacher enacts a class habit, which consists of underlining in red the words that the class ‘cannot read’ (whose knowledge has not yet been institutionalised). Even though it is eventually read correctly, “Ville” will be underlined in red to emphasise its novelty.</td></tr>
</table>

In the preceding analysis, I tried to produce a description of action that is closest to the meaning of action for the agents (the teacher and students). Where possible, I attempted to use some agentive concepts (reticence, expression, contract (‘already known’), milieu (‘structure of the to be known’), the genesis triplet), which can provide a kind of paraphrasing of the action in which – as we hypothesise – the agents might recognise themselves.

This description leads to the building of a realised strategic system, an actual strategic system that one may describe as follows at a (relatively) large scale of description.

The teacher, encountering the mistake of a student, Hugo, who confuses "*ville*" (city) and "*cadeau*" (gift), treats this mistake in a collective way. Without taking Aude's oral production into account, given this student knows the right answer, she has the class decipher the word "*ville*" without focusing on the word "*cadeau*". To do that, she has the class compare the unknown word "*ville*" to the word "*vélo*" (bike), which is a known word, belonging to the already-there repertoire. At the end of this comparison, the teacher focuses on Hugo's behaviour, and Hugo takes on the leading role to elucidate the word "*ville*", always in cooperation with the whole class. The teacher helps her achieve this elucidation by orienting the student's attention to the "little word" "*il*" (he), which belongs to the class repertoire.

This action summary can be made denser if one notes that the teacher continuously played with the expression-reticence dialectics, for example by building the "*ville*"-"*vélo*" table for the students, and by asking the class to study it. In this case, this expression-reticence dialectics is entangled with the already known–to be known dialectics, which grounds the grasping of the unknown (*ville*) on taking the known (*vélo*) into account.

We also saw that the teacher slowed the didactic pace down (a chronogenetic move), notably by employing the selective deafness with which she treats Aude's good answer, while giving the students a distinct topogenetic position, a relatively high one, that one could see as an average position. According to us, it is fundamental to understand that this kind of topogenetic position is a consequence of the game played by the teacher on the students' game, i.e., a consequence of the specific entanglement of the two dialectics (expression-reticence and contract-milieu) that we have described in the teacher's action.

This strategic system may be both guaranteed and refined by taking the teacher's discourse on her practice[6] into account: first, through her reaction to the analysis provided; then by the information that she may offer on what has been going on from her first-person viewpoint; and more generally on some sources of her action. For example, among them, an element of the 'didactic biography' of the class refers to the fact that Hugo is considered by the teacher as a capable student, but a 'very young one'. Another point is that Hugo's production can be seen as a good indicator of the average level of the class.

But one may contend that it is possible to go further in the practical study of this action by counterfactually reflecting on what it could have been, not only with another teacher in some slightly different circumstances (for example, slightly earlier or later in the year), but by the same teacher whose activity would have been oriented through other branchings of practice.

Analysis of other counterfactual strategic systems. One may distinguish four strategic systems in the counterfactual analysis of this episode, with the fifth being the actual strategic system.[7]

This conceptualisation rests, as I contend below, on practice bifurcations (branchings), but it is partially arbitrary. Its purpose is not 'to say' what could have occurred but, while imagining other possibilities to achieve a better understanding of the stratification of action by achieving a better understanding of how the actual has unfolded close to, even against, some other possible options.

- Counterfactual strategic system 1

T estimates that the epistemic state is sufficient to allow the error's immediate rectification. She thus corrects Hugo's mistake by relying on what he thinks of as already-there knowledge (for example, the fact that there is a letter and a phoneme "*i*" in "*ville*", and a letter and a phoneme "*a*" in "*cadeau*"). For instance, she tells directly Hugo and the class: "it's not '*cadeau*', one may hear '*a*' at the beginning of '*cadeau*', and there is no the letter '*a*' in '*ville*'".

In this counterfactual, T therefore relies on the known, the already-there, the didactic contract, to which she attributes some properties that enable the students to follow her reasoning. Her expression encompasses little reticence since she thinks that there are a few things to discover.

From a topogenetic viewpoint, the teacher's position is very high (she brings the major part of knowledge), the students' one is very low (they only have to follow the teacher's explanation).

The chronogenetic pace is very rapid. Little study time is given to the students to appropriate the teacher's discourse because she postulates a short epistemic distance between the students' state and what is asked to them.

- Counterfactual strategic system 2

In this strategy, T facilitates exploration of the word "*ville*". For that, she directly asks the students the first letter of the sought word. This expression consists of organising the exploration of the unknown word, a little bit as in the realised strategy, and thus relies, contrary to the first counterfactual above, on a certain amount of reticence justified by the exploration of what is to be known. However, by comparison with the realised strategy, this exploration takes the form of a 'questioning process' that may directly bring the students to the known.

From a topogenetic viewpoint, the teacher's position is high in that she assumes the responsibility to focus the students' attention on the first letter, but the topogenesis is more equally shared than in the previous counterfactual since the students are given the responsibility to search for the initial letter by themselves, and not only to 'record' their teacher's reasoning.

The students' inquiry slows the chronogenetic pace down (by comparison with the previous counterfactual), even though one may think that in this counterfactual strategy the students do not remain in an inquiry stance for a long time.

- Counterfactual strategic system 4

In this strategy, T manages the students' action by focusing their attention on the unknown. For example, she writes the word "*cadeau*" on the board, and asks the students to study it (what makes this strategy reasonable is that the letter "*a*" is known by the students, and thus is a solid known point in the unknown). It is a refutation strategy in which the teacher expects the students to produce on their own the reasoning that she produces in the first counterfactual above. The teacher's expression contains the reticence of this reasoning (she simply writes the word down on the board by asking students to study it, without giving any rationale).

From a topogenetic viewpoint, the students gain an amount of responsibility relating to the preceding counterfactual because the production of the refuting reasoning lies in their responsibility.

From a chronogenetic viewpoint, this strategy entails an opening of the didactic time, with a certain amount of study time being given to the students to work out the word "*cadeau*" and invalidate it as the meaning of "*ville*".

- Counterfactual strategic system 5

The (arbitrarily) last counterfactual strategy may consist of thinking that the students can refute by themselves the production of "*cadeau*" and/or read "*ville*". In this counterfactual, the teacher symbolically abandons the didactic stage, for example by saying: "Well, Hugo says that this word (while indicating "*cadeau*") is the word '*ville'*. What do you think of that?". In so doing, the teacher holds on strong reticence both on the known (she does not refer to any word of the class repertoire which might facilitate their inquiry) and the to be known, that she does not seek to relate to the known, which she does not even attempt to structure.

From a topogenetic viewpoint, the epistemic part taken on by the students may become very important.

The chronogenetic pace inherent to this strategy slows the didactic time down.

- The actual strategic system

The counterfactual strategic systems I described above enable a better understanding, in contrast, of the very structure and dynamics of the actually produced strategic system. One may contend that this strategic system holds a specific equilibrium, from the point of view of the entanglement of the dialectics known–to be known/expression–reticence, from the topogenetic viewpoint (the didactic responsibilities are shared by the teacher and the students), and from the chronogenetic viewpoint (the didactic pace depends on some selective deafness regarding some students' production, some slowing down, some acceleration).

The whole set of the studied counterfactual strategies is gathered in the following synoptic table as a kind of synthesis (CF stands for counterfactual, Top for topogenetic, C for chronogenetic, T for teacher, S for student).

Table 4. The whole set of the studied counterfactual strategies

Known (contract)	⊢―――――――――――――⊣			To be known (milieu)
CF strategy 1	CF strategy 2	Actual strategy 3	CF strategy 4	CF strategy 5
Saying directly: "not *cadeau, ville*"	Asking students the first letter of the word «*ville*»	Producing the «*ville-vélo*» table	Writing «*Cadeau*» on the board	Letting the students reflect on the text
Immediate recognising of the known (contract) Expression with minimum reticence	Recognising of the known (contract) Expression with little reticence	Working out specifically the relationship known–to be known (contract-milieu) Expression with significant reticence	Exploring the to be known (milieu) by relying on the known Expression with major reticence	'Free' exploration of the to be known (milieu) Reticence with minimum expression
Top T >> S	Top T > S	Top P = S	Top T < S	Top T << S
Chron pace ++	Chron pace +	Chron pace =	Chron pace -	Chron pace --

SOME CRUCIAL DIMENSIONS OF TEACHERS' PEDAGOGICAL CONTENT KNOWLEDGE

The previous analysis provides us with a theoretical framework that can be used as a way of characterising teachers' pedagogical content knowledge. In such a perspective, TPCK can be seen as a particular system of skills specific to a given piece of knowledge, which encompasses the repertoire of counterfactual strategies that a given teacher is able to concretely envision relating to this system of knowledge, through the joint action she is involved in with the students.

In that way, we see TPCK as a specific system of knowledge related to a counterfactual strategies system. It is worth delineating the nature of this system of knowledge and counterfactual strategies that we see as a core feature of TPCK. I would like to emphasise the following points.

The Nature of the Counterfactual System in TPCK

The counterfactual strategies system of knowledge refers to the teacher and students' joint action. It follows the fundamental argumentation according to which the teaching-learning activity (the didactic action) may be modelled as a teacher's game on the students' game. But the structure of this game, its grammar, needs to be recognised as such. I have determined two core dialectics of the didactic action which stem from the very nature of this process. This action is an epistemic action (i.e. relating to the mastering of knowledge), which simply means that learning occurs from a current state of knowledge towards new knowledge that is appropriated through the solving of a problem (in the more general sense of this term). Therefore, the teacher's game on the students' game has to take account of the relationship between the ancient knowledge, that has been dynamically built in the classroom transactions (the contract), and the knowledge to be acquired, that is symbolically embedded in the problem to be solved (the milieu). In the studied example, which I consider as emblematic, it is easy to note that the teacher's game rests on very good knowledge of what the students know (contract), and how a symbolic structure (a milieu) may be built to organise the emergence of new knowledge from the ancient one (for example, the *ville-vélo* table). I argue that the deep knowledge of the students' 'current epistemic state' – the contract knowledge – is a fundamental point of departure of any didactic action, and therefore a foundation of the TPCK. In a similar way, I contend that the way the teacher is able to design a milieu that embeds the knowledge at stake, while taking the current epistemic state of the students relating to this knowledge into account, is another foundation of the PCK. It is worth noticing that this part of the teacher and students' joint action, as a designing process, is essentially a priori. It is fundamentally a joint action in that the teacher's action may be thought of as transactional work in which the current students' epistemic state and the 'target' students' epistemic state are the touchstones of the designing process. In our studied episode, for example, the teacher's use of the *ville-vélo* table does not come from nowhere. This kind of table belongs to the teacher's repertoire. Given this fact, the teaching problem consists of choosing the components of the table in the course of action, and in proposing it or not to the students.

I draw a hypothesis of a difference in nature between these two foundations of the TPCK (the contract knowledge, and the milieu design). The first one (contract knowledge) asks for a kind of lucidity, for the teacher, about the students' current epistemic state, which means both knowledge of the average epistemic state, and of the possible variations among students regarding this piece of knowledge. The second one (milieu design) opens up possibilities in that it supposes creating didactic situations, although it rests on the contract knowledge. It is a first locus in which counterfactual skills are necessary to the teaching process. Designing a milieu asks for taking into account the students' current epistemic state about the piece of knowledge at stake, the variation among the different individual epistemic states, the distance between this current epistemic state and this piece of knowledge. The milieu design rests on deep knowledge of the content at stake, which I am going to characterise with help of the notion of epistemic game.

What is Content in TPCK: The Notion of Epistemic Game as a Way of Modelling the Didactic Transposition

The counterfactual strategies system of knowledge relies on a specific relationship to the content at stake through the designing of the milieu. I argue that a core criterion of TPCK's apprehension and understanding may rest on the way the didactic practice is related to a fundamental knowledge practice that one may find in culture. For example, when a teacher teaches writing, she may refer this teaching to a school practice (for example, a classic school composition in which a student relates her holiday), or to different cultural practices, for instance that of a journalist, an essayist, or a novelist. In this case, one of the main criteria of the quality of the didactic practice lies in the kind of 'authenticity' of this practice, not in the way the didactic practice tends to imitate the cultural practice (school practice and cultural practice are different), but in the way the didactic practice is nurtured by the teacher's knowledge of the main features of the cultural practice it refers to. I argue that, in order to ensure a specific kind of relevance and authenticity to the teaching-learning practice, the teacher has to become a connoisseur of the cultural practice or reference, firstly by inquiring into the way it unfolds in real practice (for example, a journalist or novelist's practice), and secondly by becoming acquainted with a model of this practice, that I term an epistemic game. In this respect, an epistemic game can be seen as an effort to accomplish the didactic transposition (Chevallard, 2007) in a manner that embeds the 'substantive marrow' of the cultural practice in the designed didactic practice.

In the reading example we studied in this chapter, one could say that it is not so simple to recognise to what cultural practice the teacher's action can be related. At a first level, however, it is possible to acknowledge that this episode may be understood as a sample of a large process of entering into reading and writing practices, which shape Western culture as such (Goody, 1977). At a second level, the analysis of this episode shows how the teacher's strategies enable the students to inquire into the nature of words by comparing them in a table (a table is a core feature of the writing culture, says Goody), in a specific topogenesis stance which enables the students to both encounter the 'table pattern' and inquire into what it displays.

I thus contend that the teacher's work in this episode is nurtured by the cultural practice at two levels, even though the class session is carried out at the beginning of primary school for 'elementary' knowledge. The didactic practice is nurtured at an epistemic level in which the deciphering process is grounded in the taking into account of a comparison that the table organises. It is nurtured at an epistemological level that one may acknowledge in the way the deciphering practice is performed through an inquiry process that one may see as students' familiarisation with a first kind of 'hermeneutics'.

TPCK 'in Action'

I argue that TPCK 'in action' is necessarily grounded on the knowledge-related generic system I tried to display above. This system may help model the teacher's intentional stance, that one may see through a threefold structure (Sensevy, 2011, 2012, 2014), which encompasses distal intentions (the general intentional structure for teaching a piece of knowledge), proximal intentions (the specific intentional structure related to a given set of situations in which this piece of knowledge is taught), intentions in action (the intentional structure as it is directly shaped by taking the situation feedback into account, the (more or less) contingent features of a situation related to this piece of knowledge). It is worth noticing that TPCK has to be described not only on the basis of distal and proximal intentions, but in the way the 'here and now' of practice orients the teacher's strategic action. For example, in the reading example I studied above, it is important to acknowledge that the teacher and students' joint action needs to be understood on the basis of a contingent fact (Hugo's proposal of "*cadeau*" (gift) in place of "*ville*" (city)) that one can see as a point of departure of the whole strategic system I described above. While managing Hugo's proposal, the teacher concretises an action that I have modelled through the theoretical framework that I describe in this chapter (notably the teacher's game on the students' game, the entanglement of the two dialectics contract-milieu and reticence-expression, the genesis triplet) but one has to keep in mind that this thick description (Ryle, 2009) rests on the initial fact that the teacher was able to monitor the behaviours of Hugo and the class within a certain kind of structured improvisation. This emphasises the way teachers' dispositions may be seen as theoretical categories in a practical state (Bourdieu, 1990a), as practical behaviours that express the logic of practice. In trying to acknowledge TPCK, the researcher has to both identify this logic of practice and produce a system of categories that may enable her to describe the feel for the game (Bourdieu, 1990a) that enables the teacher to relate her general (distal) and specific (proximal) intentions to her intentions in action in a concrete, coherent and effective whole.

OPENING UP THE DISCUSSION: A REPRESENTATION OF THE TPCK RELATING TO A GIVEN PIECE OF KNOWLEDGE

Figure 1 may be commented on as follows.

a) Arrow (0) refers to the way the problem related to a given piece of knowledge can be reflected through a connoisseur's practice, in the culture, and thus to the teacher's knowledge of this practice, that one may model as an epistemic game. In a way, this could be described by a question: "To what extent is the teacher a connoisseur's practice connoisseur?". For example, if he teaches literature, mathematics, dance, then to what extent is the teacher a connoisseur of the writer's practice, mathematician's practice, and dancer's practice. I would like to emphasise that the kind of knowledge I am referring to is the knowledge of a knowledge practice, not only of the content displayed in textbooks. That particularly means that the teacher has to be a connoisseur not only of the "knowing that" (Ryle, 2009) related to the piece of knowledge at stake, but also of the "knowing how" (Ryle, 2009) that fosters practical mastering. In particular, he has to be familiar with the epistemological system that characterises the knowledge practice of reference of his teaching. I thereby argue that the didactic transposition process (Chevallard, 2007) has to be thought of as the modelling of a given knowledge practice. I term this model an *epistemic game* in that this is an actional model ('game') which refers to knowledge ('epistemic'), and which is focused on some distinctive essential features

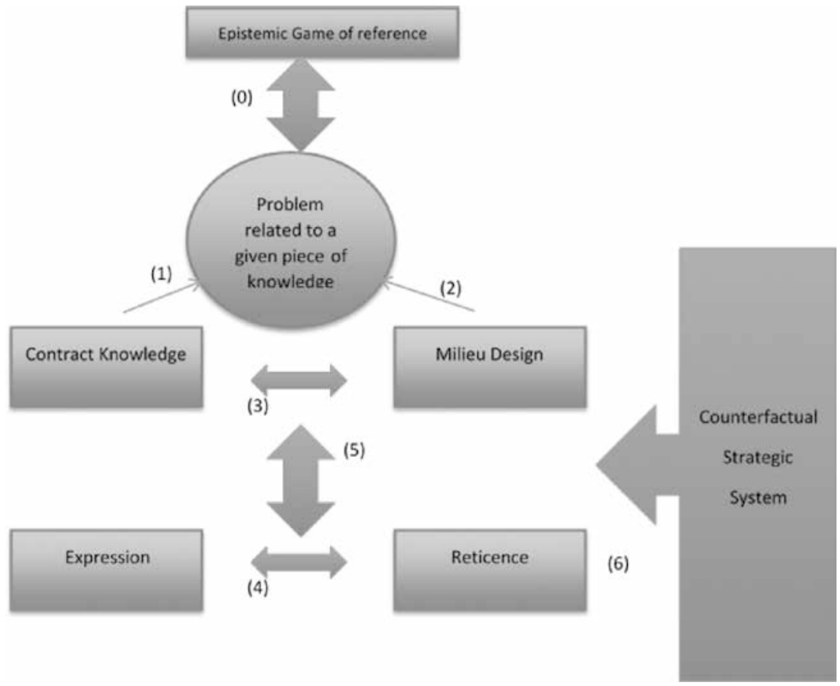

Figure 1. A representation of the TPCK relating to a given piece of knowledge

of the knowledge practice as practical connoisseurs of this practice demonstrate them. It is these features that the authors of the model want to focus on in order to nurture the didactic practice.

b) Arrow (1) is related to the teacher's awareness of the students' current system of knowledge, the 'already-there' knowledge with which the students are going to cope with the problem. It is important to note that this system, as shaping the didactic contract, can be seen not only as a system of habits or expectations, but as a system of capacities, a strategic system. Arrow (1) therefore indicates the teacher's oriented practical knowledge of the students' strategic system. It refers to a kind of the teacher's knowledge that one may describe as follows: 'relating to the problem concerning this piece of knowledge, I anticipate that some students may be able to say S and to do D; in case they say S, I can act in this way…, in case they do D, I can act in this way…'. It is one of the main loci where counterfactual strategies may be thought of.

c) Arrow (2) characterises the designing process in which the teacher commits herself to the design of a milieu that gives a specific symbolic structure to the problem to be dealt with. Of course, this designing process has to take into account the students' already-there knowledge (the contract), however this process unfolds before the class, or during it. It is a crucial part of the dialectics of contract and milieu that the teacher has to manage, and one of the fundamental features of the teacher's craft.

Arrow (3) symbolises the dialectics of contract and milieu that I delineated above. While teaching, the teacher has to rely on previous knowledge that she attributes to the students (contract), or to orient the students' activity to the symbolic structure of the problem (milieu).

e) Arrow (4) represents the dialectics of expression and reticence that I described above. While teaching the teacher speaks and/or moves, and while speaking and/or moving she expresses some meanings while being reticent on some another ones.

f) Arrow (5) designates what I term in this chapter the entanglement of the two dialectics previously described. One could describe a threefold equilibrium. The first one denotes the contract-milieu dialectics, when the equilibrium is built in teacher's practice between relying on the students' already-there knowledge, and orienting them in the symbolic structure of the milieu. The second equilibrium that the teacher enacts is a specific equilibrium between reticence (which meanings are concealed by the reticence process) and expression (which meanings are revealed by the expression process). The third equilibrium entangles the two first, which can be expressed as follows: the teacher's reticence can be focused on the contract or it can be focused on the milieu; the teacher's expression can be focused on the contract or it can be focused on the milieu.

g) Arrow (6) refers to the amount of variation the teacher is able to envision when confronting a teaching-learning issue.

NOTES

1. Dewey defined inquiry as "the controlled or directed transformation of an indeterminate situation into one that is so determinate in its constituent distinctions and relations as to convert the elements of the original situation into a unified whole" (Dewey, 1938/2008, pp. 104–105).
2. The notion of counterfactual has been developed in different fields of research, in particular in philosophy of science by David Lewis (1973). Given the limited scope of this chapter, I will not elaborate on the roots of this notion, which I use in a specific didactic way.
3. In the following, I provide a first analysis of the example within the transcript. Then I will reconsider some of these elements. «T» = teacher; «STs» means that several students are talking together.
4. The idea of 'trilogue' was proposed in didactics by M-L Schubauer-Leoni (1997). It refers to the fact that didactic communication often reunites three sources of utterances: the teacher, the whole class, and the particular student who is conversing with the teacher.
5. One may see as one of the didactic avatars of what Quine (1960) calls the *indeterminacy of reference*.
6. It is worth noting that the teacher was acting within a research team, and since then has completed a PhD in educational research (Vigot, 2014) within cooperative engineering (Sensevy et al., 2013).
7. The reader may jump directly to the synoptic table included below in this section in order to embrace in a single glance the whole set of counterfactual strategic systems and the actual strategic system.

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Gérard Sensevy
Ecole Supérieure du Professorat et de l'Éducation
CREAD EA 3875
Université Européenne de Bretagne, France

SECTION 2

BALANCING GENERAL AND SPECIFIC PEDAGOGICAL KNOWLEDGE: ROLE OF COLLABORATIVE SETTINGS

ISABELLE KERMEN

6. STUDYING THE ACTIVITY OF TWO FRENCH CHEMISTRY TEACHERS TO INFER THEIR PEDAGOGICAL CONTENT KNOWLEDGE AND THEIR PEDAGOGICAL KNOWLEDGE

Documenting teacher professional knowledge is the subject of numerous studies because teacher professional knowledge is assumed to have an effect on teaching (Crahay, Wanlin, Issaieva, & Laduron, 2011; Magnusson, Krajcik, & Borko, 1999). The analysis of teachers' discourse about their practice gives insights into their knowledge (Fernández-Balboa & Stiehl, 1995; Padilla & Van Driel, 2011) but sometimes does not always match their actions in the classroom (Farré & Lorenzo, 2009; Simmons et al., 1999). Some researchers infer teacher professional knowledge from analysis of their actions (Alonzo, Kobarg, & Seidel, 2012; Cross, 2010). Others use mixed methods combining analyses of teachers' statements or reflections and of classroom observations (e.g., Friedrichsen & Dana, 2005; Loughran, Milroy, Berry, Gunstone, & Mulhall, 2001; Park & Oliver, 2008). This study addresses the activity of two teachers working on the same subject, the spontaneous evolution of chemical systems in 12th grade, and aims to infer part of their professional knowledge from an analysis of their actions and statements.

FRAMEWORK

The analysis of classroom activity follows the methodological framework of the double didactic and ergonomic approach (Robert & Rogalski, 2002; Vandebrouck, 2013), and teachers' professional knowledge according to Shulman's typology (Shulman, 1987).

The Double Didactic and Ergonomic Approach

The double didactic and ergonomic approach falls within the activity theory. A subject's activity is constituted by what the subject does to achieve a task in context (Rogalski, 2003, 2013). The real activity is not accessible because it includes everything that the subject thinks, says or does not, does or does not (Robert, 2008). Only indications of the subject's activity, "operations on the objects of action", are observable (Rogalski, 2013). This unifying point of view enables us to consider both the teacher's and the students' activity in the classroom (Robert & Vivier, 2013).

M. Grangeat (Ed.), Understanding Science Teachers' Professional Knowledge Growth, 89–115.

The teacher's activity in the classroom denotes part of the teacher's practices which include everything a teacher does in and out of the classroom over a long period of time. It constitutes what he/she implements to achieve his/her tasks: promoting the students' learning of a given topic in a given teaching session and designing the learning environment for this.

Examining what can be perceived of students' potential activities in the classroom enables a reconstruction of the cognitive pathway the teacher proposes to the students, the working modes and the students' scaffolding implemented (Robert & Rogalski, 2002). This kind of analysis, a didactic one, was insufficient to understand what was at stake in mathematics teachers' choices (Robert & Rogalski, 2002). To explain and describe the regularity and variability of practices between teachers, it was necessary to deal with factors that are not part of the classroom context like the syllabus instructions, the teacher's personal beliefs, his/her colleagues and professional habits (Robert & Rogalski, 2002). These factors also impact the teaching session and are thus considered determinants of the teacher's practices. This point of view corresponds to an analysis of the teacher's work that takes the constraints he/she faces and the specificity of the learning session into account. Combining a didactic point of view (the cognitive aspect and the mediative aspect of the practices) with an ergonomic approach (categorising the determinants of the practices as institutional, social and personal) leads to analysing the teacher's activity according to five dimensions.

The five dimensions structuring the analysis of the activity are the following:

- the cognitive dimension concerns the design of the tasks given to the students, the lesson plan and the chemical content involved;
- the mediative dimension concerns implementation of the lesson plan, paying particular attention to the choices of classroom organisation and of students' scaffolding;
- the institutional dimension examines how the teacher takes the syllabus and the resources into account;
- the social dimension deals with the relationships between the teacher and students, people working in the school, parents and the way the teacher takes account of the students' social background; and
- the personal dimension revolves around the teacher's knowledge, conceptions of chemistry, chemistry teaching and the impact of his/her personal experience on his/her beliefs.

The constraints that determine the activity are gathered in the last three dimensions that therefore influence the two others. Splitting the activity analysis into five dimensions aims to reduce the activity's complexity, but allows approaching the coherent system that a teacher's practices constitute from different points of view (Robert & Rogalski, 2002). Combining these five dimensions then enables a teacher's acting principles to be addressed. Robert and Rogalski (2002) state that the regularities of teaching practices are the translation of a teacher's determining choices.

Attaining these dimensions is made possible by analysing the tasks proposed to the students and the lesson plan on one hand, and implementation of the lesson plan on the other. The latter analysis pinpoints the work organisation in the classroom, the relationships between the teacher and the students, the kind of help and the feedback the teacher gives the students. Interviews with the teachers are needed to complete the previous analyses.

Teachers' Knowledge

Teachers' professional knowledge is "action-oriented, person-bound and tacit" (van Driel, Beijaard, & Verloop, 2001). During the course of action, tacit knowledge is mobilised (Rix-Lièvre & Lièvre, 2012; Schön, 1996). Thus, choosing to approach teachers' professional knowledge from the analysis of action implies that most of the inferences made in this study will concern knowledge which is neither articulated nor mentally expressed.

To describe the teacher's knowledge, two models are used: Morine-Dershimer and Kent's model for pedagogical knowledge (PK) (Morine-Dershimer & Kent, 1999), and Magnusson, Krajcik and Borko's model for pedagogical content knowledge (PCK) (Magnusson et al., 1999). Among PK three facets (or components) are considered: instructional models and strategies (PK-strategy), classroom management and organisation (PK-management), and classroom discourse and communication (PK-discourse) that should be mastered by beginning teachers to attain higher professional development stages (Corrigan, 2009). The PCK model (Magnusson et al., 1999) includes five components. The first one, orientation to science teaching, shapes the others, knowledge of curriculum (PCK-programme), knowledge of assessment (PCK-assessment), knowledge of students' understanding of the chemistry topic under consideration (PCK-student), knowledge of instructional strategies (PCK-strategy), that enable the students to understand the topic at hand or overcome their difficulties. Content knowledge (CK, here knowledge of the topic "evolution of chemical systems") constitutes a separate domain of knowledge apart from PK and PCK but influences the PCK domain.

According to a literature review, PCK-strategy and PCK-student on one hand (van Driel, Verloop, & de Vos, 1998) and PK-strategy and PK-management on the other hand (König, Blömeke, Paine, Schmidt, & Hsieh, 2011) are the core components of PCK and PK, respectively.

Clearly differentiating PK-strategy and PCK-strategy is crucial to categorising knowledge. PK-strategy concerns the design of tasks, their structure and diversity without taking the content into account, and the teacher's goals. If these goals and tasks can be expressed in the same manner for another chemistry or physics course, then they will be ascribed to PK-strategy. PCK-strategy denotes a strategy devoted to overcome a topic-specific learning difficulty. PK-management includes time management (time left for thinking, for achieving tasks), the distribution of tasks among students, establishing routines.

The Link between the Double Approach and Teacher Professional Knowledge

The teacher's activity in the classroom results from decisions taken during both the planning and implementation (Wanlin & Crahay, 2012). These decisions depend on the teacher's knowledge, the constraints he/she faces and on the results of his/her actions. Focusing on the knowledge supporting the decision-making enables one to specify what type of knowledge is involved. The tasks and lesson plan design (cognitive dimension) entails choosing a global pedagogical strategy (PK-strategy) and relies on chemistry content knowledge (CK), curriculum knowledge (PCK-programme), knowledge of the students' understanding of the topic (PCK-student) and knowledge of specific methods suiting the cognitive goals to be achieved (PCK-strategy). The enactment of the course project (mediative dimension) includes the classroom organisation and the students' scaffolding which rely on knowledge of instructional strategies (PK-strategy) and of topic-specific strategies (PCK-strategy), of the students' understanding (PCK-student), of how to communicate with the students (PK-discourse) and of classroom and time management (PK-management).

Giving a broader sense to PCK "defined as a personal attribute of a teacher and … considered both a knowledge base and an action" (Gess-Newsome, 2013), Gess-Newsome legitimises the point of view adopted in this research, namely that PCK is intimately bound to a teacher's actions and can be inferred from their analyses.

CONTEXT OF THE STUDY AND RESEARCH QUESTIONS

Teacher Training Session

A three-day teacher training session was organised to develop the teachers' professional knowledge on the topic "teaching the evolution of chemical systems" during the 2010–11 academic year. The goals of the session were to enhance the CK and PCK of the trainees, support the appropriateness of and enactment of new knowledge and encourage reflection and discussion in order to reveal their teaching habits and to eventually slightly modify them. The first day was devoted to a presentation of an epistemological analysis of the syllabus of 12th grade, highlighting the three models that could be used in the syllabus and of the students' reasoning and difficulties (Kermen & Méheut, 2011). It was hypothesised that this reflection in terms of three different models was new to the teachers and that some of the students' difficulties or reasoning were unknown. The 12th grade teachers were asked to design a lesson plan about the introduction of the spontaneous change criterion and to set it out during the second day of the training session two months later. They were also told that they would have to implement the lesson plan in their classroom thereafter and that the implementation would be video recorded and discussed on the third day of the training session. On the second day, two 12th grade teachers, an experienced woman and a beginning man, set out their lesson plan and their objectives. On the last day (three months later), some extracts of each videoed teaching session were shown and both volunteers explained their specific choices and goals.

The session was preferably intended for teachers working in 12th grade, but most of the trainees were not doing so. Given the low number of 12th grade teachers involved and their different teaching experience, it appeared interesting to determine whether this difference could be noticed in their activity in the classroom, and if so how.

Chemical Content Involved

The students had hitherto only dealt with systems that comprised reactants (chemical species about to react) in the initial state and no products (species about to be formed). They had been introduced to incomplete chemical changes, which means reactants and products are present in the final state. These changes are modelled by a pair of opposing chemical reactions being symbolised by a chemical equation to which are associated the equilibrium constant K and another quantity, the reaction quotient Qr, a function of the concentrations of the solutes appearing in the chemical equation. At that point, the students knew that, when the change is over, the reaction quotient is equal to the equilibrium constant, but was different in the initial state. They also encountered chemical changes occurring in the forward direction of the chemical equation or in the reverse one. The goal of the new lesson was to establish a law: depending on the initial reaction quotient value Q_{ri}, a system will proceed in the forward direction ($Q_{ri}<K$) or in the reverse one ($Q_{ri}>K$) to reach an equilibrium state ($Q_r=K$). To induce this law, the so-called change criterion, the syllabus authors suggested studying systems initially comprising all the chemical species involved in the chemical equation. Relying on the chemical equation thus does not enable a prediction of what will happen, and a new reasoning based on the acquired knowledge is to be built.

Research Questions

Analysing teachers' activity within the framework of the double didactic and ergonomic approach intends to shed light upon the choices they make before and during the teaching session. As outlined above, these choices rely upon the various constraints they face, the local features of the teaching session (in particular, how the students behave in response to the prescribed tasks) and upon the teachers' knowledge. In this paper, the focus is on the knowledge (PK and PCK) underlying some of these choices and which can be inferred from the analysis of actions.

Examining the choices the teachers made, which components among CK, PK and PCK can be identified?

How can any difference between both teachers be specified in terms of actions and, finally, PK, PCK and CK?

METHODOLOGY

Collecting the Data

Two teachers were observed. Both were volunteers. Let us call the experienced teacher Dora (33 years old, 10 years' teaching experience and 4 years' in grade 12) and the beginning teacher Bud (26 years old, 2 years' teaching experience and none in grade 12). Both have the same qualification, a degree in physics and chemistry – a compulsory requirement to become a qualified teacher in France – and both had passed the required competitive examination. They were working in a high school in a middle-sized town in northern France. Bud is a supply teacher (like many of the new physics and chemistry teachers) and started to work in that position in mid-October. The teaching sessions took place in March.

Three types of data were collected. The first set includes some discussions between the trainees during the teacher training session. The trainees' reactions to the presentation of the lesson plan (second day) were audio recorded. In the following, for the sake of simplicity, the second day of the training session is called 'day 2'.

The second set is composed of the video-recorded sessions in the classrooms and the third one of the interviews taking place with the teachers. The teachers were briefly interviewed before and after their teaching session and told to comment on their classroom video some weeks later. All interviews were audio recorded. The third interview, a self-confrontation, is a kind of stimulated recall because each teacher watching his/her classroom video was told to comment ad lib on his/her actions and the students' behaviours. The researcher did not ask questions before the teacher addressed the topic being discussed or the extract being watched. Indeed, the teacher was considered a professional commenting on his/her work and not being judged or told what he/she should have done. Therefore, the researcher paid attention to the wording of the questions in order not to place the teacher in such a position. This had its own limitations: some topics or actions might not have been commented on by a teacher although the researcher would have liked to hear some explanation of such a choice or action. This is a methodological aspect that may change in the future.

The teaching sessions and the interviews were transcribed. The teachers' gestures and movements were also written down in case they could inform what was at stake.

Analysing the Data

The lesson plans were analysed in terms of the proposed chemical content, tasks given to the students and predictable classroom management. This analysis was carried out slightly differently for each teacher. Both teachers set out their lesson plan on the second day of the training session and, moreover, Bud gave all of the participants the labwork sheet he would give out to the students, with answers to the questions he intended to ask. The analysis of Bud's lesson plan relies on this labwork sheet and on the talk he gave during the training session. Dora did not prepare a labwork sheet. Thus, her course project is reconstructed by the researcher after watching the classroom video, looking for the nature and succession of the tasks and without noticing the students' reactions. For Dora, the analysis relies on what she said during the training session and on the reconstructed course project.

The second analysis deals with the teaching session transcriptions which were split into episodes delimited by the completion of a task. In each episode, the classroom organisation is categorised, specifying the role of the teacher and of the students in an attempt to reveal the work organisation enabling the pedagogical strategies involved to be determined. The interactions between the teacher and the students were studied to set out the verbal exchanges, the kind of help and the feedback given by the teacher.

The last analysis addresses the interviews which were read thoroughly to note the comments on the implemented strategy, the classroom management and the students' difficulties, reasoning or actions. It aimed to bring to the fore the teacher's reflective ability.

Each type of analysis reveals some components of the teacher's knowledge; the knowledge inference takes place in three complementary stages.

ANALYSIS OF THE LESSON PLANS: NATURE AND ORGANISATION OF THE TASKS

The *a priori* analysis focuses on the content of the tasks given to the students, the knowledge they need to achieve them, and the possible classroom management of the teacher.

Structure of the Lesson Plans

Bud's lesson project. When Bud set out his lesson plan on day 2, he exposed the global objective of the session, enabling the students to calculate some reaction quotients to finally deduce that a chemical system tends to reach equilibrium.

Bud prepared a labwork sheet with all the instructions needed to perform the experiments, the chemical equation involved and the questions to be answered with blank spaces to fill in. It is entitled "the spontaneous evolution of a chemical system". The sheet has two main parts. In the first part, four experiments are carried out in test tubes and are set out in the same way: mention of a chemical equation, detailed instructions to achieve the experiment, observation and interpretation. The second part is composed of an experiment with pH measurements and a list of detailed questions involving calculations, whereas in the first part there was none.

Just before the teaching session, Bud was questioned about his objectives. He stated that he wanted:

> to prompt [the students] to be attentive by showing them visual experiments … which simply show that ... a change is possible in the forward or in the reverse direction.

He then added that the second part of the lesson would be more "quantitative" and shares a similar goal regarding the direction of change by means of pH measurements, this time before "addressing the calculations".

Bud expressed his conception of the teaching of chemistry in the lab. Experiments should include visible clues of chemical change. Is this belief due to the fact that he had only taught classes in lower secondary school so far? Regarding the pH experiments, he clearly distinguished two stages, achieving the experiment should be done before "the calculations".

It would be too long to describe each experiment and which skills and knowledge the students are expected to mobilise. Thus, only a brief overview[1] to see what is at stake in the following sections is proposed here.

In the first part, section 1 deals with two experiments involving solutions of cobalt ions of different colours. In the first experiment, the colour change can be associated with a chemical change occurring in the reverse direction of the written chemical equation, which is quite unusual. Has Bud a special intention? Does he want to stress that possibility?

In the second experiment, the expected interpretation is limited to identification of the (forward) direction of the chemical change regarding the chemical equation.

Section 2 of this first part is devoted to some experiments involving the formation of a precipitate of benzoic acid as a visual indicator and is divided into two sub-sections. In the first one, the interpretation should be a forward direction of change and a reverse one in the second sub-section.

The second part of the labwork sheet begins with the chemical equation and its equilibrium constant. Two different mixtures have to be made. Both include the same four solutions, an ethanoic acid solution, a sodium ethanoate solution, a methanoic acid solution and a sodium methanoate solution, with all having the same concentration. The first mixture is made with equal volumes (10 mL) of each solution whereas the second one is realised with different volumes. The students are asked to measure the pH of each mixture and to do this they first have to calibrate the pHmeter, which is not mentioned on the paper. Finally, they have to answer a list of eleven detailed questions, nine of which are to be solved twice (for both mixtures) and most of which are calculations. Except in the second question where the students are not told to express the initial concentrations of the solutes to calculate the initial value of the reaction quotient, they have to mobilise knowledge and concepts that are mentioned in the questions, all the reasoning is set out, and it is a succession of simple tasks. It looks like an exercise where each answer leads to the following one.

Dora's lesson plan. On day 2 when Dora set out her lesson plan, she said she had conceived for the first time a lesson where the evolution criterion had to be induced from experimental situations and not applied to them. She added that the students had the conceptual tools (reaction quotient, equilibrium state) to understand such an approach. Just before the teaching session, when expressing her objectives Dora said she would prompt the students to put forward hypotheses about the direction of change, if any, of the acid-base mixtures without giving them any clue at the outset. Her main objective seemed to make the students reflect and wonder about the different factors that may affect an experimental situation.

First, she presented the solutions (two acids and two bases) that compose both mixtures the students would have to realise. These mixtures are exactly the same as those in Bud's lesson. The students are asked to write a chemical equation that can represent what could happen in the mixtures. They have to decide what acid and what base to write on the left of the chemical equation. Expressing the initial concentrations of chemical species in the mixture constitutes the next task and is more usual than the previous one: nevertheless, the students should not forget the dilution, which is a common mistake. In the following task, they have to realise the mixtures. The next step begins with a question: what is relevant to foresee the direction of a prospective chemical change in each mixture? It is still uncertain whether and in what mixture a change may occur. The students ought to think and propose reasons. Then they are asked to establish the literal expression of the ratio of the concentrations of the ethanoate ion and the ethanoic acid in the initial state of each system. Before realising the pH measurement, the students have to think about the usefulness of that measure, what it is possible to do with the pH value. In the last step, the students seek how to link the pH value and the ratio of the concentrations in the final state to obtain this ratio value and, finally, to compare to the ratio in the initial state.

Comparison of the Two Lesson Projects

Both teachers were pursuing the same final goal – inducing the evolution criterion from the study of acid-base mixtures. The acid-base experiments common to both lessons and their interpretations come from the accompanying booklet made by the syllabus authors. Bud slightly adapted it adding some detailed questions, whereas Dora imagined new tasks for the students: seeking the chemical equation, predicting a chemical change and looking for reasons of such a change, if any, and reflecting on the role of the measurement.

To introduce the topic, Bud proposes qualitative experiments which draw attention to the possible change in the forward or reverse direction of the chemical equation; moreover, he always provides the chemical equation involved in the experiments before their description whereas Dora's students have to find it. Knowing that a change can proceed in the forward or reverse direction of the chemical equation is not new to the students. Twice achieving this kind of experiment does not help the students grasp the central idea of that lesson, namely, how to determine the direction of change if all the species about to react are initially present? Bud seems to have misunderstood the issue of that specific lesson.

Obviously, both teachers did not make the same choices for their lesson plans, and these choices are now analysed to infer some of their pedagogical knowledge and beliefs.

Pedagogical strategies. No prediction is asked in Bud's labwork sheet, although it is possible. Bud's pedagogical strategy is classical and inductive: performing the experiment leads to observation and the interpretation or the answer to the questions then follows. The students are only performers of the different tasks in the sense they do not have to imagine what to do, almost everything is written down. On day 2, he simply described the succession of the tasks he intended to set for the students without mentioning the cognitive goals, and said he would gain time because the last part constituted an exercise which was closely related to certain examination topics. This is indicative of his lack of perspective as he did not have a clear vision of the sequence of the different concepts and of their relative importance (lacking in PCK-programme). The preparation for the examination is a more powerful factor of choice than the learning of concepts. The institutional dimension of his activity prevails over the cognitive one.

Dora's pedagogical strategy is more student-centred than Bud's. On day 2, Dora set out her session exposing all the questions she wanted the students to ask, stressing the knowledge they would have to mobilise in the reasoning she intended to conduct. Just before the session, she stated the students would not conduct many experiments but would have "to mobilise the knowledge they just acquired this year ... to put forward hypotheses, to discuss the way the system is about to change". So she intended to prompt them to reflect before conducting an experiment. Dora's students are engaged in a hypothetical-deductive approach.

Both strategies are different and thus not underpinned by the same tacit pedagogical knowledge. Nevertheless, the syllabus instructions recommend adopting pedagogical strategies that involve the students and enable them to ask questions, propose solutions, and debate. Bud read the programme and obviously chose to teach the prescribed content but not according to a student-centred strategy.

Possible classroom management. Just before the session, Bud stated that he had prepared the labwork sheet to allow the students to work in an autonomous way regarding the practical instructions and that he would "have an interaction with them" once the experiment is over. For the second part of the session, he said "the students should manage with their measurements" to answer the questions but immediately added that he was teaching this lesson for the first time and that they would "resolve the questions together even if this is not pedagogical". On day 2, after listening to Dora's lesson plan, Bud declared "my session will be more directive than yours". Bud intended to manage the classroom in a classical way: the students are to follow the instructions to perform the experiments all by themselves, and Bud would guide them to answer the questions, probably by asking a student to answer. He said another type of management in accordance with the institutional instructions is possible but he might not feel confident enough to do it. There is a tension between what he feels able to do and what he should do, that is between the personal and the institutional dimensions of his activity.

On day 2, Dora expressed her doubts because she wondered whether the students could write a chemical equation (two are possible). She was aware it could be ambitious to base the beginning of her session on an uncertainty, but she said "we'll see". She declared that the presence of a pH meter constitutes a clue for the students to imagine a solution to the problem. Dora's classroom management relies on the students' propositions and it is unclear how she would take the different propositions into account, but implicitly it does not seem to be a matter of concern.

Anticipating the Students' Lines of Reasoning and Difficulties

One of the core components of PCK is knowledge of the students' understanding of a given topic, of the kind of reasoning they may engage in regarding the different concepts that compose that topic, and of the difficulties they encounter when learning this topic. And this kind of knowledge influences the design of the lesson plan which is a result of the cognitive dimension of the teacher's activity. This explains why during the interview preceding the teaching session both teachers were asked what kind of students' reasoning and difficulties they were expecting.

Bud thought the students would have forgotten what they knew about the reaction quotient because they have been studying electricity for six weeks. For him, this is a reason not to let them work autonomously to resolve the questions of the fifth experiment. But he did not evoke any of the reasoning the students might have.

First, Dora said she expects the students would refer to the value of the constant of the acid-base couple (K_a) to predict what could happen in the mixture and later they would use the available tools such as the relationship between pH and pK_a. Then she described two errors she thought the students might make. First of all, she expected they would make a wrong prediction, the mixture made with equal volumes of acid and base solutions would not undergo any change. She then declared that the students often confuse the equivalent point (the end point of a titration) and the equilibrium state of a system and that this confusion might lead them to look for a limiting reagent whereas there is none in the equilibrium state. Finally, she emphasised they should realise that the measured pH is that of the final state of the system when the chemical change is over and they have to mobilise their knowledge in a new situation.

Dora was aware of the different concepts and type of knowledge the students would have to utilise. Moreover, she pointed to an error – no change if the same amounts (Stavridou & Solomonidou, 2000; Tyson, Treagust, & Bucat, 1999) – quoted during the training session to predict that her students might have this incorrect reasoning too. She also mentioned the widespread confusion (equivalence and equilibrium) among French students and the error it could provoke. This is sound evidence of PCK-student: quoting a difficulty and the error it may cause.

Bud could not imagine his students' difficulties and reasoning and just evoked a memory problem. The contrast between both teachers is obvious and was expected due to the nature of the PCK that mostly develops while teaching.

THE UNFOLDING TEACHING SESSION

Work Organisation

Introducing the teaching session. At the beginning of the teaching session, both teachers set out the goals of the session to their students.

Bud starts by saying they are beginning a new part in which they will use the reaction quotient. Commenting on the handout he gives out, Bud introduces his first goal: enabling the students "to see" the direction of the evolution of a chemical system while performing qualitative experiments in the first part of the session. He mentions his second goal: letting them carry out the experiments autonomously in order to prepare for the final examination. He immediately limits the scope of his talk, adding that the students should themselves note the observations but they will make the interpretations of the experiments together. Does this mean they will construct the knowledge to be learned together or that he will guide their reasoning?

Dora begins by telling her students they are going to study a new part she does not name because they have to discover it as the session progresses. She says they will have to mix a given volume of four different solutions, each containing either an acid or a base the name of which she writes down on the blackboard, and have to discuss what is going on in that mixture. Half the students will make the first mixture and the others will make the second one. She tells them "before realising a mixture and making any obscure measurements we are going to think it over" and asks them to write down a chemical equation on their paper. Dora expresses her main goal, making the students think. Indeed, this is the first task she assigns to them. Moreover, although they are in a labwork room she does not stress the practical work they will do and even more talks about "obscure measurements" as if these were not a goal of the session. Thus, measurements are presented as a tool to answer the questions that are asked.

Bud's session organisation. In the following table, to provide an overview of the way Bud organises his session, the different episodes and the different working modes are gathered. An episode corresponds to the achievement of a given task. Indeed, performing the experiment, noting the observation and interpreting it are considered as three sub-tasks of a global task, and thus correspond to a single episode, for the sake of simplicity. Different sub-tasks may correspond to different working modes: for example, students working in pairs, collective dialogue. Then an episode corresponding to a global task includes several work modes.

Bud's session is in two parts, like the lab sheet he gave out. In the first part, for each experiment described on the lab sheet, he lets the students perform the experiment, corrects their gestures, specifies some instructions and, when all the students have finished, stops the manipulation and asks them what they observed. During the collective dialogue stages, he strongly guides the interpretation, giving the students few chances to answer and then dictates a conclusion.

Although the first experiment led to an unusual conclusion so far – an evolution of the chemical system in the reverse direction of the chemical equation – he did not

Table 1. Description of Bud's unfolding session

Episode (duration)	*Working modes*	*Teacher's main actions*	*Students' main actions*
Introduction (6 min)	Teacher's talk	Sets out his goals and instructions	Listening
First experiment (15 min): colour changing from pink to blue, reverse direction	Students working in pairs, then collective dialogue	Moves between the benches, specifies instructions, strongly guides the interpretation, dictates	Perform experiments, ask questions about practical work, answer, write from dictation
Second experiment (10 min) colour changing from blue to pink, precipitate, forward direction	idem	idem	idem
Third experiment (13 min 30 s) precipitate, forward direction	idem	idem	idem
Fourth experiment (9 min 30 s) less precipitate, reverse direction	idem	idem	idem
Fifth experiment (41 min), performing mixtures and pH measurements	Students working in pairs	Moves between the benches, corrects students' gestures. At 26 min unexpected pH values. At 37 min asks students to interpret if measurements done	Perform experiments, ask questions about practical work
Responses to questions (12 min)	Collective dialogue	Writes on the blackboard, asks some students	Write, respond

stress that point. At the end of the second experiment, he did not mention that the evolution in the forward direction was the opposite of the previous conclusion. He also does not link the conclusions of the third and fourth experiments. To conclude the first part, he only says that "the test tube experiments are over" and the students may clean the equipment and then calibrate the pHmeter. He does not link what was done and what is supposed to be noticed (that a chemical system may evolve in the forward or reverse direction of the written chemical equation depending on its initial composition) with the following experiment (the fifth one).

During the fifth experiment, some students obtain much lower pH values than expected. He tells them to take another pHmeter but the pH values do not change and he does not propose to make the mixture again. Nevertheless, he could have suspected an error because two different ethanoic acid solutions were used during the session. A pH calculation shows that using the most concentrated solution instead of the less concentrated one leads to a value close to that measured. This incident reveals that Bud is restricted by time, he could have asked them to realise the mixture once again, and that he is not confident enough in his content knowledge.

At the end of the fifth experiment, a student asks Bud: "why doesn't the colour change?".

Bud answers: "because this wasn't the fun part of the practical work".

This answer is very revealing: for Bud, the experiments have to catch the students' attention to entertain them and the cognitive reflection comes next. This answer could also have been a joke if he had then added an explanation, but he did not.

The choice of visual experiments could have been motivated to prompt the students to ask questions, to let them make a prediction which could be easily checked or rejected. On day 2, after listening to his proposal Dora suggested he did so. Bud did not lead his students down this path and had no intention of doing so according to his previous declarations.

Dora's session organisation. The different episodes and working modes in Dora's session are gathered in Table 2.

Dora gives information orally and instructions step by step. Dora alternates different working modes while the students have to achieve various tasks. They have to think twice in silence to resolve a question set by Dora. During these episodes, Dora moves from bench to bench and discovers some unexpected answers. She asks the student to explain his/her line of reasoning, and their conversation takes place in hushed voices. During the collective dialogue stages, Dora makes some brief talks to recall the objective of her question or of the reasoning and the result they just obtained. When the students are working in pairs, she tries to get explanations from each pair she debriefs.

During the first student research stage, as she said later, she is very surprised by the chemical equation proposed by Chloé. Chloé wrote four species on the left of the chemical equation (the four chemicals were present in the initial state of the system) and was then wondering about the species she could write on the right. For

Table 2. Description of Dora's unfolding session

Episode (duration)	*Working modes*	*Teacher's main actions*	*Students' main actions*
Ep 1: Introduction (6 min 30 s)	Teacher's talk	Sets out the solutions and the mixtures to realise, asks for a chemical equation	Listen, take notes
Ep 2: Seeking a chemical equation (6 min 45 s):	Student's individual reflection	Moves between the benches, spends 4 min with Chloé and Lucile	Think
Ep 3: Sharing answers and problem enunciation (9 min 15 s)	Collective dialogue	Writes on the blackboard; sets out the problem, asks for the literal expression of the initial concentrations	Justine dictates the chemical equation, students listen, take notes, respond
Ep 4: initial concentrations (8 min 30 s)	Student's individual reflection	Moves between the benches, realises students cannot succeed and decides to change the task	Seek
Ep 5: Realisation of the mixture (14 min)	Students working in pairs and reflecting	Moves, helps some pairs	Perform experiments, try to write the expression of concentrations
Ep 6: Looking for reasons and predictions (25 min)	Collective dialogue	Writes on the blackboard, asks for predictions, tries to elicit their arguments	Listen, write, respond
Ep 7: pH measurement and calculations (28 min)	Students working in pairs and reflecting	Moves, helps some pairs, to all, focus on logarithm function, focus on the goal of the measurement	Perform measurement, write, seek

the second student research stage (episode 4), Dora realises that the students cannot write the literal expression of the solutes concentrations in the mixture they are about to make. She decides to stop this task and asks the students to make the mixture, hoping it will help them later express the solutes concentrations. This is clearly a decision she took after seeing that the students were not succeeding.

In the following collective dialogue stage, she asks them whether and how the composition of the mixtures would change. She prompts them to put forward hypotheses to support their predictions, she excludes Lucile's proposition which relied on the chemical equation and interacts with her to explain why, and requires a justification for the second proposition which is about the volumes of the different solutions, as she anticipated before the teaching session. Then she claims that pH measurements are needed to come to a decision.

Dora's pedagogical strategy was fruitful because the students dared to express their ideas, some inadequate (or unexpected) ideas arose and one of them supported a prediction so that the teaching session could continue.

Comparison of the two performed teaching sessions. Both sessions have some common features: the teachers did not come to the end of their project; they addressed the same topic of acid-base mixtures; the students worked in pairs, the teacher moved between the benches, collecting information on the achievement of the task and making some adjustments, giving precise instruction or help.

Both teachers alternated between different stages: teacher speaking without questioning the students, collective dialogue stages when they questioned different students, students working in pair stages.

The difference lies in the work organisation, the place given to the students' reasoning and the practical tasks. Dora dedicates moments in the session to the students' autonomous reflection, lets the students express their ideas and tests their plausibility during the collective dialogue stage, and sums up the questions and the statements periodically to specify the objectives they are trying to achieve together. Bud does not. Bud's students spent 1 hour on practical tasks versus 20 minutes for Dora's students (both sessions lasted 1 h 40 min). Although Dora lets her students take notes, Bud dictates everything that he wants them to write down.

Bud does not pay the same attention to the calculation of solutes concentrations as Dora. She spent time (4th episode, 22 minutes) to be sure that nearly all the students achieved the calculation. In the last episode (2 minutes), Bud questions a student who gives a wrong answer, corrects him by telling how to write the expression, writes it on the blackboard, and finally asks the other students the result of the calculation. The roles ascribed to the students are different: often performers of detailed tasks in Bud's session, they just have to give an answer, whereas in Dora's they are also prompted to suggest solutions or ideas that are not in writing.

Both teachers share some PK-management, but not all of their PK-strategy as the *a priori* analysis foresaw.

Interactions between the Students and the Teacher: Scaffolding the Students

There are several ways to support the students' activity. The focus will be on three aspects: help to achieve the manipulations, help to provide answers, and landmarks to follow realisation of the tasks.

Practical aids. During the students-working-in-pairs stages, Bud gives new instructions to all the students when some instructions are lacking or not precise enough in the lab sheet, he repeatedly corrects the students' practical gestures when they are manipulating. At about this point during the self-confrontation, he wonders why the students always ask "why", for example asking why the beaker has to be tilted 45 degrees when dispensing a liquid inside with a volumetric pipette. He says that he answers "because of the user manual" and seems quite disconcerted by the frequency of these questions. Explaining why to the students could allow them to better understand the reason for the gesture and how to better achieve it. He notices the students' difficulty but does not provide a means to overcome it (lacking in PCK-strategy).

During Dora's session, the students only have two occasions to manipulate; first, they prepare a mixture and then measure its pH. She does not correct their gestures as they transfer volumes of liquids with pipettes but repeats twice that they have to rinse the pH probe.

Aid to providing answers. To help his students answer questions Bud asks numerous simple questions. He splits the original task into several micro-tasks (PK-strategy). The students generally answer briefly. During the self-confrontation, Bud said that the students understood because they answered the questions he had asked. Nevertheless, they did not create the line of reasoning. At the end of the 4th episode, Bud wants the students to link a visible cue (the observation of a white precipitate formation) with a chemical change in the forward direction of the chemical equation. He has used this kind of reasoning twice before with them. But when he asks them to look at the chemical equation to conclude, the students fail to provide a relevant answer. Then Bud again splits the reasoning into smaller pieces and obtains answers to his successive questions. This incident reveals that, although Bud showed the students how to interpret the previous experiments, in a new situation they cannot. Without help, they are unable to link the tiny tasks Bud proposed. The collective dialogue thus looks like a teacher's talk with some holes that the students fill in (Kermen & Barroso, 2013; Venturini, Calmettes, Amade-Escot, & Terrisse, 2007).

Dora also asks her students numerous questions. But, unlike Bud, she mostly gives them time to answer. Dora tries to help her students express their idea and not just answer to the questions she asked. For instance, when she asks them in episode 6 to put forward a hypothesis to justify whether the composition of mixture 1 or of mixture 2 should change or not, Lucile suggests that it depends on "the volume put in the solution", Dora reformulates by saying it depends on the initial state and asks why. Lucile answers "the volumes are not the same" and Dora carries on specifying her response and asking a new question "the initial amounts of the species are different so what are you going to predict?". Lucile suggests a direction of change, and Dora keeps questioning her until she gives the reasons for her choice, the amount of one species is lower than the other (PCK-strategy). Dora holds detailed discussions, taking each argument into account (PK-strategy).

Landmarks. Bud's session is strongly structured, he ends the interpretation of each experiment with a conclusion he dictates. During the self-confrontation, he says he periodically concluded for the students' progress at the same rhythm but recognises he dictated too much. However, he did not link the different conclusions whereas he could have helped the students better understand the final goal of the session and how to reach it. So the experiments appear disconnected and their goals are not obvious.

Dora frequently sums up what they are seeking and why, what they know and what the problem is. She also formulates these ideas and questions in several and successive ways. Thus, she talks a lot and her students ought to be attentive. During the self-confrontation, she noticed that and justified it by saying she wants them to understand the objective before achieving the task.

To summarise, it appears that Bud tends to foster the acquisition of practical skills and the production of answers without trying to elicit the students' thinking and reasoning, whereas Dora tries to promote the acquisition of knowledge and the expression of students' ideas but pays little attention to the students' practical skills.

COMMENTING ON THE UNFOLDING TEACHING SESSIONS AND THE CLASSROOM VIDEOS

In this section, the comments made by the teachers on their pedagogical strategy, classroom management and the students' understanding are reported and linked to the domains of teachers' professional knowledge if possible and to the dimensions of their activity.

Bud's Comments

Watching his classroom video does not enable Bud to acknowledge that his students had encountered conceptual difficulties. Before the session, Bud could not foresee the students' difficulties and does not notice them in the video (lacking in PCK-student) whereas his students encountered the same difficulties in expressing the solutes concentrations as Dora's students. He simply expected the students to have forgotten what the reaction quotient is. However, a student supposed to be a low-achiever[2] gives the correct expression of this quotient in answer to Bud's question and Bud makes no comment (lacking in PCK-student).

Although Bud says he struggles to make comments at his session, he considers several modifications regarding the mediative dimension of his activity. Watching a student pair who did not mix the right solutions (3rd experiment), he says that instead of mentioning what was wrong he could have asked the other students to correct that pair (PK-strategy). Regarding the last experiment, he recognises that he should have split the students into two groups, with each group making a single pH measurement to gain time (PK-management). He reconsiders the choice he made when designing the lesson plan to let the students perform many experiments. He says that during the teaching session he became aware of the time needed to realise the interpretation of the final experiment and of the interest of this task which is closely related to what can be required at the examination. He concludes by saying he would have only a single introductive experiment achieved by a student at the teacher's desk (another distribution of tasks) and revises the role of the students who would not be compelled to write under dictation (PK-management). The cognitive dimension of his activity is influenced by two other interwoven dimensions, mediative and institutional.

As a beginning teacher, Bud mentions several times that he has no prospective vision and no point of comparison. He notices that he often reads his notes during the session, and justifies that because he does not want to blunder, which is a sign that he lacks self-confidence and may not master CK. He usually asks colleagues in the high school for advice (social dimension) but cannot for this topic because unfortunately the other teachers do not organise practical work session on it and being left behind (relative to them) worries him.

Dora's Comments

During the self-confrontation, Dora makes a lot of remarks regarding the mediative dimension of her activity. She realises that the lack of a labsheet provoked a communication problem because the students did not know the names of the chemical species and this prevented them from discussing the difference between both mixtures, and wasted time (PK-management). She could actually have anticipated this student difficulty (lacking in PCK-student). The choice of classroom management, giving a paper or not, combined with a lack of knowledge of students' difficulty has a consequence for the progress of the session.

Dora states she encountered dilemmas: i) letting each student reflect on his/her own production and then supporting the students one by one or choosing a particular student's response as a starting point and guiding all of them together to reach the goal (PK-strategy); ii) guiding the students to give rhythm to the session or giving them time to reflect, but she ignores what proportion of guidance should be chosen for keeping enough rhythm (PK-management).

Watching the video, she explains the students' errors enabled her to discover incorrect lines of reasoning she did not suspect (new PCK-student). For instance, she describes Chloé's mistake and explains that writing all species formulas on the same side of the chemical equation means not imagining that some of them will be consumed and others will be produced.

She stresses the students cannot calculate the solutes concentrations in a mixture. During the session, seeing this difficulty she interrupted the students' reflection and asked them to perform the experiment (PK-strategy). She says this change responds to a need, helps the students imagine what is at stake and boosts the rhythm of the session (PK-management). Dora reminds us of the particular goal she has pursued from the beginning of the academic year – to obtain the literal expression of a species concentration – this difficult task for her students is reinforced here by the impossibility to imagine the initial state of the system. She admits she did not expect this other difficulty (new PCK-student) and wonders about a more efficient strategy: Making the mixture and then expressing the concentration or expressing them before achieving the mixture (PCK-strategy)? According to Dora, the result was unsatisfactory for two reasons; first, the phenomenon is too fast so the students cannot visualise the initial state and, second, it is an abstract state and thus not visible, contrary to the initial state of a mechanical system.

She wonders about the relevance of the order of tasks she prescribed to the students (PK-strategy). She admits that making them reflect on the whole approach before they achieve the concentration calculation and the mixtures was too early. Although they did not construct the whole reasoning, she nevertheless thinks they understood what she proposed.

SUMMING UP THE RESULTS

Bud's activity seems to be mostly oriented to the following objectives: the students have to successfully and autonomously achieve the prescribed hands-on tasks, they must have correct written notes of the results and interpretations. He therefore specifies the instructions to achieve the hands-on tasks and strongly guides the students to interpret the experiments towards the right answer, but he does not necessarily try to discover how they reason.

Dora's activity appears principally oriented to questioning the students so that they reflect on the prescribed tasks and achieve them. She promotes individual interactions with the students while she examines the students' reasoning and tries to modify it. To maintain the students' engagement, she frequently sums up the ongoing approach and stresses the key issues. The experiment is a means to achieve the goal of the lesson and its technical achievement comes next.

The different analyses are convergent, Dora exhibits different PK than Bud (Table 3) and more PCK than him (Table 4). They reveal that Bud is subjected to tensions between the personal and institutional dimensions of his activity like other beginning teachers (Brickhouse & Bodner, 1992; Sweeney, Bula, & Cornett, 2001) and Dora expresses dilemmas about the best way to engage the students' reflection, which is a sign of her reflective ability and probably of a tension between the mediative and cognitive dimensions of her activity.

DISCUSSION AND IMPLICATIONS

The pedagogical strategy enacted by Dora enabled her to interact quite deeply with the students. She recognised the students' difficulties and reasoning and helped them use adequate elements of chemical content knowledge (Alonzo et al., 2012). Conversely Bud, who nevertheless possesses content knowledge, did not provide explanations using chemical content in response to the students' difficulties (about pH) or questions (about pipette). Using the content knowledge in interactions with students is one aspect of PCK that has an effect on students' knowledge (Alonzo et al., 2012). Alonzo and colleagues observed two German physics teachers with

Table 3 (part 1). Examples of the teachers' PK

		Description of action corresponding to reconstructed knowledge	*before or during the unfolding session*		*during the self-confrontation*	
			Bud	*Dora*	*Bud*	*Dora*
PK-strategy	global strategy	strongly teacher-guided inductive approach	x			
		hypothetical-deductive approach and students' proposals taken into account		x		
	specific strategy	holding detailed discussions with the students to elicit their reasoning		x		
		dilemma: following each student's reasoning or imposing a student's reasoning on all?				x
		interrupting a task completion to begin another task in order to revive the students' reflection		x		
		making the student think about the whole approach before thinking about a specific task				x
	nature and diversity of tasks	students perform experiments in pairs	x	x		
		students think alone		x		
		students propose reasoning, argument or hypothesis		x		
		splitting a task into separate micro-tasks	x			
		students correct other students			x	
PK-management	time available	to perform experiments	x	x		
		to think		x		
		to propose an answer		x		
		dilemma: giving time for students' reflection or strongly guiding students?				x
	tasks distribution	all students conduct the same experiment	x			
		half the students conduct one experiment		x		
		a student conducts an experiment at the teacher's desk			x	
	landmarks	notes taken by students		x	x	
		conclusions dictated by teacher	x			
		frequent summing up by the teacher		x		

Table 3 (part 2). Examples of the teachers' PK

		Description of action corresponding to reconstructed knowledge	*before or during the unfolding session*		*during the self-confrontation*	
			Bud	*Dora*	*Bud*	*Dora*
PK-discourse	communication	students express their ideas		x		
		students fill in holes in teacher's talk	x			
		instructions are written	x			x
		instructions are told orally step by step		x		

Table 4. Examples of the teachers' PCK

	Description of actions corresponding to reconstructed knowledge	*before or during the unfolding session*		*during the self-confrontation*	
		Bud	*Dora*	*Bud*	*Dora*
PCK-student	anticipating students' reasoning e.g. relying upon pK_a value to predict a chemical change		x		
	predicting some students' errors, e.g. no chemical change if species amounts are equal		x		
	explaining students' unexpected answers, e.g. Chloé's chemical equation				x
	identifying students' errors or difficulties, e.g. Nicolas' idea who thought a base could not exist in an acid solution		x		
	practical aids, e.g. correcting gestures to transfer liquid with a pipette	x			
PCK-strategy	correcting students' errors (without discussion)	x			
	eliciting students' reasoning, e.g. Lucile's proposal about the different volumes and the direction of chemical change		x		x
	time left for reflection and calculation		x		
	Dilemma: expressing the solutes concentrations then making the mixture, or conversely?				x

strong content knowledge and proved that the students who had deeper knowledge belonged to the class of teacher whose aspect of PCK was more developed (Alonzo et al., 2012). Students' knowledge was not assessed in this study, but the nature of the interactions with Dora and her students proved that her students had grasped some important points, contrary to Bud's students. Our results therefore partially agree with the findings of Alonzo and colleagues.

Bud favoured a procedural approach (answering questions) to a conceptual understanding (which Dora seemed to promote). Rollnick, Bennett, Rhemtula, Dharsey and Ndlovu (2008) attribute this behaviour in the case of two South African teachers they observed to their limited understanding of the chemical concepts. Indeed, Bud showed some limitations in his understanding of the lesson goals. When confronted with his classroom video to reflect on his practice, he revised the role of the introductory experiment and thus partially readjusted his understanding of the topic. Rollnick and her colleagues (2008) consider such a change as a sign of an approach promoting conceptual understanding in the classroom practice. Our study does not support this claim. Evidence of a future change in Bud's pedagogical strategy towards a more student-centred approach is unclear. When he proposed some modifications, he still did not consider eliciting the students' reasoning nor prompting them to ask questions whereas it is a means to stimulate constructive learning (Chin & Osborne, 2008).

The first reason to carry out the comparison between the teachers' activities was their different teaching experience. "Does the teaching experience matter?", asked Friedrichsen and her colleagues (2009). Indeed, they studied the impact of teaching experience on lesson planning in biology secondary education among beginning teachers and members of an alternative certification programme without any teaching experience, where neither had previously taught the topic "heritable variation". They found that all participants of their study relied on PK rather than PCK to plan their lesson, that they "viewed 'teaching as telling'" and that this orientation was perceptible in their lesson plan (Friedrichsen et al., 2009). The difference in both groups of participants was in PK whose components were more integrated among the beginning teachers (Friedrichsen et al., 2009). They concluded that the teachers had not gained topic-specific PCK about the topic "heritable variation" (Friedrichsen et al., 2009), which is not surprising because they had not taught it before and PCK is rooted in classroom practice (Loughran et al., 2001; van Driel et al., 1998). Moreover, they claimed that

> teaching experience, in the absence of teacher education, supported the development and initial integration of PK components, but did not lead to PCK development. (Friedrichsen et al., 2009, p. 376)

Although both methodologies vary, our findings confirm their results (Bud's case) and supplement them regarding PCK development (Dora's case). Dora integrated the students' conceptions about the direction of change (Stavridou & Solomonidou, 2000; Tyson et al., 1999) that had been presented on the first day of the teacher training session, to change the nature of the tasks the students had to achieve (predicting a direction of change instead of applying a law). There is evidence that this strategy enabled her to discover some new alternative ideas. Further, Dora did not content herself with giving rise to incorrect ideas but examined the students' reasoning that underpinned their answer, which allowed her to enhance her PCK-strategy. Examining the students' difficulties during the training session acted as a valid intervention for the development of Dora's knowledge and supports Gess-Newsome's claim (2013) as well. On the contrary, the training session had a limited impact on Bud's knowledge who needed to enact his project before considering modifying it. Having not taught that topic before, Bud could not reflect on his previous teaching experience and did not increase his topic-specific PCK during his teaching session.

Bud seemed reluctant to engage a student-centred strategy, which has been reported in other studies also involving experienced teachers (Barak & Shakhman, 2008; Laius, Kask, & Rannikmäe, 2009). A long-term study (three years) involving sciences and mathematics beginning teachers showed that the majority "espoused and enacted a teacher-centred teaching style" (Simmons et al., 1999). As Magnusson, Krajcik and Borko (1999, p. 111) stated:

> The transformation of general knowledge into pedagogical content knowledge is not a straightforward matter of having knowledge; it is also an intentional act in which teachers choose to reconstruct their understanding to fit a situation.

Dora's willingness to revise her understanding was salient when she said on day 2 that she had made a lot of errors before and, as a consequence, changed the nature of the tasks and her pedagogical strategy. Indeed, Bud knew that a strategy other than his teacher-centred pedagogy is desirable according to the syllabus instructions but he did not change it and had no intention to. Does this kind of strategy contradict his beliefs about teaching? Or does Bud consider that enacting both a new lesson content and a new strategy would exceed his capacities? Gess-Newsome (2013) states the teacher's beliefs "extinguish student-centred instructional practices" and act as a filter.

To summarise the findings of this case study, the increase in PCK especially PCK-student and PCK-strategy during and after a session about a specific topic is allowed by a student-centred pedagogical strategy and depends on the teacher's reflective ability, among others. Moreover, this case study suggests that the teacher should feel able to conduct such strategy and thus another issue arises: does the teacher's belief he/she has to be able to achieve this strategy play a significant role in such a change in strategy?

Some limitations should be taken into account. The observation of the teaching session does not give information on what the students effectively learn, but only indications of their activity. Nevertheless, in Dora's class some students' reactions lead to thinking they understood what was at stake. The training session intended to enhance teachers' knowledge in two domains, CK and PCK, and was destined for experienced teachers. Given the brevity of the session, the choice was made not to address pedagogical strategies and thus PK. Indeed, the participation of a beginning teacher was not expected because usually grade 12 classes are entrusted to experienced teachers. However, it appears that the training session should have included a third dimension encompassing pedagogical strategies and students' learning.

Teacher training sessions that address all these dimensions should continue and associate researchers and teachers of a same school in a medium-term project (Venturini & Tiberghien, 2013). Examples of such sessions could be designed according to projects like Nilsson's learning study (Nilsson, 2014) or the AeDeP (Associated educational Design-experiment Places), a research network being implemented by the French Institute of Education (IFE) in which an educational project binds teachers of an educational institution and researchers with the support of the institution.

NOTES

1 All tasks are listed, but only those of the second part are detailed because they share some commonalities with the task Dora assigned to her students.

2 According to Bud's appraisal.

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Isabelle Kermen
Laboratoire de Didactique André Revuz
University of Artois, France

MICHEL GRANGEAT

7. EXPLORING THE SET OF PEDAGOGICAL KNOWLEDGE, FROM PEDAGOGY TO CONTENT

Science teachers are increasingly called on to support students in understanding the key scientific ideas needed for making sense of phenomena in the world around us. They are expected to implement inquiry-based science teaching [IBST] in order to enhance students' learning and motivation regarding scientific activities. They have to guide students in performing processes and skills that are similar to those employed by scientists. This includes students' involvement in questioning, reasoning, searching for relevant documents, observing, conjecturing, data gathering and interpreting, investigative practical work and collaborative discussions, and working with problems from and applicable to real-life contexts (National Research Council, 2012). This complex combination of objectives is noted by Harlen (2013):

> This learning process is all supported by an inquiry-based pedagogy, where pedagogy is taken to mean not only the act of teaching but also its underpinning justifications. … Learning science through inquiry is a complex process in which knowledge and understanding and skills of collecting and using evidence are linked together interactively. (p. 12)

This complexity calls for a better understanding of the set of teacher professional knowledge that is required by inquiry-based methods. This chapter explores ways of identifying this type of knowledge and understanding its development.

The first part addresses professional knowledge. The first section summarises what is known about the nature and development of professional knowledge when actors face activities that are complex because they involve interdependent factors. The second section focuses on teaching, particularly on argumentative phases in inquiry-based science teaching.

The second part specifies the methodology for grasping actual teacher knowledge. The sample consists of three groups of science teachers [N=18] in French lower secondary schools (K6-9). This section presents the data collection methods (observations and interviews), the content analysis of the data and the expected results.

The third part draws on an analysis of the 18 science teachers' professional knowledge towards argumentation in the science classroom. This analysis stresses the importance of pre- and in-service science teacher education for keeping a balance between general and content-specific pedagogical knowledge. Finally, the

M. Grangeat (Ed.), Understanding Science Teachers' Professional Knowledge Growth, 117–133.

relevance of these results is discussed with respect to international research, and the conclusion outlines some recommendations for teacher education and training, along with directions for further research.

THE DEVELOPMENT OF PROFESSIONAL KNOWLEDGE

This section summarises the state of the art regarding the way professional knowledge is elaborated through activity. First, the role of professional settings that include complex situations and collective interactions is specified. Then, the study focuses on the growth of science teacher knowledge. Finally, the research questions are introduced.

Professional Knowledge Development

Professional knowledge is understood as a synthesis of what has been learnt through professional education, individual experience and collective interactions within the work setting (Fisher & Boreham, 2004; Grangeat & Gray, 2007, 2008). Such knowledge is seen as part of the activity system of a community, as proposed by Engeström (2001) (see Figure 1). In this perspective, professional knowledge both depends on the factors included in the activity system, and influences the effectiveness of those factors; for instance, poor leadership often implies the weak development of professional knowledge, but that negative influence can be reduced by the presence of committed subjects or a supportive community.

This construct is powerful for understanding the functioning of an institution, but it needs to be adapted in order to grasp the individual knowledge of each subject. Contrary to the usual way of analysing this activity system by focusing on the connections between its nodes, I propose scrutinising the nature of these components. I suggest that four elements of this activity system underpin professional knowledge (Grangeat, 2013b; Grangeat & Gray, 2007):

- The goal that is targeted for the different objects of the activity (e.g., I aim to make Ohm's law understandable to these students). The comparison between this purpose and student outcomes generates meanings at work (e.g., I notice that these students very rapidly identified the interaction of Ohm's law factors).
- The clues that inform about progress towards the goal. Within the work situation, actors have to identify relevant clues that will trigger relevant actions for achieving their goals. These clues are selected through a set of tools and signs that mediate the subject's actions (e.g., I saw these two students struggling with their generator and ammeter, and I decided to ask them some methodological questions).
- The repertoire of actions that represents the set of rules that might be possibly enacted regarding both the goals and clues (e.g., I might have shown them the right way to connect the ammeter but I preferred to ask them some questions).

- The reference knowledge that underlines the creation of meanings and that is a synthesis of the subject's education and experience, the professional community's culture, and expectations resulting from the division of labour (e.g., head of school, inspector, or parents). This reference knowledge is a component of the set of instruments, tools and signs that mediates the actors' performance. It allows actors to justify their choice of actions (e.g., I didn't show them the right answer because within this school we endeavour to make our students more responsible towards inquiry).

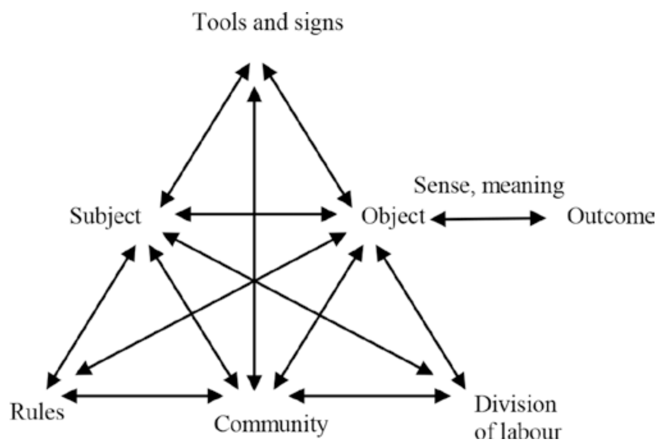


Figure 1. Activity system after Engeström (2001)

Therefore, specifying professional knowledge leads to identifying four elements: goals which orientate the actors' activity; clues which are elements of the work situation identified and selected by actors and which trigger a particular type of action; the repertoire of actions which generate and monitor the selected action according to the specific goal and object of the activity; the reference knowledge which underlines and justifies the actual actions.

A science teacher activity system is underpinned by a kind of backbone composed of the content to be taught to specific students, the teaching goal, the learning outcomes that are expected, and the clues that are selected in the classroom situation that give sense to that situation and trigger specific actions. This sequence is nourished by the repertoire of instructional strategies that is available for the teacher and the community. It is warranted by reference knowledge. This professional knowledge is influenced by the community in which each teacher is embedded and the nature of the school organisation, particularly the leadership style adopted by the head of school (see Figure 2).

This knowledge is developing through experience and collective interactions since "the object of activity is a moving target, not reducible to conscious

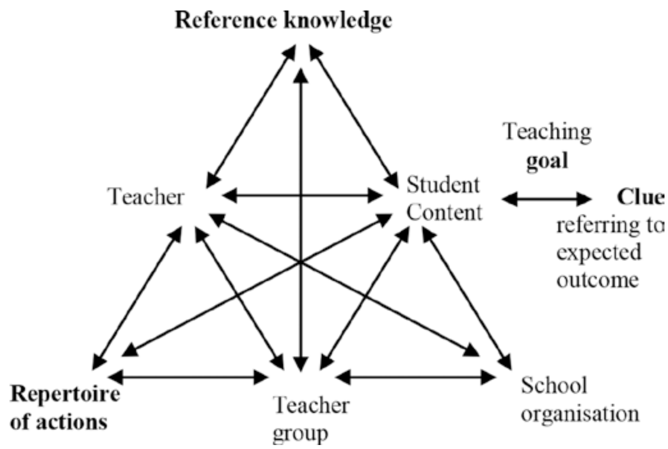


Figure 2. Components of a teacher activity system

short-term goals" (Engeström, 2001, p. 136). Such development of professional knowledge is seen as an articulation of two regulation loops (Rogalski, Plat, & Antolin-Glenn, 2002): a productive loop which consists of altering the object of the action (e.g., during teamwork, teachers lead students to argue on elaborating an accurate hypothesis; afterwards, students become more competent in formulating hypotheses); and a constructive loop which changes actors' knowledge and beliefs while they carry out the task (e.g., teachers find out that they have become more efficient in supporting students' argumentation competencies). Thus, professional knowledge represents both the way in which actors achieve work tasks, and make meanings at work. Therefore, professional knowledge is defined as a personal attribute of an individual actor and consists of a combination of actions and knowledge about action.

Professional knowledge development entails progressive and repeated reorganisations of ways of reflecting about professional activities and of acting effectively. This process of professional development is far from linear and regular but often consists of conceptual leaps, stagnations or declines. It occurs when agents need to alter their approaches or methods in order to carry their tasks out more efficiently. Such an evolution is frequently spread between two extremes arrangements of a continuum (Hudson, 2007; Postareff & Lindblom-Ylanne, 2008). These consist of ways of enacting professional knowledge.

The first arrangement is centred on the fundamental aspects of the activity. For instance, teachers focus on their personal activity since they need to know by themselves the most effective actions for achieving their goals within the main teaching situations (e.g., eliciting students' understanding of a topic by asking them accurate questions). The final arrangement enlarges the field of professional knowledge: teachers maintain a balance between subject requirements, students' characteristics, and some colleagues' activities. This enlargement allows them to complete more challenging and varied tasks (Pieters, 2004). These arrangements are not exclusive and professional knowledge actualisation varies according to teachers' commitment, experience or training, and to the teaching context that results, for instance, from the students' social characteristics, or from the school organisation (Grangeat & Gray, 2007).

Within complex situations in which actors cannot directly control all the factors that impact on their activity outcomes, professional knowledge is networked upon the main dimensions of the activity. Such a network underpins more effective actions, allowing actors to prioritise amongst interwoven objectives (Colucci-Gray & Fraser, 2008). Within collective settings like schools, professional knowledge is elaborated collectively, through actions and discussions, and is ultimately integrated into the culture of the community (Boreham & Morgan, 2004).

To sum up, professional knowledge results from prior education and in-service training, individual experience, official expectations, and debates amongst colleagues and partners. It may be described according to four interconnected elements: goals, clue, repertoire of actions, and reference knowledge. It evolves along a continuum between two arrangements (centred on the individual subject vs opened to other actors) regarding the difficulties and opportunities the actors are involved in. It is organised upon the main characteristics of the situation.

Science Teacher Pedagogical Knowledge

Teaching is a professional activity that does not merely consist of transferring specific scientific content from teachers to students. Teachers have to design sequences and methods that enable students to improve their understanding of the nature of science, their capabilities in conducting scientific reasoning and methods, their capabilities to learn in a self-regulated way, and their motivation concerning science questions and careers. This is a complex activity that necessitates specific knowledge. For this reason, over the past decades a lot of research studies have endeavoured to better understand the nature and development of teacher knowledge (Alonzo, Kobarg, & Seidel, 2012; van Driel, Verloop, & de Vos, 1998).

This research area increasingly referred to Shulman's ideas that distinguish three interconnected types of knowledge: subject matter, or content knowledge (CK), pedagogical content knowledge (PCK), and general pedagogical knowledge and skill (PK). This is coherent with the previous section's outcomes that understood professional knowledge as the integration and transformation of different sources of meanings. This chapter only addresses the linkage between PCK and PK.

According to Shulman, PCK allows teachers to make disciplinary content comprehensible to students. Consequently, PCK distinguishes a teacher from disciplinary experts, and also from colleagues who teach other subjects (Shulman, 1987). PCK is characterised by two key components: knowledge of representations of subject matter, and understanding of specific learning difficulties and student conceptions. These components underlie teachers' instructional decision-making both during the planning stage of the lesson – by deciding how best to present content to students – and during classroom instruction – by interacting with students in order to make the content understandable. Thus, PCK is both topic-specific and context-dependent and results from a combination of familiarity towards a specific topic with reflection on teaching experience (Alonzo et al., 2012; van Driel et al., 1998). According to this perspective, PCK implies reflection on action and in action. This is relevant with the double loops of constructive and productive processes that underline professional knowledge development.

According to Shulman, general pedagogical knowledge complements knowledge linked to a specific content, but very few researchers have tackled this question. Some research only considers PK as part of a wide teacher professional knowledge base (Gess-Newsome, 2014), while other research merely explores declarative PK through tests (König, Blömeke, Paine, Schmidt, & Hsieh, 2011). This chapter aims to contribute to a better understanding of the nature and role of this general pedagogical knowledge.

Research Question

Teacher professional knowledge combines diverse types of knowledge that are drawn from various sources, as is the case with other professionals performing complex and collective activities. This knowledge may be organised in line with three interconnected categories regarding subject matter (CK), general pedagogy (PK) and specific content pedagogy (PCK). The point is to understand the linkage and interaction among these three types of knowledge; this chapter will only focus on the link between the last two.

Two research questions have to be answered. Over the past few decades, PCK has been described more and more specifically but PK left unexplored. The first question consists of describing this general pedagogical knowledge and distinguishing it from PCK. The second question entails exploring the repartition of these two categories in science teachers' approaches and practices: Is one of these two prevalent? For which type of teacher? The responses may contribute to orientating teacher education and training.

The study focuses on teacher professional knowledge toward argumentation in IBST methods. It compares new science teachers (NST) with experienced teachers (EST) and science teachers who are committed in their colleagues' in-service training (CST).

IDENTIFYING TEACHER PROFESSIONAL KNOWLEDGE FOR IBST

This section specifies the differences between these three types of teachers. Then, it presents the way the data were collected, and the process of producing the results. Finally, it sets out the expected results.

Three Types of Science Teachers

The sample consists of 18 science teachers (eight males, ten females). They are teachers of mathematics, biology and earth or physics and chemistry in lower secondary schools in France. They cover the three contrasted types of teachers that are expected to encompass a wide range of professional knowledge.

The first type comprises six teachers who are considered experts by the hierarchy (i.e. inspectors). They frequently meet together and with inspectors in order to improve their teaching approaches and practices, and to design and carry out teacher professional development programmes for other science teachers. Each year, these in-service sessions address a new part of the French programmes, and thus IBST is not the sole object of these teachers' training activities. Henceforth, they are called committed science teachers [CST].

The second type comprises six new science teachers [NST]. During their first teaching year, they attended five specific CPD sessions which emphasised specific teacher collaboration based on discussion and exchange about IBST topics and five sessions about specific content that may be included in IBST lessons (Leroy & Grangeat, 2010).

The third type comprises six experienced science teachers [EST] who are neither involved in professional networks nor in-service programmes about IBST. The French education system is centralised, and these teachers have merely followed the national requirements about IBST. They have likely received some brief instructions from their respective inspectors, but that happened at least three years before the current study.

These three types of teachers are contrasted in such a way that they have the potential to cover the full set of variables: teachers who are in their first teaching year versus those who have more than five years of practice; teachers who are isolated versus teachers who are involved in a collective activity.

Data Collection

The data were collected through videotaped, inquiry-based lessons and audiotaped interviews about the video with each science teacher.

First, the research team asked each teacher to carry out a lesson that he or she considers an inquiry-based lesson. In focusing on a unique lesson, the researcher incited the teachers to select what are for them the more representative aspects of inquiry-based teaching. The lesson was videotaped from the back of the classroom and audio-recorded through a lavaliere microphone on the teacher. The lesson lasted about 55 minutes.

Afterwards, each teacher was interviewed about the last 20 minutes of the video. In focusing on the same sequence of each lesson (the last 20 minutes) comparable and searchable data are produced. The teacher was asked to stop the video when there was an event – expected or unexpected – that involved him or her choosing from amongst alternative instructional strategies. Thus, the teacher was asked to make explicit both the event that challenged his or her teaching strategy, and the goals that underlay the observed action; most of the time, teachers explained the professional knowledge that underpinned their choices, and alternative actions carried out in previous lessons. The interviewer was also able to stop the video and ask questions about clues picked out of the situation by the teacher or changes in the teacher's activity. Each interview lasted about 60 minutes.

Data Analysis

All lessons and interviews were fully transcribed. Afterwards, two complementary content analyses were carried out in order to identify the set of professional knowledge of each teacher and how this set of professional knowledge is organised.

The first content analysis consisted of analysing the lesson and interview transcriptions in order to identify the four elements of teacher professional knowledge: the teacher's goal; clue(s); repertoire of actions; reference knowledge. This analysis resulted in identifying the set of professional knowledge of each teacher with respect to inquiry.

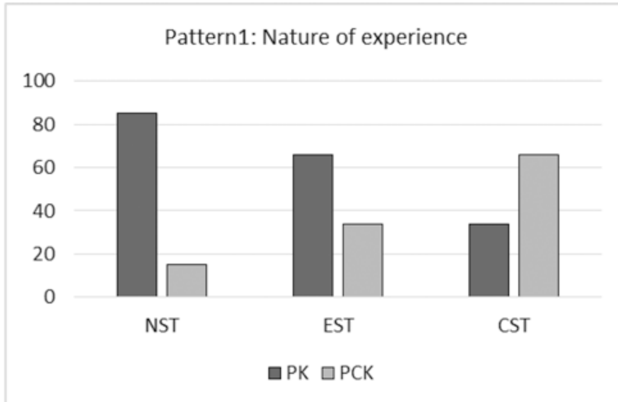
The second study addressed the activity system of each teacher towards argumentation. The set of professional knowledge of each teacher was classified according to the six crucial dimensions of inquiry-based teaching: origin of questioning; nature of problem; students' level of responsibility; awareness of students' diversity; development of argumentation; teacher's goal explanations (Grangeat, 2013b). The set of professional knowledge addressing 'argumentation' was analysed in order to distinguish PK from PCK. If professional knowledge referred to a specific content it qualified as PCK, if not it was labelled as PK.

Expected Findings

The comparison amongst the three groups of teachers may create two alternative patterns. The results may depend either on teachers' experience or commitment.

The first pattern is based on teachers' experience: the more the teachers have the opportunity to reflect on their practice as science teachers, the more their knowledge is specific. Thus, the results' pattern might be: NSTs demonstrate more PK than PCK, ESTs are in an intermediary position, and CSTs demonstrate the maximum PCK (see Figure 3 P1).

The second pattern is based on teachers' commitment: the more the teachers have the opportunity to exchange and debate with colleagues about science teaching methods, the more their knowledge is specific. Thus, the results' pattern would be: ESTs demonstrate more PK than PCK, NSTs are in an intermediary position, and CSTs again demonstrate the maximum PCK (see Figure 3 P2).



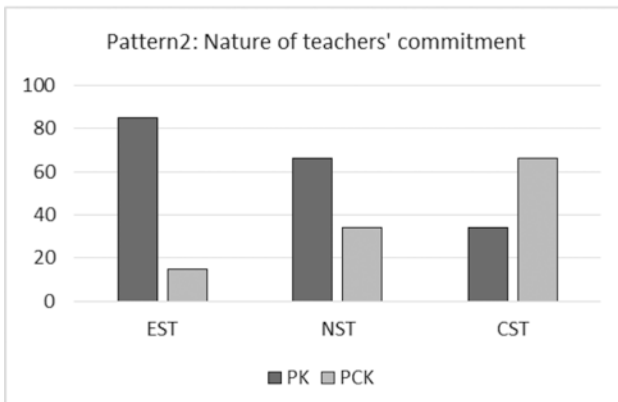


Figure 3. Possible results

THE IMPORTANCE OF TEACHERS' PRE- AND IN-SERVICE EDUCATION

Two analyses were conducted. The first involved describing what general pedagogical knowledge is and distinguishing it from PCK. The second consisted of exploring the repartition of these two categories in science teachers' knowledge of the sample and testing the relevance of the above two patterns.

Distinguishing PK from PCK

The content and video analysis of each interview and lesson allowed inferring the teachers' professional knowledge. According to the theoretical framework, it consists of goals and sub-goals, clues, actions and justifications. Two types of professional knowledge were distinguished: PK that concerns the general instructional strategies performed by a teacher in any lesson, and PCK that is linked to a specific content.

General pedagogical knowledge. PK refers to general pedagogical methods that can be applied by a teacher in various lessons or by diverse teachers, whatever their discipline is. They thus form part of professional knowledge. The following example addresses the way teachers may support students in debating. It is one of the first stages of argumentation (see Table 1).

The activity of the mathematics teacher that is studied here is structured upon three coordinated sub-goals: to help each team deliver some material that might support an exchange within the whole classroom, to choose the relevant groups that will be able to present useful results and, finally, to organise a debate based on what the team has actually done. Within the actual classroom activity, each sub-goal

Table 1. An example of general pedagogical knowledge

Goal	*To communicate the learners' proposals to the class*
Sub-goal 1	To prepare how the learners are going to put their work together
Clue	This group did not have time to rewrite it properly. It was still a rough paper.
Repertoire of actions	I asked them for their rough paper. I photocopy it on a transparency film.
Sub-goal 2	*To choose those groups that will go to the board to present their results*
Clue	For the putting together at the end of the lesson.
Repertoire of actions	I started with groups that did not go far. They just had their drawings. Then I went on with those who had a process that might lead them to the right answer. I ended up with two groups that got the right answer.
Sub-goal 3	*To present what the groups did together in an understandable way*
Clue	It was not an easy task. Some groups were still at the preliminary level of research. Others were wasting time to put what they did on their transparency. Others were advancing in their rough papers and, in that case, there was no longer any transparency film.
Repertoire of actions	I was flexible with instructions. I collected rough papers.
Reference knowledge	My goal was that they should use their rough paper like a resource to solve the problem. Some had a problem with the transparency. I was afraid that if they were to use normal paper I would obtain four similar papers in each group. That is why I had to insist on transparency films. I allow them to use their rough papers. Finally, I was able to use their presentation to explain the lesson to the rest of the class.

allows this teacher to identify a piece of information, a clue that results in an action or a series of actions. Finally, a rationale allows the teacher to create meanings from these actions. It acts as reference knowledge underpinning the teacher's choices

This type of professional knowledge addresses the classroom management in order to meet the teacher's objectives. Accordingly, it is pedagogical knowledge. On the other hand, this knowledge is not specific to a type of subject since any teacher can apply this kind of knowledge. Thus, it is general pedagogical knowledge (PK).

Pedagogical content knowledge. A second type of professional knowledge refers to a specific content that distinguishes teachers of diverse subjects. It addresses the way teachers may manage the classroom in order to better explain a notion or method that is specific to a disciplinary notion. In this sense, it represents PCK.

The following example is extracted from the activity analysis of the same mathematics teacher as above (see Table 2). His goal is to enable learners to take into consideration the arguments of their classmates. It necessitates actualisation of the specific vocabulary and methods that characterise a specific scientific domain: this example addresses mathematics. The difference with PK is threefold. First,

Table 2. An example of pedagogical content knowledge

Goal	*To enable learners to take someone else's arguments into consideration*
Sub-goal 1	*Facilitate understanding and debate among members of the group*
Clue	This boy was not very certain of the opposite vertex. He said it could be the one on the left, the one on the right or the one in the middle.
Repertoire of actions	I lead this pupil to reformulate his idea using words that will be understood by all his team mates.
Reference knowledge	His first sentence does not make sense. He should try and express his idea with appropriate mathematical terms. The goal is to make sure that the three other members of the group take part in the conversation, that they share the same idea and that the terms used are understood by everybody.
Sub-goal 2	*Facilitate oral argumentation when summarising the lesson*
Clue	On the transparency film they wrote incomplete things. Nothing was wrong in the drawings.
Repertoire of actions	I asked one group member or the group as a whole to explain the different steps that led to the right answer. I proposed the different possible solutions.
Reference knowledge	So as to make some comments, I push them to intervene. The goal is really to put together the work of the pupils. The two groups were able to convince the other groups that their approach was interesting and that it has the potential to solve cases of polygons with a large number of sides. I told them that we can replace the number of sides with the letter n and that responds to the last given question.

the nature of the clues that are checked by the teacher is subject-specific: in this example, these clues are related to a particular notion (the opposite vertex of a polygon) or method of problem-solving (writing mathematical reasoning down that is understandable by classmates). Second, the repertoire of actions is centred on the disciplinary subject: using relevant vocabulary, and accurate data and warrants. Third, the reference knowledge is connected to a specific domain: mathematical vocabulary and methodology.

It is important to keep in mind that these PK and PCK are not necessarily effective professional knowledge. It is the role of teacher pre- and in-service education to support teachers in improving their beliefs, approaches and practices in order to be more efficient. The researcher's role only comprises identifying these two sets of professional knowledge.

To sum up, PK and PCK are similar regarding the nature of their four constitutive elements. They are also similar regarding the goal that orientates teachers' activity. Nevertheless, they differ regarding the types of clues that trigger specific actions, the nature of the repertoire of actions that is available to the teachers for achieving their goals, and the reference knowledge that warrants the teachers' choice (see Table 3).

Table 3. Commonalities and differences between general pedagogical knowledge and pedagogical content knowledge

	PK	*PCK*
Goals	To achieve key competencies	To achieve key competencies
Clue	Classroom management: e.g., accurate proceedings of all the pupils' teams; adaptation of the task for some specific learners.	Understanding of specific subject notions: e.g., using of the appropriate vocabulary or problem-solving method.
Repertoire of actions	Actions that are similar for all teachers (e.g., supervising all of the pupils' teams) or within a large subject domain (e.g., using graphical representations).	Actions that are specific to a notion and that tackle the learners' difficulty regarding this notion (e.g., 6th grade learners cannot easily identify all the diagonals of a polygon with numerous sides).
Reference knowledge	Referred to crosscutting competencies (e.g., motivation, self-regulation, formative climate etc.)	Referred to content-specific competencies (e.g., particular scientific inquiry methods etc.)

The analysis of the videos and interviews of the 18 teachers regarding the dimension "argumentation" of IBST resulted in identifying 73 types of professional knowledge. Their repartition between the two arrangements on the continuum is not equal: two-thirds of these types of professional knowledge is teacher- and content-centred (48/73), and one-third is student- and learning-centred (25/73). The sample includes 59 PK and 14 PCK units. Thus, in the sample more than 80% of professional knowledge types are general (see Table 4).

Table 4. Repartition of pedagogical (PK) and pedagogical content knowledge (PCK)

	PK	PCK	Total
EST [N=6]	20	0	*20*
CST [N=6]	23	3	*26*
NST [N=6]	16	11	*27*
Total	*59*	*14*	*73*

This first result is complemented by a second analysis regarding the repartition of these sets of professional knowledge depending of the types of teacher.

Repartition of Professional Knowledge Depending on the Types of Teacher

The set of PCK is not equally distributed among the sample of teachers. The result does not correspond to any expected pattern.

New teachers report PCK more frequently than teachers who benefit from more experience. Teachers who are not involved in collective settings do not report any PCK (see Table 4).

The balance between PK and PCK is modified regarding the teacher types. Within this sample, NSTs report an expected repartition (60% vs 40%). Nevertheless, the absence or quasi absence of PCK was not expected (see Figure 4).

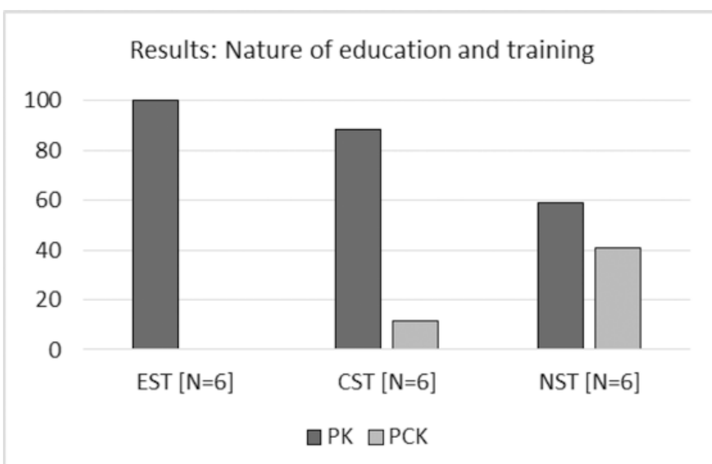


Figure 4. Importance of pre- and in-service education

From these results, the PCK actualisation seems to depend on neither the length of experience nor the teachers' commitment.

New teachers report the most PCK. They have benefited from a specific teacher education programme that has been designed and carried out by a team of teacher educators including pedagogues and didacticians (subject specialists). The analysis shows that these new teachers have adapted the approaches, practices and methods that were discussed during this education programme.

On the opposite, isolated teachers (ESTs) report TPK that relies only on a very general repertoire of actions and justification. They seem to not focus on the specific scientific knowledge elaboration by their students. They report very vague crosscutting competencies, and the video analysis demonstrates that their IBST methods are far from efficient: for instance, they seldom explain their goals to their students, and they never help them summarise what has been learned during the lesson.

Surprisingly, the situation is quite similar for the teachers involved in a group in charge of designing and carrying out CPD programmes for their colleagues. These first results need to be balanced through an analysis of the nature of these sets of professional knowledge, thus by taking the modalities on which this knowledge was enacted into account. Within the sample, most of these professional knowledge units are focusing on teacher and content, this represents more of a view of teaching as a notion of transmission. Only one-third goes beyond this view by considering students' needs and interests. Nevertheless, amongst the three types of teachers the repartition is not equal. A large part of professional knowledge reported by the new and experienced teachers is uniquely teacher- and content-centred (respectively, 20/27 and 15/20). Conversely, committed teachers reported more balanced professional knowledge because half of the identified types of professional knowledge (13/26) are student- and learning-centred. Nevertheless, their professional activity might be underlined by a poor connection between cross-cutting and specific competencies.

To sum up, the most PCK was reported by teachers who are in their first teaching year, and who have been involved in a specific programme held jointly by teacher educators who are a specialist in either general pedagogical knowledge or specific content knowledge. Expert teachers who are involved in collaborative projects dedicated to designing and carrying out in-service programmes report more PK than PCK, and a set of professional knowledge which demonstrates that they combine effectively content- and learning-centred teaching methods. The analysis of the totality of their activity shows that they enable their students to be responsible for the enquiry process, they take care of the differences amongst them, they are aware of the importance of argumentation, and they make explicit their goals and targeted learning outcomes to the classroom. Experienced teachers who were neither involved in collective project nor in-service teacher education programmes do not report any PCK and demonstrated teacher- and content-centred professional knowledge.

Therefore, the results tend to support the idea that the lack of teacher education leads teachers to elaborate very poor professional knowledge that seems unable to underpin the complexity of inquiry-based teaching. On the contrary, the teacher involvement in the collaborative project focusing on specific professional issues leads the teachers to demonstrate professional knowledge that underpins the uptake of students' diverse needs and interests. Nevertheless, this is the conjunction of teacher education focusing on both general and content-specific professional knowledge that allows teachers to elaborate and demonstrate PCK.

DISCUSSION: THE CRUCIAL ROLE OF TEACHER EDUCATION

The findings are not totally in line with our expectations. As expected, the results demonstrate an evolution from an imbalanced situation between PK and PCK towards more balanced conceptions and practices of teaching. This evolution does not uniquely depend on the length of experience or on the teachers' commitment in collective settings. This is quite coherent with van Driel, Verloop, and de Vos (1998) who noted that the PCK of experienced science teachers may differ considerably. This is also consistent with Nilsson and van Driel (2010) who showed that new teachers may demonstrate more PCK than expert teachers (mentors), and that these latter report more open and flexible PK.

This study draws on a sample of 18 science teachers and shows that the main factor influencing the development of PCK is the teachers' involvement in CPD programmes that in a coordinated way tackle general and specific competencies.

These results are consistent with another study that is still in progress but may provide some insights for understanding the results of the current research. That study concerns 11 lower secondary science teachers who are engaged in a joint project with teacher educators and researchers who are experts in pedagogy or in subject-specific teaching methods. All together, they design, try, evaluate and refine science education lessons that combine IBST and formative assessment methods. The project is lasting three years. Even after the first year, teachers reported many changes within their teaching conceptions and classroom practice; for instance, their lesson plans are more precise, there are more aware of the importance of accurate vocabulary (Grangeat, 2013a). After the second year, they reported that they are more precise in identifying their students' difficulties during the lesson and in providing them with relevant feedback. During the third year, they make visible their teaching purposes and their criteria for assessing learning outcomes to the students. Video analysis confirms these self-reports. We thus assume that they are developing more diverse and accurate PCK.

Consequently, we argue that PK and PCK need to be handled together by pre- and in-service teacher education. Nevertheless, further studies need to be designed in order to explore the connection between these two fundamental types of teacher professional knowledge.

CONNECTING GENERAL AND SUBJECT-SPECIFIC TEACHER EDUCATION

This chapter's aims were firstly to identify and distinguish PCK and PK, and secondly to explore their reciprocal development. This study addressed the linkage between these two types of teacher professional knowledge by focusing on learners' competencies toward argumentation in science.

The study shows that these two types of teacher professional knowledge are interwoven, but distinguishable. Criteria are elicited in order to classify these two types. The study reveals that general pedagogical knowledge (PK) represents the major part of the science teacher professional knowledge repertoire of the 18 teachers of the sample. It also shows that pedagogical content knowledge (PCK) is more frequently reported by new teachers who are engaged in a pre-service programme designed and carried out by researchers and teacher educators in pedagogy and science subjects. Consequently, the results argue for the current models to be refined. These models are based on the assumption that PK is a component of the teacher professional knowledge base, and contribute to the development of PCK. The results of this study show that PK and PCK interact as equivalent components of the teacher professional knowledge repertoire. A better understanding of the integration of such components into accurate, efficient and flexible professional knowledge is called for.

The study needs further research based on crosscutting perspectives between pedagogy and subject-based approaches. The strong and complex interactions between general and content-specific pedagogical knowledge that are enlightened by this study contribute to reorganising the explicative models of teacher professional knowledge. This reorganisation might result in a better balance of the respective role of these two professional knowledge components.

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Michel Grangeat
Educational Science Laboratory
Higher School for Teaching and Education
Univ. Grenoble Alpes, France

SUZANNE KAPELARI

8. COLLABORATIVE PEDAGOGICAL CONTENT KNOWLEDGE CREATION IN HETEROGENEOUS LEARNING COMMUNITIES

Current science education reform initiatives require fundamental changes in how science is taught and in how teachers are supported to engage in alternative ways of science teaching (Rocard, 2007; Osborne & Dillon, 2008; National Research Council, 2007). Modern science teachers can no longer simply deliver subject knowledge but are asked to support their students to develop their interest in science as well as to understand the 'Nature of Science' and the 'Nature of Scientific Processes and Methods'. Since the beginning of the 20th century, inquiry-based science learning environments have been assumed to provide fruitful ways for improving science teaching while including the learning goals mentioned above. Ever since, science education research has not provided a straightforward understanding of inquiry-based teaching that has proven to meet these expectations. Capps and Crawford (2013) were recently forced to conclude that "today there is still no consensus as to what it [Inquiry-based Science Education = IBSE] actually is and what it looks like in the classroom" (p. 525). Their study showed that teachers in the United States, a country in which "inquiry has been a buzz word in science education for many years" (ibid., p. 523), holds many misconceptions and myths about inquiry and equates it with questioning, student-centred teaching approaches, and hands-on teaching. The authors continue that "it was particularly troubling that many teachers in this study believed they were teaching science as inquiry even when they were not" (ibid., p. 522). In addition, there is disagreement about the various ways these learning processes can be facilitated and the degree of structure that needs to be provided by the teacher. Minner, Levy, and Century (2010) found that "classroom inquiry shows varying degrees of direction or instruction given by the teachers and these distinctions are often poorly articulated by scholars and practitioners alike" (p. 476). However, the amount of direction and decision-making applied by the teacher versus the student is known to be particularly influential on students learning. Thus, the scope between open and guided inquiry, and the role scaffolding plays in students' learning outcomes, have frequently been discussed in the literature (Hmelo-Silver et al., 2007; Wichmann & Leutner, 2009; Kirschner et al., 2006; Mayer, 2004). "Precisely the lack of shared understanding of defining features of various instructional approaches has hindered significant advancement

M. Grangeat (Ed.), Understanding Science Teachers' Professional Knowledge Growth, 135–154.

in the research community on determining effects of distinct pedagogical practices" (Minner et al., 2010, p. 476).

So far, research has reported on the difficulties of enacting IBSE in schools and still does not provide a clear picture of how it can be carried out (Anderson, 2002; Windschitl, 2003). Images such as students raising questions and designing scientific investigations to collect evidence or discussing their findings in the light of evidence are somewhat obscure for teachers who have not been socialised in a scientific community in the first place. However, even if this has eventually happened, an implicit understanding of how science works does not provide a performance bond when it comes to guiding students to work with and make sense of the experiences gained in inquiry learning.

New curriculum initiatives, which focused on inquiry using complex instructional strategies, were found to more often promote a significant increase in learning among students. These effects were, however, not always sustained as curriculum reforms were scaled up and used by teachers who did not have the same degree of understanding or skill in implementation (Barron & Darling-Hammond, 2010). Teachers often hold very personal views on teaching, their students' confidence to achieve tasks, subject matter, and student learning etc. These beliefs about teaching and learning have a strong impact on teachers' classroom practice (Fang, 1996). While trying to implement inquiry-based teaching in day-to-day teaching, 'procedure models' have mainly been developed, discussed, favoured and dismissed over the last two centuries of IBSE history and it cannot be ignored how both critical and challenging it is for teachers to plan and/or enact inquiry-based instructions (Capps & Crawford, 2013). When it comes to supporting practitioners to refine their understanding of inquiry-based science teaching (IBST) and to improve their classroom practice, one needs to be aware that putting abstract concepts into practice may not only have explicit but also implicit knowledge components which cannot be fully described in words or in teaching material published on various related teaching material websites, nor does it become obvious by simply observing others presenting best-practice examples in face-to-face training programmes.

Thus, the purpose of this paper is to report on design-based research applied in a European project that valued the innovative potential of making explicit tacit pedagogical science content knowledge (PCK) about how to teach inquiry in class and outside the classroom. Opportunities for observing each other's practice were provided on a regular basis and observers were asked to give detailed feedback. Building on Nonaka and Takeuchi's (1995) Model of Knowledge Conversion and Engeström's (2001) Model of Expansive Learning, IBST-related PCK development was supported by focusing on the interaction between tacit and explicit knowledge embedded in reflective learning cycles. In addition, explicit knowledge provided by IBSE research literature and scientists was introduced. The on-going interaction between individual educators working at Botanic Gardens and a consortium of 17 partner institutions led to innovative knowledge development that finally offered participants the opportunity to confirm, interconnect and develop their professional knowledge. The purpose of this paper is to draw attention to the tacit knowledge applied in inquiry-based teaching as the root and foundation of developing an explicit understanding of how to teach inquiry in class and outside the classroom and therefore values tacit knowledge as an important part of innovation and expansive learning.

PEDAGOGICAL SCIENCE CONTENT KNOWLEDGE IN INQUIRY-BASED TEACHING

When Shulman published his ideas of Pedagogical Content Knowledge (PCK) in 1987, his definition of the concept was relatively vague.

> [Pedagogical Content Knowledge] represents the blending of content and pedagogy into an understanding of how particular topics, problems or issues are organized, represented and adapted to the diverse interests and abilities of learners, and presented for instruction. Pedagogical content knowledge is the category most likely to distinguish the understanding of the content specialist from that of the pedagogue. (p. 8)

While Shulman explained PCK as an amalgam of content and pedagogical knowledge and exclusive to teachers' professional knowledge, research literature refers to PCK as either a discrete domain of teachers' professional knowledge or as dependent on content knowledge, pedagogical knowledge and context knowledge and therefore inseparable (Kapelari, 2014).

Although the concept of PCK is sometimes considered academic construct, the idea is deeply rooted in the belief that science teaching, for instance, requires more than just delivering science knowledge to students. According to Schneider and Plasman's (2011) literature review (n=91 relevant research articles), well-developed science teacher PSCK includes five components, which are knowledge about the Orientation to Teaching Science, Students Thinking About Science, Instructional Strategies in Science, Science Curriculum and Assessment of Students' Science Learning. Nevertheless, it is obvious that PCK components such as knowing about students' alternative conceptions, important big ideas related to the context, conceptual hooks or triggers of learning are not well understood when a rich understanding of the subject content is lacking (Loughran et al., 2006). PCK thus intrinsically ties subject matter to pedagogical and context knowledge and stands for more than the sum of its parts. However, the literature does not often refer to PCK that is not explicitly understood by teachers but becomes visible whenever teachers do the right thing at the right time. The kind of knowledge that is implicit and commonly paraphrased as enculturation, intuition, sure instinct, talent, beliefs, attitudes and values was termed tacit knowledge by Polanyi (1966/2009) to explain why it is "that we know more than we can tell" (p. 4). Tacit knowledge about how science works that is evolving while people are studying to become a scientist or a science teacher may be one reason why it is so challenging for teachers who do not have a science background to implement IBST strategies into their everyday teaching.

Tacit and Explicit Knowledge

Polanyi (1966/2009) argues that we can teach appearances such as cases of diseases, specimens of rocks, plants or animals only by "relying on the pupil's intelligent co-operation for catching the meaning of the demonstration" (p. 5). He continues:

> Any definition of a word denoting an external thing must ultimately rely on pointing at such a thing. This naming-cum-pointing is called 'an ostensive definition'; and this philosophic expression conceals a gap to be bridged by an intelligent effort on the part of the person to whom we want to tell what the word means. Our message had left something behind that we could not tell, and its reception must rely on it that the person addressed will discover that, which we have not been able to communicate. (p. 7)

In 1995, Nonaka and Takeuchi presented a model of innovation processes in Japanese organisations. The authors distinguish between two kinds of knowledge, tacit and explicit. While explicit knowledge is easy to articulate and express formally and in clear terms, tacit knowledge is "personal knowledge embedded in individual experience and involves intangible factors such as personal believes, perspectives and value systems" (Nonaka & Takeuchi cited by Paavola et al., 2004). According to Nonaka and Takeuchi (1995):

> Tacit knowledge is highly personal and hard to formalize, making it difficult to communicate or to share with others. Subjective insights, intuitions, and hunches fall into this category of knowledge. Furthermore, tacit knowledge is deeply rooted in an individual's action and experience, as well as in the ideals, values, or emotions he or she embraces. (p. 8)
>
> Tacit knowledge may consist of two types of ingredients. "One type refers to the skills as well as fingertips experience in mastering a certain domain of practical activity. The other one refers to the mental models, beliefs and perceptions so ingrained that we take them for granted". (Nonaka & Takeuchi cited by Bratianu, 2010, p. 194)

According to Nonaka and Takeuchi (1995), knowledge creation is based on a spiral of four types of knowledge conversion (see Figure 1). The first step is labelled *socialisation* and is characterised by developing, e.g. in our case, an understanding of how to interact with students while teaching an inquiry-based science lesson by simply observing an experienced teacher doing it. Tacit knowledge is thus transformed from tacit expert knowledge to tacit knowledge held by the novice. However, this knowledge development is not recognised by the teacher nor by the learner. The second step is called *externalisation* and describes a process of knowledge transformation by which the tacit knowledge is made explicit. The novice, another expert or a researcher, articulates his or her observation and explicitly addresses a particular aspect of the tacit knowledge applied by the expert practitioner. The third step is called *combination* and takes already existing explicit knowledge into consideration. Explicit knowledge may be added by various means such as by externalisation or explicitly introduced by experts/learners or is gathered individually by reading literature etc. Finally, knowledge is *internalised* whenever explicit knowledge is transformed into tacit knowledge and put into practice intuitively again.

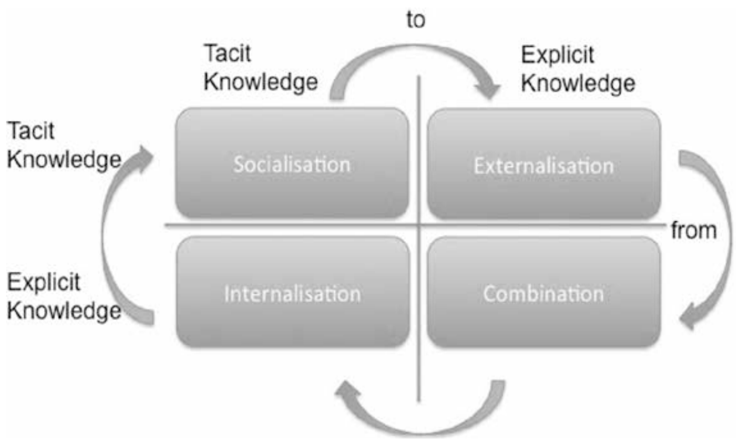

Figure 1. Knowledge conversion processes (Nonaka & Takeuchi, 1995)

Referring to a body of knowledge gained in organisational knowledge development research, Venkitachalam and Busch (2012) point out that “There are a number of other individual parameters that influence tacit knowledge transfer” (p. 363) and they name the establishment and maintenance of a good relationship between the sender and the receiver of knowledge, the ability of the individuals to believe they are capable of doing something, competency in perception and language, the time in which the transfer takes place, perceived values and ownership of knowledge and the distance of the knowledge transfer between the sender and receiver. These authors argue in reference to Polanyi that “we must distinguish between what we can say we know, and what a suitable equipped observer could say we know, between what we cannot put into words and what cannot be put into words” (Venkitachalam & Busch, 2012, p. 360). Tacit knowledge and theories of its development appear to be better addressed in organisational development research than it is in science education research. However, it is likely that teachers’ tacit PCK about teaching science as an inquiry may inhibit or trigger positive student learning outcomes whenever IBSE is put into practice.

Expansive Knowledge Creation

As already mentioned, sharing explicit and tacit knowledge is a source of innovation and development. Teacher professional development research has shown that sharing this knowledge in learning communities is a fruitful way of supporting teachers in developing their practice (e.g., Timperley et al., 2007). While traditional professional teacher training mostly aims to support teaching to learn a given task and thus evolve from a novice to an expert in a given practice, Engeström (2007) argues that 'Expansive Learning' is – in reference to Lave and Wenger's (1991) original legitimate-peripheral-participation framework – not a one-way movement from incompetence to competence but includes horizontal movement while learners construct new concepts or objects for their activity. Thus "Expansive Learning refers to processes in which an activity system, for example a work organization, resolves its pressing internal contradictions by constructing and implementing a qualitatively new way of functioning for itself" (p. 24). Engeström's (2000) understanding of learning as an expansive process is not a one-way movement from incompetence to competence but includes spiral as well as horizontal movement while learners construct new concepts or objects for their activity. Thus, expansive knowledge creation is concerned with learning of new forms of activities as they are created rather than the mastery of already known and well-defined existing knowledge and skills. Engeström's (2001) Expansive Learning Theory expands Vygotsky's constructivist approach of 'socio-cultural learning' and Lave and Wenger's (1991) ideas of 'situated learning in communities of practice' and assumes that a collaborative knowledge creation approach to learning holds great potential to support individual as well as organisational development. It is mainly concerned with collective learning rather than individual learning and, although it acknowledges spiral learning, Engeström (2000) suggests that "we [should] focus on constructing a complementary perspective, namely that of horizontal or sideway learning and development" (p. 533). It is assumed that an expansive learning environment supports collaborative knowledge creating systems, such as a group of European project partners, to perambulate through cycles of change, which includes seven steps (see Figure 2).

In our case, to ascend from the abstract understanding of inquiry-based science teaching to putting it into practice in a real-world classroom or botanic garden setting, specific epistemic or learning actions need to be achieved. "The process of expansive learning should be understood as construction and resolution of successively evolving contradictions in the activity system" (Engeström & Sannino, 2010, p. 5). Contradictions arise from looking closely at students' learning outcomes while associating them with predefined learning goals. This reflecting on the process of teaching is not only advocated by expansive learning theorists but by many scholars in order to improve teacher development (Dewey, 1938; Loughran, 1996, 2002; Pollard et al., 2008; Regan & Dillon, 2013). However, a real and serious issue for teachers' professional development is the individual participant's ability to capture, portray and share knowledge of practice in ways that are meaningful to others. Teachers engaging in reflective practice, or so-called practitioner inquiry, collect evidence which helps them share their experience and knowledge gained from practice with colleagues in a learning community (Taber, 2007). Practitioners' inquiry is characterised by sharing knowledge in a predominately written format such as reports, case studies, portfolios, online platforms etc. because writing about an experience is considered to be helpful to make individual learning processes explicit. Through reflective practice, professionals develop an understanding about the way they conduct their work and develop and refine their practice to become even more effective. The knowledge base generated helps practitioners better understand what they know and what they learn in practice and therefore supports the emancipation of practice by learning through practice (Loughran, 2002). However, while reflective practice or teachers' inquiry are helpful tools for teachers to share their explicit PSCK, many tacit aspects might be ignored. Accordingly, teachers' inquiry combined with observing each other's praxis is assumed to be a fruitful way to trigger knowledge conversion.

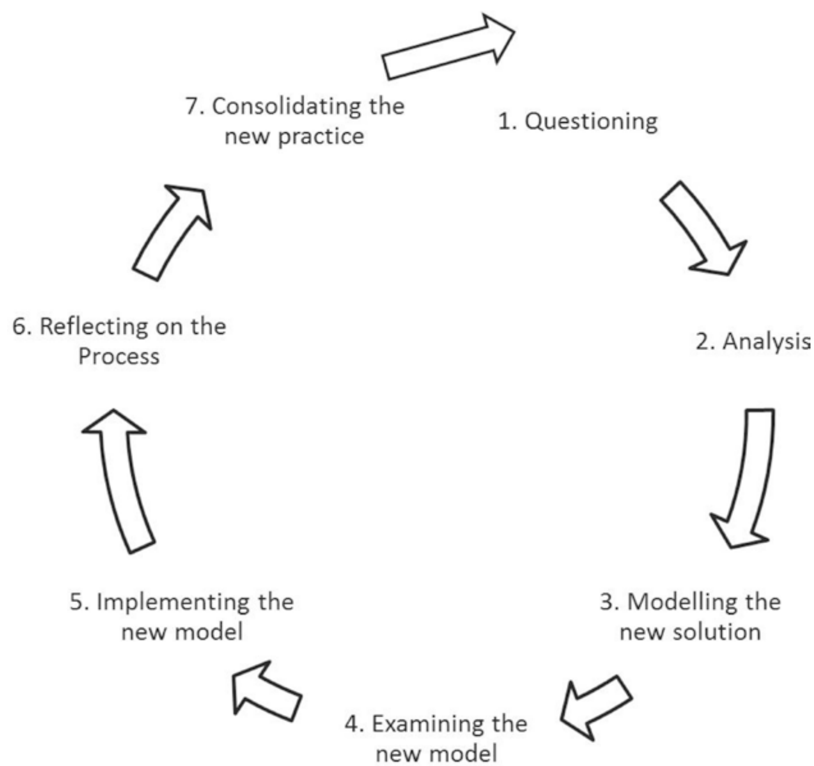

Figure 2. Expansive learning cycle according to Engeström (2007)

CULTURAL PSYCHOLOGY DESIGN-BASED RESEARCH

> Design-based research is premised on the notion that we can learn important things about the nature and conditions of learning by attempting to engineer and sustain educational innovation in everyday settings. Complex educational interventions can be used to surface phenomena of interest for systematic study to better promote specific educational outcomes. (Bell, 2004, p. 243)

Cultural psychology design-based research (CPDR) recognises the influence of the social context in which a particular work takes place. It thus has the potential to contribute to our understanding of learning in complex settings such as those created in an international project. CPDR was applied in this study to learn more about how international educational reform-based projects need to be structured and implemented in order to become successful in ensuring change in educational practice, at schools, as well as at Learning Outside the Classroom institutions. It was assumed that if the members of a particular learning community develop their explicit understanding as well as their tacit knowledge about how to put IBSE into practice collaboratively over time, a collective understanding and experience evolves and becomes collaborative knowledge. Expansive learning (Engeström, 2000) was applied as a framework to interpret the significant steps of transformation that occurred during the project's three-year duration. Traditionally, we would expect that learning is manifested as a change in the subject, in the behaviour and cognition of the individual learner. In this respect, this study challenges the traditional view of learning as an isolated activity in which an individual acquires knowledge from a de-contextualised body of knowledge. According to Engeström (2001) and Paavola and colleagues (2004), expansive learning is primarily manifested as changes in the object of the activity system. Thus, the objects in this study are IBSE lesson plans and the teacher training course design developed and implemented at the different partner organisations. In addition, object artefacts, such as portfolios of evidence, posters, deliverables handed in by partner institutions, as well as knowledge artefacts such as partner interviews, are at the centre of attention when interpreting the consortium partners' sense-making and societal transformation. As such, this more pluralistic and multi-levelled interactional approach offers conceptual tools to achieve a more nuanced picture of the significance of IBST development in the botanic gardens' educational practices. The centre of attention is therefore not put on the individual learner but the organisation as a social unit. According to Engeström's (2001) understanding of third-generation cultural historical activity theory, this unit (Subject) is embedded in a social context (see Figure 3).

Engeström (2001) continues by saying that:

> the object [in our case this is *e.g., a lesson plan*] moves from an initial state of un-reflected situationally given 'raw material' to a collective meaningful object constructed by the activity system [e.g., *the partner institution*] and

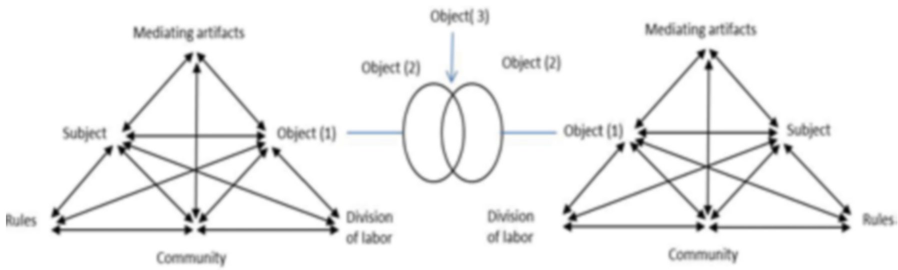

Figure 3. Labour model of Engeström's Third Generation of Activity Theory

finally to a potentially shared or jointly constructed object [e.g., *the best lesson plan published by partners at the end of the INQUIRE project duration*]. Thus the object is a moving target, not reducible to short-term goals. (p. 136)

RESEARCH QUESTION

In exploring the potential to create an expansive learning environment as a framework for supporting botanic gardens in putting IBSE into practice, data were analysed amongst other perspectives to answer the following questions:

- Does the expansive INQUIRE learning environment contribute to sharing and transferring tacit and explicit knowledge about Inquiry-based Science Teaching?
- Does the INQUIRE learning environment enable individual educators to believe they are capable of implementing IBSE in their educational offers?

METHOD: THE INQUIRE LEARNING ENVIRONMENT

The project "INQUIRE: Inquiry-based teacher training for a sustainable future" (EU No. 266616) was one of several initiatives funded by the European 7th Framework programme (2007–2013) Science and Society. This three-year project ran from 2010–2013 and brought 17 partners together from 11 European countries. Fourteen Botanic Gardens engaged in designing and implementing inquiry-based training courses for teachers and botanic-garden-educators on site while improving their own understanding of reflective practice and evidence-based teaching. Course content revolved around contemporary major issues of climate and biodiversity change. INQUIRE efforts were founded on the idea that humans of any age learn more effectively through 'personal inquiry experience with others' than through didactic teaching and telling. Multiple expansive learning cycles were integrated into the INQUIRE project design from the very start in order to develop a new and specific understanding of inquiry-based science teaching at botanic gardens.

The project management never advanced a monological view of the 'one and only best practice model of inquiry-based science teaching' but repeatedly asked the consortium partners to question their understanding of inquiry-based science teaching, to develop lesson plans and model new solutions, examine them in practice and reflect on them not only in their own institutional context but to consolidate their understanding in dialogue with other consortium partners. Partners presented their findings in 'Portfolios of Evidence' which were introduced as a tool to promote reflective practice, share explicit knowledge with colleagues and encourage cooperation. The portfolios were valued as a process that is owned by the partner and was not used for evaluation purposes. They were assumed to support the partners by enabling conditions (Klenowski, 2002). In addition, the partners were asked to do workshops to show others how they put their inquiry-based educational offers into practice or discuss individual experienced gained in small groups and thus collect feedback. To value the fact that expansive learning is a long-term process, a first and a second INQUIRE teacher training course were planned and implemented to provide the opportunity for the partners to adapt their training course design in the light of the experience, reflection and feedback from the network partners and to see whether their new understanding proves successful.

METHOD

In this study, Cultural psychology design-based research was applied. Designing the INQUIRE structure was an explicitly theory-driven activity. The theoretical knowledge mentioned above was taken into consideration to develop the INQUIRE project design and implement a learning environment that has the potential to produce the desired effects. Emphasis was put on the localised nature of individual botanic gardens' IBSE practice and the norms of the social setting in which it was applied. This helped us learn more about whether or not the INQUIRE learning environment was appropriate for the project partners to change their teaching practice as we assumed that they had already developed cultural practices before they joined the project (Kapelari, 2014). The findings presented in this chapter emerged from a case study conducted with two botanic gardens participating in the project. Taking Engeström's (2000) as well as Nonaka and Takeuchi's (1995) knowledge development models into consideration, the focus of this case study is put on the groups'/teams' development.

The analysed data include semi-structured interviews, portfolios of evidence, and artefacts such as a proposed and amended course design, posters, course plans, lesson plans, contributions to the project deliverables and interviews. Lesson plan, poster and course design development was analysed using a rubric based on Bybee and colleagues' (2006) "5E Instructional Model". Thus, this rubric uses the five codes: engagement, exploration, explanation, elaboration and evaluation for labelling phases of activity. Interviews and deliverables were analysed by applying qualitative content analysis with deductive category application (Mayring, 2008).

Case study findings were selected and interpreted in the light of the Final Quality Management Report (QMR, Regan, & Dillon, 2013) published by the project partners from Kings College London, Elaine Regan and Justin Dillon, to get a better understanding of whether particular aspects of this case are representative for the whole INQUIRE consortium. The QMR data analysis did not focus on the same research questions addressed in this case study but some findings allow for comparative interpretation.

RESULTS

The Spanish Team is a group of five people employed at two different Botanic Gardens but forming a discrete activity system in the INQUIRE consortium. The two Spanish institutions are taken as a social unit which acts as the sum of its components. They were chosen for three reasons. One garden was founded more than 260 years ago while the other was founded 12 years ago. In reference to Engeström's activity theory, these two gardens became one activity system in Spain. The history of both educational departments is closely linked and they had been sharing a very close partnership for many years already before they entered the INQUIRE project. Three co-workers were newly employed through the INQUIRE project budget while the two heads of the botanic garden education departments had been working at their institutions for many years already. All project-related work and deliverables were handed in as joint group work and thus cannot be assigned to one institution or the other. Retrospectively, one representative of the Spanish Team explains in the second interview that

> … at the beginning, I didn't know anything about IBSE, I'd just seen a few activities in our botanic garden, they were very practical, but not exactly IBSE, so for me, it was a new topic, so I've developed a whole knowledge, not whole knowledge but from zero to more advanced. (Interview 2, p. 31)
>
> Many partners' knowledge and experience of inquiry-based approaches were limited at the beginning of the project (Regan & Dillon, 2013, p. 50). Thus, the initial starting point for the Spanish Team is representative of the INQUIRE consortium.

To trigger the development of PCK in inquiry-based teaching, the Spanish Team was given opportunities to share lesson plans and gain feedback from other partners three times during the course of the project. The Spanish team handed in a series of lesson plans developed over the course of the three-year project. Not only did they design new lesson plans at a given time in the project but adapted those they had already handed in at an earlier stage. These lesson plans are a visualisation of their understanding of IBST at a particular stage of the INQUIRE project.

The lesson plan analysis shows that the Spanish Team changed their understanding of the role the educator plays in an inquiry-based setting. While early lesson plans refer to the educator or teacher as the person "in charge of the knowledge" and responsible for "explaining the contributions of biodiversity to human beings and to the environment" (Lessonplan 1a, 2011) or "explaining what real scientists do at seed banks"(Lessonplan 1a, 2011) as well as the one who performs the experiments, the final lesson plans ask students to think about how they can use the experiment e.g., to "design another experiment that proves plants absorb CO_2". All five LP3s (Lessonplan 3a-e, 2013) handed in at the end of the project demonstrate an obvious change in the role the students are expected to play in the knowledge gaining process. Students are required to become more responsible for their own learning and frequently design their own experiments to prove their hypothesis. Instructions contain advice such as asking the "How could you prove it? Encourage them to use the material you provide in order to design their own scenario and check how water acts on different types of soil" (Lessonplan 3d, 2013). Learners are asked to explain their knowledge right from the start and formulate hypotheses. Taking all the lesson plans into consideration, the Spanish Team obviously developed their understanding of good IBSE teaching in terms of 'Instructions – Scaffolding', 'Quality of Questions', 'Number of alternative approaches to solve a problem' and 'Emphasising a systematic scientific approach' (Bybee et al., 2006). The partners do not refer to this development explicitly in either the interview nor in their portfolios of evidence. Thus, these lesson plans presumably provide an insight into their implicit PSCK development.

However, the Spanish Team explicitly mentioned that they had become aware that IBST needs to find a balance between an open/unstructured and a closed/very structured approach and mentioned teachers recognising this in the course of the training programme.

> The beliefs of the teachers have changed a lot from the beginning of the course. For example, the most significant discovery was that most of them thought that IBSE was chaotic and disorganised at the beginning, but their answers completely changed when they were asked the same question at the end of the course. (Portfolio 2 Case Study, p. 10)

The Spanish Team values their reflective practice and sees sharing their findings with the learning community as important for their own benefit. "Moreover, we took into account the suggestions and ideas from the National and Regional Education Authorities, the Advisory Group and other INQUIRE Partners. These improvements consisted of improved lesson plans and conferences given by experts and invited teachers" (Portfolio 2 Case Study, p. 10).

They appreciated the new ideas introduced not only by the consortium partners or advisory group members but by the teachers participating in the training course. This explicit knowledge was valued and as soon as it was shared at meetings and via lesson plan publications it became INQUIRE consortium knowledge.

> I remember that during the final discussion, this was a big issue, the evaluation methods, and they [teachers] even suggest new methods and they were helping

> each other with very quick methods and they were very inspiring, for us too. (Interview 2, p. 12)

The Spanish Team explicitly values the reflective approach to designing and implementing the educational offer as well as sharing their experience with consortium partners. They mention in their portfolio of evidence outcomes that emerge spontaneously from this process.

> The impressions of the Spanish team are that through gaining experience in organising the courses, in the last course we have felt much more confident and prepared than in the first one. Attending the Inquire meetings and getting feedback from other partners was also crucial to increasing the inquire skills. (Portfolio 2, p. 4)

Gaining experience and reflecting on outcomes led the Spanish Team to put more emphasis on particular learning phases.

> The balance between theory and practical activities was basically maintained, but in the second and third courses the practical activities had much more space for teachers' comments and were continually compared to the IBSE learning cycle so that every step of the activities would fit on it. (Portfolio 2, p. 3)

Some ideas and approaches shared by the partners during these contact sessions were ignored; however, several were copied or adapted for the partners' own purposes. The idea of investigating different types of honey, which was finally published as the Spanish lesson plan: "Do we know what we eat?" was presented by another partner during an earlier stage of the project in a different context and was then adopted by the Spanish Team as a starting point for developing their own approach to teaching plant diversity. In contrast, an experiment introduced by the Spanish Team that visualises CO_2 gas qualities was used in IBSE activities developed by others.

The Spanish Team explicitly valued the opportunity to visit each other's institutions and observe others 'doing' their work.

> Ideas, not only about the inquiry-based learning but visiting each other in our gardens and institutions gives us the opportunity to see how […as I] said before, how other people work in a botanic garden, maybe they have very different ways to do things but still we have always something to learn. (I2/2013, p. 30)

They take advantage of participating in the INQUIRE learning community.

> The INQUIRE courses have definitely been very positive for both institutions as they have helped to grow the teaching role of the Botanic Gardens. They also served as a link to connect formal and non-formal education. In addition, we have learnt a lot from our collaboration between both the Botanic Gardens and between other INQUIRE Partners. (Portfolio 2 Case Study, p. 12)

In addition, organisational learning took place, as was recognised by the partners as such and mentioned explicitly.

> The staffs of the Botanic Gardens have gained a lot of experience and we will try to continue running these courses in the future because we have raised and improved our contact and understanding with teachers. It has been also positive not only for the education team but for the rest of the staff who have been involved in the development of the courses, meetings, dissemination plan, conferences etc. (Portfolio 2 Case Study, p. 12)

PSCK used in IBST is now embedded in educational programmes/lesson plans and routines and attests to the partner's growth. Although not done before, developing written lesson plans to share the knowledge amongst educators in the same organisation became a new strategy to improve the educational practice in both gardens.

> because [writing lesson plans] it's hard work, I mean, we have lesson plans for everything we make, so we have [over talking] I mean, it's something we have to do from now on. (Interview 2, p. 28)

This knowledge enables the partners to use these resources accordingly as well as to improve their education programmes in the future. Nevertheless, the partners realise that there is still room for improvement. Learning and sharing knowledge needs to continue in the future.

> yeah, for me as well. I think like we've spent three years learning, learning, learning and practising a bit and we will need at least another three years, put in practice a lot, a lot, a lot and then getting back to, so [I don't feel to be already] an expert [in IBST] really. (Interview 2, p. 31)

However, after three years, the Spanish partner feels confident and competent about running IBST teacher training courses successfully.

> Throughout the whole reflection, we are positive we can conclude that there has been a clear improvement in the practice of the courses from the first one. (Portfolio 2, p. 11).

DISCUSSION

Although practical experience is valued in education research, the focus is mainly put on explicit knowledge gained from theory and practice while the tacit knowledge applied by practitioners is often neglected.

With reference to organisational development research, Brown and Duguit (1991) argued that

> in a society that attaches particular value to 'abstract knowledge', the details of practice have come to be seen as nonessential, unimportant, and easily

> developed once the relevant abstractions have been grasped. Thus education, training, and technology design generally focus on abstract representations to the detriment, if not exclusion of actual practice. (p. 40)

> Even if knowledge has been articulated into words or mathematical formulas, this so called explicit knowledge must rely on being tacitly understood and applied. (ibid., p. 360)

The history of inquiry-based science education and efforts to implement modern science teaching in the USA and Europe have already shown how problematic an approach is that does not value both the implicit and explicit aspect of science teaching. Science education research literature is quite clear about the fact that we still do not know much about how to teach inquiry in everyday science classrooms and the concept of inquiry-based science education is still not well understood by researchers or practitioners alike (Capps & Crawford, 2013; Anderson, 2002; Minner et al., 2007). In terms of PCK applied in inquiry-based science teaching, (IBST) research has shown that different views on inquiry teaching are based on different views of 'science inquiry', 'science learning' or 'attitudes to students and their ability to learn science'. It is also widely accepted that teacher beliefs about teaching, learning and the nature of science can influence their practice (Hogan & Berkowitz, 2000). Presumably, those more or less tacit aspects of understanding or misunderstanding inquiry practice contributes to research findings that practitioners think they are teaching inquiry even if they are not (Capps & Crawford, 2013).

Building on the Model of Knowledge Conversion (Nonaka & Takeuchi, 1995) and the Model of Expansive Learning (Engeström, 2001), the INQUIRE project was developed to establish a methodology which explicitly values both stages of PCK – the tacit and the explicit. The multicultural collaborative expansive knowledge creation process (Engeström & Sannino, 2010) established in INQUIRE can be explained by the interaction of tacit and explicit knowledge about IBST available in the consortium. Because different people hold various types of tacit and explicit knowledge and they apply their knowledge in unique ways, multifaceted knowledge, experience and creativity were contributed through scientists, education researchers, botanic garden educators, teachers, horticulturalists and others who joined the INQUIRE consortium. All of these different people shared their knowledge and experience and accounted for horizontal as well as vertical learning. Not only did the consortium repeatedly go through spirals of action, reflection and revision of explicit knowledge but tacit knowledge about IBST was transformed via spirals of socialisation, externalisation, combination and internalisation (Nonaka & Takeuchi, 1995). Knowledge transformation took place whenever inquiry-based activities were presented in consortium meetings and discussed with partners in feedback sessions. Although tacit knowledge is difficult to detect by novice learners, research has shown that a more experienced eye releases different facets more easily (Venkitachalam & Bush, 2012). While giving feedback, the partners not only addressed the explicit

PCK presented, but discussed aspects of how this knowledge was enacted. Nonaka and Takeuchi (1995) termed this phase socialisation.

Although the Spanish partner did not mention in the interview what they had explicitly learned from meeting the partners , they regard them as most valuable because "visiting each other in our gardens and institutions gives us the opportunity to see how [...] how other people work in a botanic garden" (Interview 2/2013, p. 30). Observing others doing something in a particular way may either lead to realising a particular aspect explicitly and/or adopting others implicitly. Therefore, it was important that this first phase was followed by an externalisation phase to conceptualised tacit knowledge by means of presenting lesson plans and discussing a commonly accepted definition of IBST to be published on the project website. Explicit knowledge about IBSE evolved while it was continuously discussed in a series of consortium meetings. Individual/organisational knowledge was combined with knowledge gained from research literature or another external source. Some knowledge conversion finally reached the fourth phase that is called internalisation and is characterised by absorbing the explicit knowledge gained in the project so that it becomes tacit again. Document analysis showed that lesson plans provide evidence of continuous knowledge development in terms of 'Instructions – Scaffolding', 'Quality of Questions', 'Number of alternative approaches to solve a problem' and 'Emphasising a systematic scientific approach'. However, the interviews showed that even at the end of the project it was still difficult for the partners to find the words to explain their individual understanding of IBSE properly. This may count as a tacit understanding of IBST which has either been taken over intuitively or was explicit at a particular stage in the project but became tacit again as IBST was implemented in the partners' educational repertoire.

Critiques of this model argue that, by integrating the four basic processes of knowledge dynamics into a pattern of knowledge conversion, "Nonaka is blurring the line between individuals and groups" (Bratianu, 2010, p. 195). However, Nonaka and Takeuchi's (1995) model of Knowledge Conversion focuses on organisational learning which inevitably leads to understanding knowledge transformation not only at the individual level but also at the group and organisation level as well as the level between organisations and thus values learning as a situated and social process.

Engeström (2000) argues that individuals and groups are never single islands floating in the sea but always embedded in an activity system that exerts an influence on the individual or group which may be experienced explicitly or implicitly.

With respect to teaching science as inquiry, some tacit knowledge that IBSE experts hold may result from a process of enculturation in a particular social community while being educated as a scientist or a science teacher in a particular country. This tacit knowledge of 'how to do science' may be interpreted by members of these communities as common-sense knowledge and is put into practice intuitively. Teachers who may not have a science education background and/or may lack this common-sense may have difficulties interpreting what they observe while participating in IBSE pre- and in-service training. It might become even worse if the latter apply readymade teaching material in class. Thus, the INQUIRE project design valued Expansive Learning Processes (Engeström, 2001) and did not focus on Lave and Wenger's early understanding of situated learning which was seen as a "predominantly vertical movement from the stage of incompetence to competence, with little serious analysis devoted to horizontal movement and hybridization" (Engeström & Sannino, 2010, p. 2). Shulman and Shulman (2004) noted that ongoing interaction between an individual professional and the community leads to shared knowledge of the team/organisation which finally offers members the opportunity to confirm, interconnect and develop their professional knowledge. Van Aalst (2003) and Van Driel and Berry (2012) highlight the importance of including experts in the field when it comes to maintaining communities of learners because these people help the group to speed up their learning process. Experts were therefore asked to inform the INQUIRE community in two areas of knowledge development: Scientific background knowledge about "biodiversity loss and climate change" and Science Education Research based knowledge about IBSE, Reflective Practice, Teachers' Professional Development and Assessment. The discourse and different views of the practitioners and researchers served to enhance the process of reflection and to expand the horizon, understanding and capabilities of both agents. Looking at the research literature and outputs of initiatives pursued to implement inquiry-based science teaching and learning all over the globe, it seems likely that tacit knowledge about how to teach inquiry-based science might have been underestimated so far.

CONCLUSION

The aim of this article was to draw attention to tacit PCK and tacit PCK conversion as a source of innovation and horizontal learning in collaborative learning groups. Van Driel and Berry (2012) argue that "programs aiming at the development of PCK, like other recent forms of professional development, should be based on constructivist and situative theories rather than on behavioural approaches" (p. 27).

The INQUIRE design reflects such a constructivist and situative approach and proved to be successful in various aspects.

It is high time to overcome the idea of focusing on abstract understanding of IBSE first to make it work in practice later but to look more closely at what teachers or educators actually do when they think they are implementing inquiry-based learning (Grangeat, 2013). It might be more fruitful to start from there and to engage practitioners in expansive knowledge creation to enhance our research as well as a practice-based understanding of good science teaching. As individual learners, practitioners are embedded not only in a socio-cultural but an organisational context and thus are embedded in activity systems resulting in the division of labour (Engeström, 2001). This has an impact on how new ideas are perceived and put into practice. Organisational development was thus the focus of this study. While discussing knowledge creation in a European project, this paper tried to develop a framework that enables science education researchers to recognise the distinctive challenges and insights associated with the work pursued in organisational research. The accommodation of comprehensive approaches can help create space for experimenting with different permutations of concepts, methods, data and interpretation in the processes of teaching and learning and to learn more about how professional development offers need to be designed to support teachers and learning outside the classroom educators in improving their practice.

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Suzanne Kapelari
Austrian Education Competence Center Biology
University of Vienna, Austria

PERNILLA NILSSON

9. LEARNING FROM A LEARNING STUDY

Developing Teachers' PCK through Collaborative Practices

PEDAGOGICAL CONTENT KNOWLEDGE IN FRAMING TEACHER KNOWLEDGE

The inherent complexity of teacher knowledge, and hence teacher learning, has been well documented in science education research literature (e.g. Nilsson, 2008; 2014; Loughran, Mulhall, & Berry, 2006). In order to teach science in ways that promote students' understanding, Shulman (1986, 1987) claimed that teachers need pedagogical content knowledge (PCK), a special kind of knowledge that teachers have about how to teach particular content to particular pupils. PCK was originally developed to represent one of the professional knowledge bases that an expert teacher possesses, and was later described as representing "the blending of content and pedagogy into an understanding of how particular topics, problems, or issues are organized, represented, and adapted to the diverse interests and abilities of learners, and presented for instruction" (Shulman, 1987, p. 8). Hence, PCK has become a way of understanding the complex relationship between pedagogy and content through an integrated process rooted in classroom practice (Van Driel et al. 1998).

Schneider and Plasman (2011) noted that PCK is a "heuristic for teacher knowledge that can be helpful in untangling the complexities of what teachers know about teaching and how it changes over broad spans of time" (p. 533). According to Park & Oliver (2008), PCK development means the development of individual components of PCK or the integration of these components to linking one with another. Another approach to conceptualising PCK is to explore all the components in a model, like in the study by Park and Chen (2012). The authors used a pentagon model (Park & Oliver, 2008) comprising five components: (a) Orientations Toward Teaching Science; (b) Knowledge of Students' Understanding in Science; (c) Knowledge of the Science Curriculum; (d) Knowledge of Instructional Strategies and representations; and (e) Knowledge of Assessment of Science Learning. Park and Chen (2012) argued that understanding the interactions between the components of broader PCK would foster the development of a more holistic perspective of the construct, something that is also useful for our thinking about the linkage between the different knowledge bases that together comprise PCK.

Ever since Shulman established the concept, many researchers have come to believe that PCK is an important topic in science education, and that high levels of

M. Grangeat (Ed.), Understanding Science Teachers' Professional Knowledge Growth, 155–168.

PCK will predict high levels of student achievement (Abell, 2007). In her review, Kindt (2009) noted that if we can identify PCK as the knowledge a teacher uses in the teaching process, our understanding of what 'good science teaching' looks like and how to develop this more consistently might be enhanced. Yet, since few concrete examples of PCK exist in the literature this has been a difficult task (Nilsson & Loughran, 2012). The varied perspectives on PCK have, however, strengthened the value of the construct in many ways, in particular for implementation in science teacher development programmes (Abell, 2008).

But how can teachers develop their understanding of PCK in order to make a difference in students' learning? And what is the linkage between teachers' more general knowledge (often defined as pedagogical knowledge, PK) and the topic-specific pedagogical content knowledge (PCK)? Although there is no universally accepted conceptualisation of PCK, there seems to be a consensus that PCK is to be distinguished from subject-matter knowledge (CK) on one hand, and from general pedagogical knowledge on the other. It is reasonable to suggest that PCK goes beyond subject matter knowledge (SMK) as it not only refers to the subject matter but also to the teaching of a subject in ways that promote students' understandings. Hence, a teacher needs to have deep knowledge of content (CK), as well as pedagogical knowledge (PK) and an orientation towards teaching content to students in a specific context. Despite the numerous definitions described above, there is little doubt that the complexity of teaching highlights the need for more extensive research into the relationships between the different elements that constitute teacher knowledge, and how these are developed and supported.

One way for teachers to develop their professional knowledge with a focus on specific science content and the ways students learn such content is through being involved in researching their own practice in a learning study (Marton, 2014; Marton & Pang, 2006; Pang & Ling, 2012; Runesson, 2008). A learning study is a collegial process in which teachers work together with a researcher to explore their own teaching activities in order to identify what is critical for their students' learning. In a learning study, the conditions for students' learning are identified and reflected upon. Such awareness is important in terms of PCK as it focuses on the relationship between the content, the teaching and students' learning. A learning study is a cyclical process (see Figure 1) in which teachers reflect on the necessary conditions for learning a specific content and how to meet these conditions in the learning situation.

This chapter aims to renew the perspectives about the linkage between PK, SMK and PCK by referring to a project in which three teachers were engaged in collaboration and critical reflection on their teaching of science in a learning study. It stresses that teacher collaboration, and particularly interactions between teachers, may underpin the development of PK, CK and PCK. The research question that frames the study is: "How does science teachers' learning about science teaching (PCK) develop as a shared practice by participating in a learning study?". As such, the project aims to investigate how teachers' professional knowledge of teaching is enhanced and, further, how students' learning might be developed as a consequence.

With its particular focus on *learning,* a learning study differs from the Japanese lesson study (Lewis, Perry, & Murata, 2006; Yoshida, 1999) where teachers can test hypotheses about good instruction, experiment with classroom practice, collect and analyse data from the classroom and thereby use the classroom as a laboratory for learning. Lewis, Perry and Hurd (2009) examined a lesson study in the USA and reported on teacher changes in motivation and capacity to improve instruction, in mutual accountability, shared goals for instruction and a common language for analysing instruction. However, the extent to which such experiences have impacted on the individual teacher's classroom practice outside the community of practice is seldom reported. In a modified version – the learning study (Marton & Pang, 2003) – in which the teachers in the current study participated, has an additional element to assess how their actions affect *learning* (teachers and students) as an effect of teachers' collaboration and critical reflections. Therefore, an important aspect of the learning study is that it pays attention to how the teachers' collective construction of professional knowledge is enacted by making a shift from professional development as something that is done *to* the teachers toward considerations of professional *learning* which entails the work *with* and *by* teachers in collaborative settings (Nilsson, 2014).

COLLABORATIVE REFLECTION TO STIMULATE THE DEVELOPMENT OF TEACHERS' PROFESSIONAL KNOWLEDGE

Even though the development of PCK is well explored in the research literature, there is still more to be presented on how it can be developed and enhanced through different forms of collaborative reflections. In this section of the book, all three authors highlight collaborative reflection as a way to make the tacit knowledge of teachers explicit. The chapter by Isabelle Kermen addresses how experienced and beginning teachers work together to develop their professional knowledge by sharing and discussing their lesson plan and goals before implementing them. Kermen also describes the importance of collective reflections on classroom teaching in order to analyse teachers' choices and actions and the students' behaviour.

Through a careful reflection on the combination of PK and PCK, Michel Grangeat's chapter indicates how teachers' professional knowledge can be strengthened through teaching experience, professional development and teacher collaboration. In the chapter, teachers are interviewed about a videotaped lesson they have just carried out. The study leads to support the idea that teacher involvement in a collaborative setting entails a set of professional knowledge that is more balanced between general and content-specific and more open to learners' needs and interests.

Suzanne Kapelari reports on design-based research applied in a European project that valued the innovative potential of making tacit knowledge explicit while aiming to improve the practitioner's ability to teach science inquiry. In her chapter, Kapelari focuses on how PSCK development was supported by focusing on the interaction between tacit and explicit knowledge embedded in reflective learning cycles. The on-going interaction between individual professionals and the community led to shared knowledge of the group which finally offered the participants the opportunity to confirm, interconnect and develop their professional knowledge. All three chapters provide evidence of how collaborative settings among teachers might contribute to the development of pedagogical knowledge as well as pedagogical content knowledge for science teaching.

Recently, in their argumentation on teachers' professional development focusing on PCK, Van Driel and Berry (2012) highlighted the importance of "forms of professional development for teachers that are built on collaboration, collegial interaction and the fostering of relationships" (p. 26). These arguments are strongly supported in the international discussion on building teacher professional knowledge coming out of the recent THALIS report from the OECD (2015). For instance, Schleicher (2015) reports how collaboration among teachers, whether through professional learning or collaborative practices, is related to higher levels of both self-efficacy and job satisfaction. In particular, teachers who report that they participate in collaborative professional learning activities five times a year or more also report significantly higher levels of self-efficacy (in almost all countries) and greater job satisfaction (in two out of three of the participating countries/economies).

Although an increasing number of professional development activities for teachers are structured around collaboration, more evidence is needed on the conditions for successful collaboration and the development of teacher knowledge related to collaborative practices. Yet researchers have described a myriad of different structures and processes to create a collaborative culture among teachers in schools (Erickson et al., 2005; Nelson et al., 2008). Empirical evidence shows that collaboration among teachers may enhance their efficacy which, in turn, may improve student achievement and sustain positive teacher behaviours (Liaw, 2009; Puchner and Taylor, 2006). In a meta-review of empirical studies, Cordingley et al. (2003) reported that collaborative professional development is related to a positive impact on teachers' range of teaching practices and instructional strategies and to their ability to match these to their students' needs. Further, Harrison et al. (2008) suggested that effective professional development needs to provide an opportunity for teacher reflection and learning about how new practices can be developed or shaped from existing classroom practice. This requires teachers to re-examine what they do and how they might do it differently (Harrison et al., 2008). There is also evidence that collaborative professional development activities are linked to a positive influence on student learning processes, motivation and outcomes. For example, Hattie (2009) argued that teachers' professional knowledge of teaching (i.e. PCK) is the most crucial factor for student learning.

According to both research and policy, there is no doubt that learning about and understanding the complexities of teaching is important. Desimone (2009) stated that teachers experience a range of activities and interactions that may increase their knowledge and skills and improve their teaching practice as well as contribute to their personal, social and emotional growth as teachers. As professional learning is personal and appropriately shaped and directed by each of us as individuals (Loughran, 2010), teachers themselves must be committed to changing their own practice. Teachers' professional learning requires opportunities for teachers to be engaged as learners and to further reflect on how the process of framing and reframing practice might result in a personal understanding that can be translated in their own context. Introducing and exploring the academic construct of pedagogical content knowledge (PCK) is one way in which these complexities and the relationships between PK, CK and PCK can be explored. By having teachers involved in a study that forces them to explicitly engage with and explore their own developing PCK, it is envisaged that they might develop a deeper conceptual understanding of what it means to teach and learn, and ultimately lead to a heightened awareness of the complexities of teaching. This aligns well with Van Driel and Berry (2012) who argue that providing teachers with specific input (e.g. to collectively reflect on key notions of teaching and learning a specific topic) can contribute to their PCK.

CONTEXT OF THE LEARNING STUDY

During one semester, three secondary science teachers and a science education researcher (the author) worked together in a learning study in which the object of learning was to understand the concept of ion and how ions are formed. The students were in grade eight (aged 14–15) and had previously been taught about the atom and the atomic structure, but not yet about ions. All three teachers were experienced science teachers, had worked together for several years and had volunteered to participate in the project. During the learning study, data were collected from video-recorded lessons and stimulated recall sessions in which the teachers and the researcher reflected on the lessons to analyse how the teachers developed knowledge of students' learning and the impact of that knowledge on their own teaching. The learning study started with the teachers identifying the 'object of learning' (ions and how ions are formed). Then, the students' prior knowledge and their existing perceptions were investigated with a pre-test. The teachers, together with the researcher, then analysed the test to provide an insight into how students experience what is to be learned and that which is critical (critical features) in order to learn about ions and how ions are formed. The variation in how the students experienced what was to be learned then became a source of planning the first lesson. Following that, the first teacher conducted the lesson (lesson 1) that was video-recorded.

After the lesson, the students were given a post-test in order to provide an insight into how the students' understanding of the object of learning had changed (or not) after the instruction. The three teachers and the researcher collaboratively analysed the video-recorded lesson (lesson 1) together with the pre- and post-tests in a stimulated recall session (Nilsson, 2008, 2014) in order to share their experiences of the lesson with a focus on evidence of student thinking and analysis of the teacher's instruction. Then, in the next phase of the learning study the second teacher conducted the (revised) lesson with his/her class (lesson 2) and the same procedure with analysis of the lesson and the post-test was repeated. Finally, the third teacher conducted the (again revised) lesson with his/her class and the lesson together with the post-test was analysed. As such, the learning study was an iterative process of planning, analysing and revising a lesson with the aim to improve both the students' and teachers' learning.

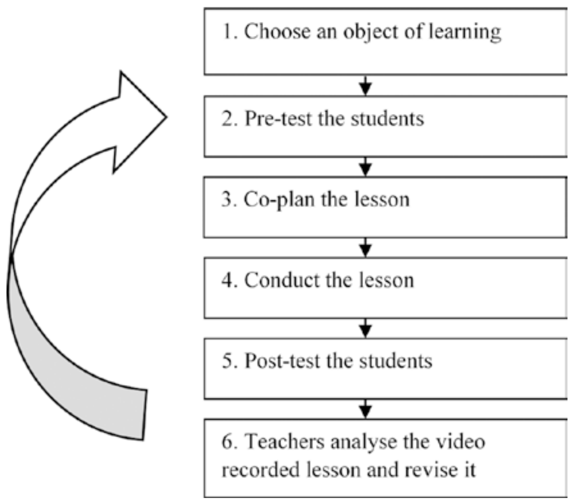

Figure 1. Steps in the learning study

In the learning study, the researcher's role was to stimulate the teachers to identify and communicate important aspects within their teaching and encourage them in their planning and revising of the lessons. The learning study lasted for almost a whole semester and the team had five meetings to plan, analyse and revise the specific lesson on ions. There was also a final meeting to discuss the findings and what the teachers had learned from the project. Every meeting lasted for about two to three hours.

- *Meeting 1*: Discussing the object for learning and designing the pre-test
- *Meeting 2:* Analysing the pre-test and planning the lesson
- *Meeting 3:* Analysing the post-test and stimulated recall reflection on lesson one to revise the lesson
- *Meeting 4:* Analysing the post-test and stimulated recall reflection on lesson two to revise the lesson
- *Meeting 5:* Analysing the post-test and stimulated recall reflection on lesson three
- *Meeting 6:* Final reflections on the whole process

The data analysis involved two steps. First, and most importantly, the video-recorded PCK test-lessons were analysed with a sharp focus on how the teachers enacted the specific content in the lesson and how their teaching had changed (or not) between the two lessons. Second, the transcribed tape recordings were analysed through content analysis (applied in the way described by Miles & Huberman, 1994) in order to identify changes in the teachers' ways of reflecting on their teaching. A content analysis of this kind is based on the view that it facilitates the production of core constructs from textual data (e.g. a systematic method of data reduction; data display; and conclusion drawing and verification). Through content analysis, data from all six meetings were read repeatedly in order to identify recurring themes and produce thick descriptions (Miles & Huberman, 1991; Geertz, 1973) of the experiences, tensions and emotions raised by the teachers.

RESULTS

To give an insight into how the teachers developed different aspects of their PCK during the process (meetings 1–6), the three categories that derived from the data are presented below.

To Focus on the Content and Identify Critical Features for Students' Learning

During the first meeting, together with the researcher the teachers carefully discussed the object of learning and questions such as: what does it mean to know about ions, why is it important for students to learn about that specific object, which difficulties and limitations do students usually experience when learning about the object, and which features do students need to identify in order to understand the ion and how ions are formed (i.e. the critical features). In the discussions, the teachers highlighted several concepts they considered as crucial for students' understanding of the object. One such concept was the relationship between the energy level of an electron and its principal quantum number. Another critical feature included the atomic structure and how the ionic charge varies depending on the number of valence electrons. Further, that ionisation energy depends on the number of electrons and that the nucleus with protons and neutrons remains unchanged even though the number of electrons changes. Finally, the students needed to identify the principles of the periodic table and how atoms with one or two valence electrons more or less than a closed shell are highly reactive as the extra electrons are easily removed or gained to form positive or negative ions.

> T2: If we think of ions and atoms, we cannot explain what an ion is without having an understanding of the particles, electrons and protons. The important thing is that they see the differences and relationships between the ion and the other concepts that are critical for understanding this … for example, the atomic structure.

T1: And really, one cannot talk about this without talking about the periodic table. Why are there ions with minus and plus, what are the differences and the relationships as well? What we can do in the lesson is to show both an ion and an atom to make them notice that both of them have a nucleus of protons and neutrons, both of them have electrons orbiting the nucleus, but the difference between these two is that the number of electrons varies. (Meeting 1)

This discussion emphasised the importance of making students focus on critical features and the *difference* between an atom and an ion instead of only focusing on the ion alone. In terms of PCK development, identifying the object of learning and its critical features offered access to the way in which the teachers conceptualised the topic as a whole and, hence, became an important aspect of articulating the teachers' PCK. When the teachers collectively began to unpack their content knowledge in this way, it helped them develop a clear conceptualisation of the subject area, both for themselves and their students. In so doing, the participants began to think about linking content and pedagogy in new ways that may well be a catalyst for developing PCK.

To Challenge Students' Ideas and Difficulties within Teaching

In order to identify students' preconceptions and previous knowledge of the object of learning, the three teachers designed a pre-test consisting of six questions. The test paid attention to the critical features for understanding the object of learning such as the atomic structure, understanding of the periodic table and the difference between a substance and an element. In the analysis of the pre-tests, several issues concerning students' existing understandings were raised. For example, the students did not understand the relationship between an atom and a molecule and did not know about the structure of an atom. Further, the students had difficulties distinguishing the concepts chemical "substance" and chemical "element". Likewise, they had difficulties seeing the connection between the atomic, molecular and elemental structure. The pre-test also indicated that the students had problems understanding how the number of electron shells influenced the atom's reactivity. These difficulties (and ways to approach them within the lesson) were carefully discussed by the three teachers and the researcher. Finding ways to illustrate the difference between elements in the same group, with the same number of valence electrons in their atoms but with different numbers of shells, became an important teaching strategy.

T1: All substances in group eight have a noble gas structure but if you look at them you see that they have a different number of shells. This is a great opportunity to make the students identify what they have in common and what separates them. They are in the same group and have the same number of valence electrons but they have different numbers of shells. So we can use a demonstration with lithium, sodium and potassium to make the students see the relationship between periods and groups and introduce the concept of noble gas structure. (Meeting 2)

As such, the co-planning of the lesson helped the teachers develop their ideas on how to challenge the students' identified difficulties and conceptions in a way that should most effectively promote the students' understanding of the object of learning. The teachers came to see that only small variations in their teaching and students ways of discerning critical features of the object of learning made a crucial difference in the students' learning. As such, the result of the pre-test gave the teachers a better insight into aspects of the students' learning they needed to approach in order to teach effectively.

To Identify and Analyse Critical Aspects of a Teaching Situation and to Make Qualitative Assessments of Student Learning

Identifying that which makes it easy or difficult to learn a specific content is a crucial aspect for a teacher's PCK. As such, when analysing the pre-tests the teachers' taken-for-granted assumptions were clearly challenged in a way that forced them to reconsider their planning. In the analysis of the post-test and the first lesson (lesson 1), it was clearly indicated in the students' responses that they still had difficulties distinguishing between an atom and a molecule, a chemical element and an atom but also between an element and a substance. Hence, the teachers realised that they needed to put a stronger emphasis on these aspects and also stimulate the students to identify the difference between the properties of chemical elements in the periodic table. As such, the analysis of lesson one gave the teachers important information on how the students experienced the teaching and what they needed to revise in order to better meet the students' learning needs.

When analysing the video of the second lesson (lesson 2), the teachers noticed that even though they had revised several aspects from lesson one, the second version of the lesson was experienced as much ´busier´ and messier and the results in the post-test were not as the teachers would have expected. The teachers' taken-for-granted assumptions (e.g. that the students understand the atomic structure and the relationship between a chemical element and a substance) was challenged already in the first lesson and the teachers came to understand that the complexity of the content was greater than they had thought in their planning. When the teachers analysed the video from lesson two, they became aware of how many students seemed to believe that the electron shell protects the nucleus of an atom in the same way as a banana peel protects the fruit itself. In their discussions, the teachers highlighted the notion of 'occupied words' as something that seemed to make it difficult to learn a specific concept. Building on the insights from lesson one and lesson two, the third lesson put a stronger focus on the object of learning and teacher three (T3) introduced the lesson with the question "What is the difference between an atom and an ion?". As such, a key insight from analysing the three lessons was about presenting concepts individually or together, to focus on different aspects of the content and not just on one aspect at a time. In their final reflections, the teachers highlighted that small variations in the way they approached the content within their teaching proved to play a crucial role in the students' understanding. They also became aware of the importance to vary the different ways to represent the content (learning object) with various metaphors and experiments, but also to reflect on their use of metaphors and how these can cause confusion if not used correctly.

> T1: I have never thought like this. It is obvious for me what a substance is, but how can I convey this to my students? As a teacher, I think the hardest challenge for us is to transform our own knowledge to students' understanding and to really focus on the object of learning and not a million other things in the same lesson. (Meeting 6)

For example, restructuring the lesson, clarifying differences, similarities and relations between concepts, taking things in a different order or reflecting on their use of concepts in the teaching situations were all features that made a difference in the students' learning. What became clear for the teachers in terms of instructional strategies was that restructuring the lesson, making the abstract concrete, clarifying differences, similarities and relations between concepts but consequently, not presenting too many concepts at the same time, taking things in a different order or reflecting on their use of metaphors and concepts in the teaching situations were all features which created a difference in the students' learning.

DISCUSSION – LEARNING FROM THE LEARNING STUDY

> What is it that a teacher knows and is able to do that a specialist in the subject matter that that teacher is teaching, no matter how smart they are, doesn't understand and can't do? (Shulman, quoted in Berry, Loughran, & Van Driel, 2008, p. 1275)

This study pays attention to this question by focusing directly on how teachers handle and organise the content in order to promote students' learning. Recently, in their argumentation on teacher professional development focusing on PCK Van Driel and Berry (2012) stressed the importance of "forms of professional development for teachers that are built on collaboration, collegial interaction and the fostering of relationships" (p. 26). This study is an example of such an approach to understand teacher professional learning through a careful investigation of how teachers' professional knowledge of teaching (PCK) is enhanced by their participation in a learning study and, further, how students' learning might be developed as a consequence. It points to the particular role of research-based learning in providing an opportunity for teacher learning as a metacognitive lens through which to view the task of science teaching in the secondary classroom. The study indicates that the teachers' participation in the learning study proved to be helpful in their (re) considerations of their science teaching. It also challenges the taken-for-granted assumption that ‘if you teach – students learn’. Research about the effects of a learning study supports the conjecture that the students’ learning increases from lesson one to lesson three (see e.g., Marton & Pang, 2006; Runesson, 2006, 2008). However, an important aspect of this study is that, for lesson two, the students’ results decreased, something that forced the teachers to reconsider their taken-for-granted assumptions and pedagogical decisions. Further, as Nuthall (2005) noted, teachers commonly attribute failure in student learning to the students’ lack of ability or motivation, rather than to their own teaching. Participation in a learning study challenges this view as the focus is moved from more general aspects of pedagogy to content-specific aspects of teaching and learning. The study contributes to the teaching and learning of science as it points to the particular role of research-based learning in providing an opportunity for ‘learning practice’ as a metacognitive lens through which to view the task of science teaching in the secondary classroom. During the learning study process, the teachers developed their self-understanding in which they questioned their own epistemological beliefs, aims and objectives of teaching and taken-for-granted assumptions about science teaching and learning. An important implication of this project is the importance of teacher professional learning as a collective process in which teachers and researcher(s) together explore students’ learning in relation to science teaching.

The message inherent in this project is the potential to positively focus on teacher collaboration in developing science teachers’ professional learning in ways they personally value. Therefore, an important consequential activity is the ability to develop a framework of quality in-service science teaching that builds on the ways in which, through collaboration and reflection, teachers play an active role in understanding and developing their PCK. This project highlights that participating in a learning study is an important vehicle for supporting science teachers’ competence in teaching as it allows them to identify strengths and weaknesses in a continuous, non-threatening way. By stimulating teachers to research their own practice, teachers are helped to identify the complexity of teaching and further become aware of what they need to do to improve their teaching and learning practices.

Shulman (1987) noted that developing PCK involves a considerable shift in teachers’ understanding “from being able to comprehend subject matter for themselves, to becoming able to elucidate subject matter in new ways, reorganize and partition it, clothe it in activities and emotions, in metaphors and exercises, and in examples and demonstrations, so that it can be grasped by students” (p. 13). Twenty-five years later, Hattie (2012) noted that great power emerges from teachers learning from each other and talking together about planning, learning intentions, learning progressions and success criteria. Collegial reflections about what makes a difference in students’ learning leads to important debates about evidence of students’ learning and the quality of teaching. When teachers begin to collaborate and develop common understandings, particularly a common understanding of what makes a difference in their students’ learning processes, then they all begin to move in the *right* direction based on collaborative reflections, shared practices and multiple interactions. What became evident in this study is that there are several ways to engage teachers in collaborative discussions about student progression. The result presented in this study supports the idea that teachers do not simply receive knowledge that others create to teach, but produce knowledge for teaching through their own experiences. What is important is that teachers are open to looking at evidence of their impact on students' learning and providing a critical analysis of each other's practices to better meet the needs of the students.

With its focus on collegial planning and reflection through the learning study design, this study also corresponds with the ideas of Van Driel and Berry (2012) who highlighted the importance of "forms of professional development for teachers that are built on collaboration, collegial interaction and the fostering of relationships" (p. 26). Therefore, the learning study can be described as both a research method and a successful model for the continuous professional learning of teachers.

When the teachers collectively began to unpack their content knowledge in this way (i.e. through identifying critical features), it helped them develop a clear conceptualisation of the subject area in terms of the students' understandings, their own subject understanding and their instructional strategies. In doing so, the possibility emerges that the participants may begin to think about linking content and pedagogy in new ways, something that may well be a catalyst for developing their PCK. The teachers also stressed that their joint planning and collegial reflection was central to their own learning process. The findings further indicate that the use of a learning study as a research method encourages teachers to begin to embrace PCK in their own practice. This research process therefore offers a number of interesting learning outcomes. The first is that of the research design and associated outcomes through the use of learning study methodology. The second is the manner in which, through involvement in the research itself, teachers are supported and empowered in their learning about science teaching.

As Loughran (2006) noted, "professional learning is not developed through simply gaining more knowledge, rather, professional learning is enhanced by one becoming more perceptive to the complexities, possibilities and nuances of teaching contexts" (p. 136). As such, real possibilities for meaningful approaches to knowledge growth and practice emerge as recognition of the necessary primacy of professionals' knowledge. In such a way, a learning study responds to teachers' professional needs and concerns with regard to teachers' engagement, ownership and decision-making within their classrooms.

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Pernilla Nilsson
Halmstad University, Sweden

SECTION 3

ALTERNATIVE PERSPECTIVES AND FRAMEWORKS

SHULAMIT KAPON

10. FROM NEW EDUCATIONAL TECHNOLOGIES TO A PERSONAL-INSTRUCTIONAL REPERTOIRE

The nature and function of technology in education is rapidly changing. This constantly presents new challenges to teachers who wish to effectively use technological tools to promote their students' learning, and requires reflective practice and the constant adaptation and evolution of instructional methods and practices. Hence, the incorporation of educational technology into formal schooling provides a unique arena for studying the development and use of professional knowledge for teaching during practice.

This chapter starts by charting one such incorporation. I describe episodes from Miriam's (a pseudonym) first two years of teaching physics in a fully online high school (10th and 11th grades) after almost 20 years of teaching in 'regular' schools. I then use her experiences to ground a theoretical discussion on the development and function of teachers' professional knowledge for teaching during practice.

A CASE STUDY: TEACHING PHYSICS IN A VIRTUAL CLASSROOM FOR THE FIRST TIME

The Teacher

Miriam has been teaching K12 physics for nearly 20 years. She has taught advanced-level physics in high schools in Israel, preparing students for their matriculation exams in physics, teaching gifted, regular and struggling groups. She is also an expert in project-based learning and has successfully led and advised several students' research projects in physics. She holds a B.Sc. in Mechanical Engineering and worked for a few years as a mechanical engineer in industry prior to her work as a physics teacher. She also holds a teaching certificate in physics. Miriam is highly technologically literate, and a true life-long learner. She constantly updates her knowledge of physics and her pedagogical content knowledge by reading, browsing the Internet, and participating in professional development courses.

The Context and the Challenge

In September 2012, in response to the shortage of qualified teachers at advanced-level mathematics and physics in the periphery of Israel, a virtual high school (CET, 20012) was founded to provide fully online lessons in advanced-level mathematics

M. Grangeat (Ed.), Understanding Science Teachers' Professional Knowledge Growth, 171–185.

and physics for small schools with fewer than five students enrolled in advanced-level mathematics and physics. Three mathematics teachers and three physics teachers were recruited from the best schools in the centre of Israel to teach one class each. Although all the teachers were recognised as excellent physics and/or mathematics teachers, teaching in a fully online classroom was a new experience for them. Special curricular materials were developed for the teachers in the virtual school.

All the lessons in the school are synchronous. They are recorded and students can access these recordings if they want to watch part of the lesson again. Lessons take place while the students are in school, and they attend the lessons in their schools' computer laboratory. A class is composed of 25 students who meet with the teacher in a full-class synchronous format for three hours per week. In addition, two hours per week are dedicated to small group (3–4 students) synchronous recitation, not with the teacher, but with a teaching assistant (an undergraduate student) who later reports to the teacher. The instructional platform allows the students to raise their hands and ask questions, and they can draw on the shared whiteboard. The students and the teacher can also send and receive text messages and use this function as an additional way to communicate with one another and the teacher during the lesson.

In the first year, Miriam taught students in 10th grade. The topics included geometric optics and one-dimensional kinematics. In the second year, Miriam continued with the same group to 11th grade, and prepared them for the first part of the advanced-level matriculation exam in physics, which covers all the mandatory topics in classical mechanics and geometric optics.

Teaching physics for the first time in the virtual school presented many professional challenges:

- Miriam found herself teaching an extremely culturally diverse group of students, both ethnically and geographically, in one class.
- Miriam was unable to see the students' faces during the synchronous lessons; hence the very basic feedback of 'students' eyes' that teachers often rely on was not available.
- Miriam had to delegate work to her teaching assistants, and manage their work.
- There was hardly any access to a 'real' laboratory. Although clips of demonstrations and kits of simple experiments that could be conducted at students' homes were developed and used by the teachers; for a teacher like Miriam, who uses the laboratory on a regular basis in her daily work for project-based-learning, inquiry, demonstrations, problem-solving etc. the minimal access to a physics laboratory was greatly missed.

I start by providing examples of the range of ways in which Miriam appropriated new educational technologies in her physics teaching to meet the challenges described above. Namely, how Miriam explored, learned to use and later idiosyncratically adapted and used these resources in her instruction, as well as how her personal perspective of the goals of physics teaching and her role as a teacher guided this appropriation.

Method

I followed Miriam's work during the first two years of her teaching in the virtual school. The data include:

- informal discussions that were documented as researcher's notes;
- recordings of lessons;
- Miriam's correspondence with the students (chats and e-mails); and
- interviews, in a stimulated recall format (Shkedi, c2005) about the design and enactment of specific activities. The interviews took place near a computer to allow Miriam and myself to relate to specific activities and moves. The computer screen was synchronised with the video using Camtasia Studio 8.1.

Enlarging and Adapting One's Instructional Repertoire

Naturally, it is impossible to describe the range, width and depth of Miriam's instructional activities over two years in this short chapter. This section presents two examples that illustrate the nature of the changes that unfolded in Miriam's professional knowledge and instructional practices.

Learning, exploring and adapting GeoGebra. GeoGebra is free mathematics software that links geometry and algebra to create and explore dynamic visual simulations of mathematical ideas. In Israel, it is mainly used by mathematics teachers and mathematics instructional designers. Miriam heard about it, but had only seen it in action when she started to work in the virtual school. As a new teacher, she was curious about how her colleagues were coping with the challenges listed above, and she sometimes watched the recordings of her fellow teachers' lessons. Although she is a physics teacher, she also watched some mathematics lessons. Some of the curricular materials developed for the mathematics teachers made extensive use of GeoGebra and she was impressed. She decided to learn about the software and explore its applicability to the instruction of physics.

Figure 1 presents a screen shot from the first simulation Miriam designed. The physics content of the simulation is constant acceleration in one-dimensional kinematics. The simulation presents a car moving at constant acceleration. A moving car, a number axis that represents the path on which it moves, the time axis that represents the time, a graph of the place of the car vs. time, X(t), and the velocity of the car vs. time, V(t), and vector representations of the acceleration and velocity all appear on the screen. The time, and the points (t, X) and (t, V) on the graphs, along with the vector representations of the acceleration and velocity change simultaneously as the car moves. The student can change the initial conditions; namely, the initial location X_0 and velocity V_0, as well as the value of the constant acceleration a. As the student changes the initial conditions, the graphs X(t) and V(t) change accordingly. Pressing the play button runs the simulation again with the new initial conditions.

When asked why she designed the simulation in Figure 1 with GeoGebra when there are so many readymade simulations on this topic on the Web, she said: “For one, it allowed me to learn the tool so if I want to take a student, if I want to give him a project, I can advise him”. When asked what kind of project she said: “He could construct this kind of file, or if he has an idea how to improve it”. The last part of the sentence reflects a repeating motif in the way she works with students, which involves creating an initial example and then asking them to improve it. Note that: (1) Miriam created a need to use the technology in her instruction to give her an opportunity to learn the tool; and (2) she was sensitive to the opportunities for project-based learning provided by GeoGebra, and explicitly wanted the students to construct something. This is a central instructional goal that came across many times during our conversations. Her exploration of GeoGebra was strongly informed by her strong commitment to project-based learning.

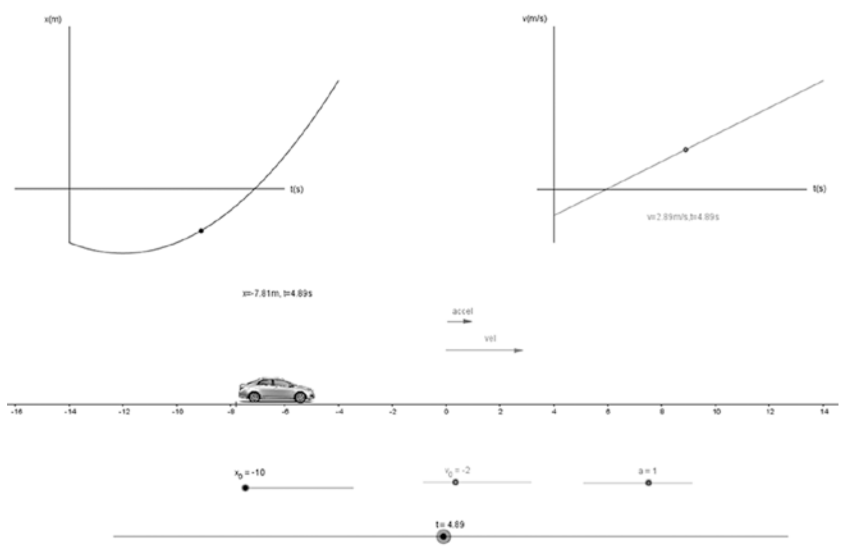

Figure 1. A screen shot from the first GeoGebra simulation Miriam designed for her students.

It was very clear that Miriam explored and used GeoGebra with regard to disciplinary demands and her knowledge of students’ difficulties. For instance, when discussing the simulation in Figure 1 she explicitly referred to students’ specific difficulty in understanding graphic representations of motion: “After all, in one-dimensional kinematics, they look at the graph [points to the moving (t, X) points on the position vs. time graph in the simulation] and they think that this is the point [the actual moving thing], and it is indeed confusing. Because the car is not here [points to the line of the position vs. time graph]. So there is an emphasis that the point represents something. So now we can discuss exactly what this point represents”. Hence, she is saying that the simulation helped her draw the students’ attention to a particular feature that is difficult to grasp, and to ground the discussion in class in a concrete example.

Miriam was highly aware of the dynamic representational opportunities GeoGebra provides, even after the first simulation she designed (Figure 1). This awareness was coordinated with what she knew about the discipline and the students. For instance, she said that “I haven’t seen a simulation that gives me the tools I have here [refers to the simulation in Figure 1], the vector direction [points to the vectors of the position, and velocity that are synchronised with the movement of the car], the ability to control the initial conditions and immediately see that on the graphs. There is so much simultaneous information here. Sometimes it can ‘choke’ a student, you know, not being able to see the forest for the trees. So you can build /…/ add or delete”. Hence, the rich representational potential of the software was only one aspect that drew her attention. What made the software so appealing was that it allowed her to control this richness and decide which and how many representations to use, based on professional considerations, something that is impossible with readymade simulations.

It is important to note that Miriam did not know the tool well when she started to use it in her teaching. She noticed its potential usefulness for explicitly addressing specific instructional goals, started to explore and play with it, and by so doing discovered additional educational affordances and limitations in the process, became more fluent with the software, and iteratively changed her design and her understanding of it. An example of the iterative and reflective process described above was when she critically examined her first simulation (Figure 1) a year later: “Look, building this is not easy /…/ I mean it’s hard /…/ I sweated over this /…/ You just need to spend time learning the tool /…/ Can you see the potential for mechanics? Here we could add [points to the empty upper right-hand side of the simulation (Figure 1)], I could insert questions relating to the simulation [and she gives examples] /…/ multiple choice, but they [students] could also draw vectors /…/ and get correct/incorrect feedback”.

She proudly showed me some of her students’ projects – successful and unsuccessful in terms of the physics involved. When we discussed the GeoGebra projects, she constantly mentioned how these projects provide her with a window into individual students’ thinking, and the way to support their learning: “Having to design a simulation sharpens things they [students] do not understand /…/ Things that we [teachers] have already forgotten [how confusing they are]”. She voluntarily showed me ‘unsuccessful’ projects, for instance, a simulation in geometrical optics that one of her students designed from scratch. In this simulation, an object is placed between two mirrors. The simulation makes it possible to change the angle between the mirrors. All the images of the object are created, and the field of vision is marked on the screen. She described how she used the mistakes she noticed in her student's work, and referred to the ongoing iterative nature of the work. "When he [the student] started, he did not pay attention to the physics /…/ what he did, he made this very simple division. So we said the physics here is not correct. Let's start by understanding the physics". Note the "we". One of Miriam's repeated instructional patterns is that she uses her students' work in her instruction. Students feel very comfortable showing work in progress and are not afraid of being wrong. The class discussed the problematic features in the project, and Miriam used this discussion as leverage to explain ideas from a different angle. When describing how the particular student corrected his project, she said: "and it's quite beautiful. It took a lot of time till he finally /…/ look, here you can see the field of vision from this direction /…/".

The discourse and actions above reflect Miriam's beliefs about teaching and learning. For instance, it was quite evident in all of our discussions that she believes that knowledge is constructed by people in a community. For example, she said many times that she expects her students to improve the simulations she designs: "everything I make, I would be very happy if they improved it", and she showed me concrete examples of such improvements. She also gave examples of how she used her students' projects as a basis for new designs and she publically gave them credit for this. "I think everybody can contribute an idea and together we can achieve something better for all of us".

All in all, Miriam used GeoGebra for various purposes: to probe the students' understanding, as a venue for the students' projects, as a tool for creating dynamic simulations for lessons, and as a tool to prepare introductory activities for the laboratory. Moreover, her use reflects an awareness of the advantages and disadvantages of the tool for each purpose, which was motivated and guided by her beliefs about teaching and learning.

Adapting and adding to official curricular materials. GeoGebra is a generic tool that can be used for the instruction of many topics. However, Miriam was given many ready-made curricular materials. Her approach and use of existing curricular materials was very interesting. A metaphor that constantly echoed in her talk about her use of existing curricular materials was that they are the "lemons" from which the teacher "makes lemonade". She was not expecting to get perfect curricular materials, and did not seem to think that such materials exist, including her own designs. Apparently, in her opinion there are always things that can be improved and attuned better to specific class needs, but she did not see this as a problem. For instance, when relating to a video clip she had received, which presents an experiment that demonstrates the conservation of momentum, she pointed out both the good and problematic features of the clip. However, she also said that she had used this clip in her lesson, saying that "We discussed the problematic features [in class]". Hence, she encouraged her students to examine the materials they see critically, and use this discussion to deepen their understanding.

As mentioned earlier, many curricular materials were developed for the school, including demonstration video clips. Miriam received a clip that aims to illustrate

Newton's third law. In this demonstration, a ball is hung from a dynamometer, and is dipped into a glass of water that is placed on an electronic scale. The demonstrator notes the dynamometer and the scale readings before and after dipping the ball into the water, and then briefly explains the differences. When Miriam decided to use this clip in her lesson, she added an interactive questionnaire which she built with Google Forms. In her rationalisation of this addition, it became clear that it was motivated by her beliefs about the nature of teaching and learning physics, as well as her understanding of students' difficulties: "You have to explain to the kids what they see /…/ If they can repeat what he just said, does this mean they understood? /…/ What did they see, what did they understand?".

Her knowledge of the students' specific difficulties in understanding Newton's Laws, as well as her understanding of the main ideas that should be stressed when teaching them are apparent in the questions she wrote. The interactive questionnaire requires the students to identify the free body system, the external forces, the objects that exert these forces etc. Miriam gave two reasons for her use of Google Forms for this purpose: (1) "A student who answers can get immediate [automatic] feedback"; (2) "And I get [feedback] /…/ I can see where they are wrong [she showed me the Excel file of students' answers] /…/ [Discuss] problematic questions in class". The addition of an interactive questionnaire to a video clip was a recurring instructional pattern in Miriam's practice. She used the Google Form as a diagnostic tool to inform her own practice and provide immediate individual feedback to each of her students. This technique also addressed a concern she had expressed from the very start of her online teaching: how to reach the students, know if and what they understand, when she cannot even see their faces during the lesson.

MODELLING THE CHANGE IN TEACHERS' KNOWLEDGE

Method

The recorded lessons and the correspondence with students were mainly used as a basis for the stimulated recall interviews. A grounded theory approach to the analysis was taken (Merriam, 2002; Shkedi, c2005). First, the interviews were segmented thematically (e.g., references to beliefs, students' difficulties, curricular goals, knowledge of physics). The segments were iteratively examined to find connections and relations that were triangulated with the researcher's notes. A theoretical analysis followed in which the emerging categorisation was refined in light of relevant concepts and ideas from the literature. Miriam's exploration, integration, adaptation and usage of different technological tools in her instruction were conceptualised in the analysis as a process of appropriation (Bakhtin, 1981; Levrini, Fantini, Tasquier, Pecori, & Levin, 2014; Rogoff, 1995). The 'hidden' instructional potential of these technologies is conceptualised as affordances (Gibson, 1986; Greeno, 1994), where Miriam's ability to see these affordances and explore their potential use are considered a hallmark of her professional knowledge of teaching. Informed by the Knowledge in Pieces epistemological perspective (diSessa, 1993, 2002; diSessa & Sherin, 1998; diSessa & Wagner, 2005; Wagner, 2010), teachers' knowledge is conceptualised as a complex knowledge system that informs their action. The analysis concludes with a dynamic model of teachers' professional knowledge inspired by perspectives of teachers as designers (Laurillard, 2012; Tabak, 2004) and links the theoretical constructs of affordances, appropriation, and knowledge systems. The model is then related to the literature on Pedagogical Content Knowledge (Shulman, 1986, 1987) and the model of teacher professional knowledge bases that motivated this volume (Gess-Newsome, 2013).

Recognising Instructional Affordances

The term affordance was originally suggested in the literature of perceptual psychology to describe properties of objects in the environment measured relative to the user (Gibson, 1986). The concept was adopted and elaborated in the context of design and human-machine interactions to describe possibilities for action related to particular artifacts as they are perceived by the user (Norman, 1999). In the context of education, Greeno (1994, 2006) argued that affordances reflect conditions in the environment for constraints to which the agent is attuned and thus contribute to the kind of interaction that occurs. He suggested that some affordances can be directly perceived as the agent interacts with the environment, whereas others need to be recognised as features of an object that are matched against stored patterns, and this is where education and experience come to bear.

In this study, I regarded Miriam's realisation of how she can use particular technological tools for specific purposes in her teaching as her sensitivity to the unique affordances of the tool, and considered this sensitivity an important part of her professional knowledge for teaching. The description of how Miriam explored GeoGebra provides many examples of Miriam's sensitivity to the affordances of the tool.

Miriam explicitly expressed her awareness of the affordances of GeoGebra: (1) the variety of representational options, specifically mentioning those that are relevant to the instruction of specific topics in physics. Consider, for instance, what she said about the vector representations. (2) The dynamic nature of the representation in the context of the instruction of a specific topic in physics. For example, consider how she described the ability to simultaneously see the point on the placement vs. time graph and the actual moving car in the context of teaching one-dimensional kinematics. (3) The inherent control the software provides supports the teacher in choosing which and how many representations to use. For instance, she explicitly mentioned this feature with regard to the very rich simulation screen she had created in her first simulation in kinematics. (4) The potential to use GeoGebra as a 'sandbox' for project-based learning with students, particularly in a virtual classroom. In the same manner, she was attuned to the affordances of other tools such as her realisation of the affordances of Google Forms in providing immediate feedback to the user, and articulated feedback to the designer, or her ability to think of creative use of the 'imperfect' curricular materials in ways that sometimes differed from the designer's initial plan.

Appropriation

Bakhtin (1981) used the term appropriation to describe the process in which a speaker adapts a word, which is part of an external language and culture, for personal use that reflects semantic and expressive intentions. Rogoff (1995) expanded the term appropriation to encompass norms and behaviours, and discussed participatory appropriation as the process by which individuals who engage in the activities of a community adapt the norms and rules of this community and become part of it. Rogoff argued that both the community and the individual change via this process since the idiosyncratic adaptation of words, norms and behaviours percolates back to communities and cultures as individuals continue to participate.

In a recent study based on an empirical analysis of data collected during implementation of a unit on thermodynamics, Levrini et al. (2014, p. 7) wrote that "the way they [students] 'shaped' their understanding of content according to personal approaches was striking". Levrini et al. used the term appropriation to describe the idiosyncratic sense of productive science learning. In a bottom-up approach, they also suggested five discourse markers that can support inferences regarding students' appropriation of ideas and norms in science classrooms. In the current study, I adapted their markers to infer the appropriation of specific tools in educational technology from Miriam's discourse. I now define each marker and provide an example of a classified quote drawn from the episodes described in detail in the previous sections.

- An expression of a personal idea: "Here [in the simulation] /…/ I could insert questions relating to the simulation".
- An expression grounded in the discipline being taught: "After all, in one-dimensional kinematics, they look at the graph and they think that /…/".
- An expression that involves a metacognitive and epistemological dimension: "Having to design a simulation draws attention to things they [students] do not understand /…/ Things that we [teachers] have already forgotten [how confusing they are]".
- An expression that is non-incidental, in the sense of being consistently used throughout instructional activities: "What did they [the students] see, what did they understand?".
- An expression which is a carrier of social relationships that positions the teacher within the classroom as well as the larger education community: "I think each one can contribute an idea and together we can achieve something better than all of us separately".

How Knowledge Informs Perception and Action

The Knowledge in Pieces (KiP) epistemological perspective (diSessa, 1993, 2002) conceptualises individual knowledge as a complex system with loosely interacting small knowledge elements that are not intrinsically right or wrong. In this perspective, learning involves a progressive systemisation driven by mundane and accumulated experiences, which necessitates the reorganisation and recontextualisation of existing knowledge elements and the integration of new ones, and the creation of hierarchical and complex subsystems. The path Naïve => Novice => Expert is thus considered as a continuous and gradual process. From this point of view, 'concepts' are not modelled as unitary elements but as complex knowledge systems that evolve along this path.

According to KiP, information in the world is not considered to be transparently available. An underlying assumption is that the knowledge system provides ways of perceiving the 'right' and the 'relevant' information (diSessa, 2002; diSessa & Sherin, 1998; diSessa & Wagner, 2005; Wagner, 2006, 2010). From this perspective, sensitivity and attunement to the particular educational affordances of a particular technology, such as those Miriam presented, are guided by Miriam's knowledge.

DiSessa and Wagner (2005) and Wagner (2010) suggested that knowledge systems which form concepts function as an ensemble of assimilatory schemes with which a knower assimilates and interprets that which is available to be perceived in relation to this concept. They regarded each assimilatory scheme as a concept projection in a particular context. They argued that: (1) concept projections are derived from experiences; and (2) experts have numerous concept projections of a particular concept, a variety that affords the expert's ability to perceive relevant information regarding a particular concept in a wide range of contexts and appearances.

Teachers' professional knowledge can be seen as a complex knowledge system made up of simple and more complex elements that reflect knowledge of disciplinary content, technology, pedagogy, students, epistemology etc. This system informs teachers' perceptions and interpretations of incidences of learning and instruction as well as the instructional affordances of various resources. In this sense, a specific appropriation is evidence of concept projection. Moreover, feedback from students results in adaptations of the knowledge system.

Take, for instance, Miriam's appropriation of GeoGebra as an arena for project-based learning. She projected what she knew about project-based learning in the context of a virtual learning environment, thus creating computational instead of experimental projects with the students. Her sensitivity to the affordances of GeoGebra was certainly informed by her knowledge about the students' representational difficulties which drew her attention to the rich and extremely flexible representational power of GeoGebra. Her deep belief in the importance of figuring out and responding to what students actually think and understand suggested that letting students design their own simulations might be productive. This is also what drew her initial attention to Google Forms. The belief that a teacher can and should design her students' learning environments, as well as her successful previous experiences in self-learning and using new technologies, informed the way she explored the software, for instance, by building a simulation of her own. It also supported her self-efficacy. The feedback from the students refined her understanding of using GeoGebra as an instructional resource as well as her knowledge about project-based learning in a virtual learning environment.

Teaching as a Design Science

Tabak (2004) differentiated between what she termed exogenous and endogenous educational designs. Exogenous design refers to instructional materials, activity structures or instructional strategies that have been developed by researchers and instructional designers, whereas endogenous design refers to the set of materials and practices that are either in place in the local setting or devised by the teachers 'in action' as part of the enactment. Tabak, a leading design-based researcher, openly acknowledged the important role played by teachers in educational interventions, a role that goes far beyond mere 'facilitation'. However, Miriam presented both exogenous and endogenous designs, and her use of existing curricular material such as the video clip experiments extended beyond the 'in-action' phase.

Miriam's practice strongly coheres with the view of teaching as a design science, as illustrated in the following paragraph:

> Every individual teacher has the opportunity in their interaction with students to discover which methods or techniques work best, and in that sense the feedback loop between teaching design and learning outcomes may be completed. /…/ In education it is the research community that does this, not the teaching community. If teaching like engineering and architecture were treated like a design science, then practitioners themselves would be building the knowledge base. (Laurillard, 2012, p. 5)

Miriam actively designed the curriculum she used in the lessons as well as their implementation, and constantly refined her design and practice based on her students' feedback.

Figure 2 presents a model that aims to account for the constant and dynamic development of teachers' knowledge during practice, and the relationships between the theoretical constructs discussed in the previous subsections. The model is cyclical: a knowledge system that includes many simple and complex elements of knowledge (note that I also consider epistemological beliefs as knowledge) informs the teacher's perception, and leads to the recognition of instructional affordances in the technology as well as other potential resources the teacher encounters. This recognition that is related to the teacher's instructional goals, which are informed by his/her knowledge system, leads to an idiosyncratic appropriation of these resources to the teacher's instructional repertoire. This repertoire is enacted in teaching, and the insights from the implementations are fed into the knowledge system. This feedback loop sometimes leads to changes in the knowledge system, and a new cycle begins.

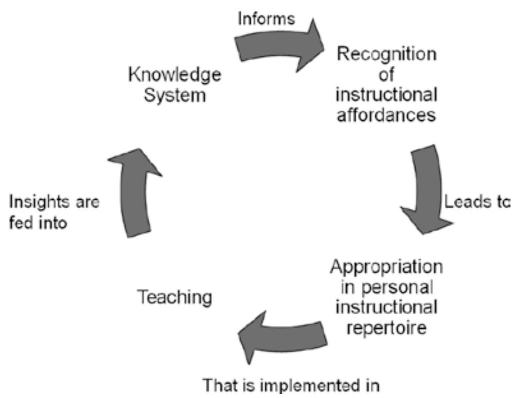

Figure 2. Practising teaching as a design science

Practising Teaching as a Design Science vs. Professional Knowledge Bases (Gess-Newsome, 2015)

Lee Shulman's influential work reframed the study of teachers' knowledge in ways that attend to the role of content in teaching, and represent the specialised understanding of content that is unique to the teaching profession. Shulman (1986, 1987) defined seven categories of knowledge for teaching, and argued that the category that is most likely to distinguish the content specialist from the pedagogue is the category of Pedagogical Content Knowledge (PCK). He described PCK as "ways of representing and formulating the subject that make it comprehensible to others" (1986, p. 9). Since its introduction in 1986, PCK has become widely employed in the context of teacher education. Many studies have highlighted the central role of PCK in teachers' practice and in teacher education. However, some educational researchers (Ball, Thames, & Phelps, 2008; Borko & Putnam, 1996; Friedrichsen, Driel, & Abell, 2011; Gess-Newsome, 1999; Lee, Brown, Luft, & Roehrig, 2007; Magnusson, Krajcik, & Borko, 1999; Marks, 1990; Schoenfeld, 2006) have also argued that an understanding of the nature of PCK; namely, a clear unambiguous definition of its scope, structure and function, is needed both theoretically and empirically.

Questions regarding the nature of PCK – whether it is knowledge base, a set of skills, a disposition or some kind of combination, its elements, how is it measured, and directions for future research on PCK – were guiding forces behind the PCK Summit (Berry, Friedrichsen, & Loughran, 2015). One product of this summit was a map of teachers' professional knowledge bases, and its relationship to their practice and students' outcomes (Figure 3.1 in Gess-Newsome, 2015; Reproduced as Figure 1 in the introduction to this volume, Grangeat and Kapelari, 2015).

The amalgam of pedagogy and knowledge that Shulman described as PCK is certainly evident in Miriam's practice. The issue is how Miriam's practice and the dynamic model of practising teaching as a design science that was suggested above relates to the model suggested by the PCK Summit. There are points of congruence and incongruence. First, knowledge of technology is missing from the PCK Summit model but is central to Miriam's practice as well as being part of her knowledge system. In addition, the categorical division of knowledge according to the PCK Summit model is not in line with the approach of the knowledge system advocated in the previous section. On the other hand, the model of practising teaching as a design science implicitly articulates the idea of 'amplifiers and filters' that was advocated in the PCK Summit model. The knowledge system also includes the teachers' epistemological beliefs, and it informs the teacher's perception and action, guiding the teacher in identifying specific instructional affordances in the environment that can lead to specific appropriations of instructional resources. Further, the arrows that connect the students' outcomes to the other components in the PCK Summit model cohere with the feedback loop described in the practising teaching as a design science model.

FINAL THOUGHTS

The rapid changes in technology suggest that the adoption and use of technology in education is an interesting arena to study the development of professional knowledge for teaching during practice. I presented the experience of an excellent physics teacher who found herself teaching in a virtual classroom for the first time. Based on this analysis, I suggested a model that aims to account for the constant and dynamic development of teachers' knowledge during practice. The model is cyclical: a knowledge system informs the teacher's perception, and thus leads to the recognition of instructional affordances in the environment. This recognition, which is related to the teacher's instructional goals, leads to the appropriation of these resources in the teacher's instructional repertoire. The repertoire is implemented in the classroom and the insights from this implementation are fed into the knowledge system.

I am aware that I am basing my proposal on the analysis of the practice of only one exceptional teacher. A fair question would be what kind of generalisation can be drawn from this analysis. My answer is twofold. First, this is an exploratory study, and currently data are being collected on the incorporation of new technologies with other physics teachers who are exceptional in terms of the scope and quality of their incorporation of technology. The preliminary findings are in line with the model suggested here. However, a more important question is why these teachers are so exceptional, and why there are not more of such teachers. A possible answer might be the nature of teacher education. The 'lemon-lemonade' metaphor that was repeated several times in Miriam's discourse is something that we, as teacher educators, are not successfully reinforcing in mainstream teacher education and professional development programmes. We teach applications instead of teaching our students to search for affordances. Perhaps our instructional methods courses should be transformed to better empower pre-service teachers, provide them with tools to design their students' learning and help them to construct their self-efficacy in so doing.

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Shulamit Kapon
Department of Education in Science and Technology
Technion – Israel Institute of Technology, Israel

PHILIPPE DESSUS, FRANCK TANGUY
AND ANDRÉ TRICOT

11. NATURAL COGNITIVE FOUNDATIONS OF TEACHER KNOWLEDGE

An Evolutionary and Cognitive Load Account

Instructional process management (encompassing instructional design and classroom management) is known to be very complex, mainly due to its context and the large and diverse amount of knowledge driving it: content knowledge, pedagogical knowledge (PK), curriculum knowledge, knowledge of learners and their characteristics, knowledge of educational contexts, pedagogical content knowledge, and knowledge of educational ends (Shulman, 1987). This complexity makes researchers unable to detect well-defined practices, and a knowledge base leading to efficient teaching with low training cost is missing (Koedinger, Booth, & Klahr, 2013).

The attempts so far to investigate these pieces of knowledge can be categorised in two paths. The first path considers novice vs. expert knowledge comparisons to model knowledge growth across experience (Hogan, Rabinowitz, & Craven, 2003). The second path considers knowledge bases every teacher needs in order to work efficiently. These two paths both have some concerns. Teachers' expertise is not so clear-cut and the way teachers develop it through experience is difficult to model and diagnose. Further, specifying a comprehensive knowledge base about teaching is often externally-driven (Hattie, 2009; Wang, Haertel, & Walberg, 1993), listing a superficial knowledge base of 'what works', often unrelated to teachers' beliefs and knowledge and/or their cognitive abilities.

Pedagogical Content Knowledge (PCK), as Shulman (1987, p. 8) argued, is "that special amalgam of content and pedagogy that is uniquely the province of teachers, their own special form of special understanding". This proposition, as well as Shulman's professional knowledge development model, has become widespread in the educational sciences research field. However, some problems can be raised, notwithstanding its vagueness ("special amalgam", also see Kind, 2015). First, teaching is mainly seen as a "learned profession" (see Shulman, 1987, p. 9), while the social and informal facet of this activity, relying on mainly innate abilities, remains unaddressed. Second, we refer to van Driel et al.'s (2001) definition of PCK: "the knowledge the teachers *must* have in order to teach science" (emphasis added) to highlight that the orientation of such a knowledge base is highly prescriptive in nature: it states *appropriate* knowledge so that anyone having it can be a good

M. Grangeat (Ed.), Understanding Science Teachers' Professional Knowledge Growth, 187–202.

teacher, and many research lines have been oriented to differentiating novices from experts with regard to PCK. Third, this model emphasises a unidirectional way in which teachers' beliefs and knowledge influence his or her social behaviour, whereas bidirectional ways are more likely to occur (Rimm-Kaufman & Hamre, 2010).

The aim of this paper is to explore a cognitive way to define teachers' professional knowledge (TPK), arguing that some 'natural' knowledge, stemming from several human social abilities – and, for many of them, animal – is thus engaged in teaching as well. The actions grounded on such knowledge are undertaken automatically or at a low cognitive load due to the nature of the latter. Some theoretical views on teaching include such an assumption (Csibra, 2007; Csibra & Gergely, 2011; Strauss, 2005; Strauss & Ziv, 2012), but so far, little research has investigated teachers' cognitive processes in relation to both natural cognition and Cognitive Load Theory (CLT) (see however Feldon, 2007; Moos & Pitton, 2013).

The remainder of this paper seeks firstly to consider teachers' actions through the lens of natural cognition and pedagogy, then to set up a framework for teacher cognition and knowledge, showing that several social abilities and knowledge can be used for teaching purposes, and with a low cognitive load. Then, we describe the abilities for teaching as primary vs. secondary knowledge. Eventually, we use this framework to assess or predict which cognitive load is in relation with teachers' performances according to the CLASS, a renowned classroom observation system.

TEACHER COGNITION AND NATURAL PEDAGOGY

There is a large bulk of work about teacher cognition (e.g., Clark & Peterson, 1986; Leinhardt & Greeno, 1986; Yinger, 1986), traditionally splitting teachers' activity into two phases: the tasks teachers perform *before* actually working with learners (planning phase), and the tasks *in the presence* of the latter (interactive phase). Natural pedagogy, from a different perspective, posits that teaching is a more integrated and social activity (Csibra & Gergely, 2011), likely performed in natural contexts using early-emerged communication capabilities like triadic communication about knowledge referents (like eye-contact, turn-taking reactivity, ostensive object or event pointing) (Gergely, Egyed, & Király, 2007). The main traits of a definition of teaching as a natural ability are summarised as follows (Caro & Hauser, 1992; Dessus, Mandin, & Zampa, 2008; Thornton & Raihani, 2008):

- Teaching is a cooperative activity in which someone (the teacher) "engages in an activity that benefit another, at some cost, or with no immediate benefits to itself" (Thornton & Raihani, 2008, p. 1825).
- The conveyed knowledge is teleogically and causally opaque (Csibra & Gergely, 2011), and thus not directly guessable through mere observation.
- The teacher modifies and arranges his or her behaviour (and the environment) to manage easier learning and communication (Sterelny, 2003).

- There is behavioural coordination and matching between the teacher and learner (Strauss, 2005).
- Intention-reading is one of the core activities involved in natural teaching and is managed through Theory of Mind (ToM) processes (Baron-Cohen, 1994; Rodriguez, 2012).

Briefly put, teaching involves intensive use of social and communicative skills employed by animals, even non-human, and grounded on natural abilities, thus not learnt formally. The next section introduces Geary's theory, predicting which kind of knowledge is to be more or less formally learnt, depending on its epigenetic acquisition.

PRIMARY AND SECONDARY KNOWLEDGE INVOLVED IN INSTRUCTION

According to Geary (2007), culture is built from cognitive and motivational systems that underlie naive knowledge: "Cultural innovations (e.g., scientific method) are retained across generations through artifacts (e.g., books) and traditions (e.g., apprenticeships). These advances result in a gap between folk knowledge and the theories and knowledge base of the associated sciences and other disciplines" (id., p. 185). This refers to the so-called naive vs. scientific knowledge distinction. The first type of knowledge evolves slowly whereas the second one develops very quickly, exponentially. Naive, folk or *primary knowledge* (k_1) is implicitly acquired through adaptation to natural, linguistic, social or physical environmental constraints. Scientific, recent or *secondary knowledge* (k_2), is explicitly acquired through formal education. Primary knowledge has been present in the human species long enough (for 200,000 years) for the species to have evolved so that each individual can acquire it by simply adapting to the social, linguistic, physical or living environments. Secondary knowledge (k_2) is the result of rapid and successive changes and has to be learned explicitly. From this dichotomy, Geary (2007) proposes that:

- Schools are cultural innovations that emerge in societies where cultural and scientific advances have widened the gap between primary knowledge and skills necessary to live in society.
- Schools organise activities for children so that they can acquire the secondary knowledge and skills that will help them bridge the gap between primary knowledge and the requirements of society.

Secondary knowledge-based skills are compiled from primary knowledge and the adaptability of humans to social settings. The primary knowledge can be learned through adaptive learning for many years, mainly before and for the period of schooling. However, from the age of six, a child continues to gain primary knowledge (about himself and group life, the physical environment or living), while beginning to learn secondary knowledge.

Sweller (2008) built on Geary's theory of knowledge to develop a theory of teaching and learning. Primary knowledge, which can be very complex (e.g., foraging), is acquired without teaching, and works by maturation (impregnation–adaptation). Secondary knowledge (from cultural or scientific innovations) requires education, effort and motivation, and its learning works either by random generation and selection (discovery learning), or by guided, direct and explicit teaching. Secondary knowledge can formally be quite simple (e.g., chess), although difficult and time-consuming to learn. The k_1 vs. k_2 alternative explains why learners can acquire some information easily, unconsciously, and without a strong motivation, whereas other types of information may only be acquired at the price of a significant conscious effort, often requiring external motivation. For any k_2, we need explicit instruction to foster motivation and support learning, which is not requested while acquiring k_1 (Geary, 2012). This is the main reason schools were created to transmit and learn secondary and demanding knowledge. Teachers have to deploy strategies in order to foster learning, that is, to give learners tasks involving a sufficiently moderate cognitive load so that learners can allocate their cognitive resources to learning k_2 (Tanguy, Foulin, & Tricot, 2012).

Our primary argument elaborates on Geary's (2007) and Sweller's (2008) to transpose the k_1 vs. k_2 dichotomy from learning to teaching, and posits that teachers use a large number of instructional strategies (communication, social interaction) for pedagogical purposes (i.e., classroom management), more or less consciously and at a low cognitive load (i.e., k_1), while more k_2-related skills (i.e., more content-focused) are triggered consciously and at a higher cognitive load, and continuously evolve with changes in culture and society. All in all, k_1 may be one of the bases of Pedagogical Knowledge, while k_2 may be linked to Content Knowledge and Pedagogical Content Knowledge. The next section elaborates the relationships between cognitive load and knowledge acquisition (expertise).

COGNITIVE LOAD AND TEACHERS' EXPERTISE

Cognitive load refers to the total amount of mental activity imposed by the complexity of a task at a given point in time (Sweller, 1988). Cognitive load depends on the basic characteristics of the information to learn, as well as the pedagogical strategy. Sweller (1988, 2011) describes three types of cognitive load:

- *Intrinsic cognitive load* relates to the level of difficulty of the information delivered to the learner. The quantity of items to be processed and their interactivity during the production of the learning task is considered to play a role in this difficulty. The intrinsic cognitive load is high when there is a lot of information to process and when their inter-relationships are complex. This cognitive load source can be managed by teachers, but this change is limited and very demanding (from an Instructional Design viewpoint).

- *Extraneous cognitive load* is the cognitive load that is imposed by the structure of the material used (Sweller, 1994), and by inappropriate educational strategies that may interfere with learning strategies. An adequate design of both material and strategies can lessen this amount of unnecessary cognitive load.
- *Germane cognitive load* is the minimum amount of cognitive load necessary to process information by the learner in order to learn.

According to Cooper (1998) and Sweller (2011), both intrinsic cognitive load and extraneous cognitive load, associated with the presentation of instructional material, can be manipulated by the designers of learning scenarios.

- First, when the intrinsic cognitive load engaged in a task is *low*, the learner has sufficient mental resources (i.e., germane cognitive load) in order to learn, even if the task requires a high extraneous cognitive load.
- Second, when the intrinsic cognitive load engaged in a task is *high*, indicating both that the quantity of items to be processed is too large, and the extraneous cognitive load is also high, the cognitive load exceeds the total mental resources of the learner so there is no relevant cognitive load (germane cognitive load) for learning.
- Eventually, when the presentation of the instructional material sets the extraneous cognitive load to a *low level*, learning is facilitated, provided that the learner's mental resources are fully available for the task.

The extrinsic cognitive load – and to a lesser extent the intrinsic cognitive load – can be controlled by the teacher in order to give the learner sufficient resources to acquire or build the knowledge involved in the learning task. The identification of the knowledge to be taught is therefore essential. In the following section, we provide some evidence about the use of primary knowledge during teaching.

LINKS BETWEEN COGNITIVE LOAD, EXPERTISE AND PRIMARY AND SECONDARY KNOWLEDGE

With reference to Sweller's (2008) theory, it is necessary to adapt the learning strategy by controlling the extrinsic and intrinsic cognitive load with regard to the type of knowledge to learn in order to facilitate their building by students. For example, the categorisation of living beings (living vs. non-living) may be affiliated with k_1 and the phylogenetic classification may be related to k_2 (Geary, 2007). The first type of knowledge is acquired early, regardless of cultural influences (Descola, 2013; Murphy & Medin, 1985). The handling of this knowledge by the learner engages a small amount of cognitive resources and learning does not seem sensitive to the conditions of instruction: a small amount of information to be processed (low intrinsic cognitive load) and a relatively simple learning device (low extrinsic cognitive load) (Tanguy, Foulin, & Tricot, 2013) – the learning device being the structure of the material used to teach, how to present the information in teaching activities and strategies for learning. The learning device needed to understand the living vs. non-living categorisation is simple because it relies on the use of a dichotomous key with two choices: to decide whether the entity presented is alive or not. Information is presented in a clear manner which limits the extraneous cognitive load for the individual (Tanguy et al., 2012). Teaching such knowledge requires less control by the teacher of content and minimal pedagogical knowledge since these notions are intuitively grasped by students.

On the other hand, the phylogenetic classification of living beings pertains to k_2. This classification has recently emerged in science and is a product of the evolution of our culture. Learning such knowledge has a significant cognitive cost, first, due to the amount of information to process for designing the affiliation of living beings, which is large (high intrinsic cognitive load) and, second, because it requires a suitable learning device: building a phylogenetic tree (high extrinsic cognitive load) (Tanguy et al., 2012). These high values of cognitive load may interfere with a student's learning. The teacher has to manage these costs and limit the amount of information provided in the task, as well as their interactivity (Sweller, 2010). The teaching of such knowledge requires the teacher to have greater control over the content and more sophisticated Pedagogical Content Knowledge.

In a nutshell, pedagogical knowledge related to the content (PCK) is knowledge that a teacher develops to support students in understanding and learning the content. This knowledge is mostly learned during training, but also during teaching practice, at significant cognitive cost. When teachers face difficult and demanding goals, their cognitive load is high and/or their performance is low, and/or the time to achieve the task is long. To perform such difficult tasks, teachers can either:

- ask for help from other humans, which is not very easy while teaching;
- use their primary knowledge; dual processes theories show that in many domains (e.g., decision-making, reasoning, economy), humans frequently use their k_1 instead of their secondary (rational) knowledge, even when available; or
- learn, in order to become more expert, by acquiring schemas and automatisms which will decrease the intrinsic cognitive load; acquiring expertise is possible by practising (expertise based on problem-solving, on experience) and by learning academic knowledge (expertise based on training, on k_2).

Since asking for help from another teacher is mostly impossible (at least in most instructional environments), teachers only have two solutions to face difficult and demanding goals and to reduce their cognitive load: to learn (i.e., acquire more expertise) or make use of their primary knowledge. The next sections are dedicated to a natural cognition view of the teacher's knowledge that may ground PK and PCK.

NATURAL MECHANISMS UNDERLYING TEACHING: A FRAMEWORK

We argue that, even before using secondary knowledge, teachers anchor some of their behaviours and knowledge in k_1. In a given instructional environment (e.g., a classroom), the teacher (and learners as well) is moving and acting to behave adequately, thus using basic social and communicative abilities. Elaborating from Baron-Cohen's (1994) modules of mind reading, below we list by growing order of complexity and required cognitive load three sets of 'modules' (i.e., cognitive functions) that may be activated during teaching and may serve as k_I. It is worth noting that the functioning of any module necessitates the lower ones (Dessus et al., 2008).

The first set is about detecting intentionality and comprises two different kinds of detection: person and knowledge detection.

- *Face Processing and Gaze Direction Detection (Theory of Mind)*. These modules detect learners' overall attention to infer who places attention on which piece of information, or participates in the lesson flow. Learners' gaze direction is processed for two different purposes: to analyse which data individual learners process (individual attention, dyadic); and to analyse which data is jointly processed (joint attention, triadic).
- *Knowledge Gap Detection*. This ability enables teachers to become aware of pupils' lack of understanding, thus making them able to propose explanations or lacking pieces of knowledge to pupils.

A second set of abilities, grounded on the previous one, is about *alignment.* As Rodriguez (2012) pointed out, synchrony (or alignment) is a crucial ability for teachers and learners to share a common viewpoint. Two kinds of alignments are necessary:

- *Affective and Motivational Alignment*: The teacher and learners affectively aligned can share their emotions about their social engagement in instruction and thus their motivation is fostered.
- *Activity-focused Alignment*: The teacher and learners can smoothly perform activities, being aligned with each other, intentionally or not (Gergely & Csibra, 2006).

A third set of abilities is action-oriented towards the environment and is termed "arrangement". This set lies on top of the previous set since arranging an activity cannot be done without being aligned with it. Recent work has proven that this environmental arrangement to foster the acquisition of new skills by young conspecifics is often observed in non-human animals (Leadbeater, Raine, & Chittka, 2006; Sterelny, 2003; Thornton & McAuliffe, 2006).

- *Environment Arrangement*: The teacher and learners set up their proximal environment so that it contains the necessary material for teaching/learning.
- *Activity Arrangement*: The teacher and learners monitor/control their activity and that of others.

Based on top of the three previous modules, the fourth and latest set of abilities allows the triggering of instructional actions intentionally initiated. These actions are the basis of many more sophisticated instructional activities, although used in many other social situations, and are adapted from Merrill (2013).

- *Show*: explain and/or show specific material or content.
- *Conversation*: used when discussing certain content or an activity (open or more restricted discussions with learners).
- *Feedback Loops*: (engaging learners and the teacher in feedback loops to guide their learning).

This framework can serve as a grammar of actions to describe and model instructional contexts and interactions. It describes teaching abilities as nodal actions by growing order of complexity and cognitive load. All of them can be considered as the grounds of k_1 – they are all involved in social learning. The next section aims to validate this framework. Since the role and effect of each of these modules in instructional interactions are hard to detect separately because of their complexity, we use a classroom observation tool to make a first rough assessment of our framework.

FRAMEWORK VALIDATION WITH THE CLASS OBSERVATION SYSTEM

We now have to check how teachers actually behave in classrooms with regard to these modules. Since the observation and measure of cognitive load of teacher behaviour is costly, we decided to base our analysis on a well-known classroom observation system, the Classroom Assessment Scoring System (CLASS) (La Paro, Pianta, & Stuhlman, 2004; Pianta, La Paro, & Hamre, 2008), which will serve as a proxy to determine which abilities ground which the teacher's behaviour. This is a theoretically-sound system, validated through the observation of more than 4,000 classrooms across the United States of America. Its reliability (across observers and during a school year) and validity (both construct-related and predictive) have been extensively and repeatedly reported. The CLASS is a way to measure the classroom climate and teacher/student relationships in three main domains, distributed across 10 dimensions, which are in turn distributed across several behavioural markers:

- *Emotional Support*: Positive and negative climate, Teacher sensitivity, Regard for student perspectives.
- *Classroom Organisation*: Behaviour management, Productivity, Instructional learning formats.
- *Instructional Support*: Concept development, Quality of feedback, Language modelling.

Measures of climate quality are processed during at least four instructional sessions (20 min each) through Likert scales. Research showed convergent score patterns across the observed classrooms. We assume that these score levels are related to the cognitive load and the type of knowledge that is entailed in: the higher the score, the lower the level of knowledge (and the cognitive load) involved.

Research showed that average scores of K-3 classrooms on emotional support and classroom organisation range from moderate to high level (likely relying mostly on k_1), whereas those on instructional support are low in quality (likely relying mostly on k_2).

In order to validate this hypothesis, the different dimensions of the CLASS, together with their indicators, were analysed in function of the ability level mostly involved (see the previous section) by the first author of this paper, a certified CLASS assessor. Some behavioural markers were removed because of their pupil-centration (Teacher Sensitivity>Student Comfort, Behaviour Management>Student Behaviour, Instructional Learning Formats>Student Interest, with the ">" connecting a given dimension with its behavioural markers), as well as the whole "negative climate" dimension. Tables 1 to 3 below depict the CLASS domains/dimensions/indicators (lines) in relation to the four sets of natural abilities they are likely involved in (columns). The grey slots code the likely presence of an ability solicited in the processed dimension. Each ability has a value so that a mean score can be eventually processed by dimension (e.g. Teacher sensitivity>Awareness scores 9, which is the mean of {10, 9, 8}, the respective values of each of the Detection module abilities).

Emotional support, as depicted in Table 1, mainly involves low-level modules (Detect and Align). The *Positive climate* dimension is affected by the Detect and Align modules (Knowledge gap detection is not used in this dimension since no formal knowledge is at hand). The Relationships indicator affects the Activity module because it is related to several and diverse abilities: physical proximity, shared activities, peer assistance, matched affect, social conversation). Moreover, Conversation is triggered with the presence of Positive communication and Respect. The *Teacher sensitivity* dimension mainly taps into the Detect module (Addressing problems excepted, which needs Feedback to work). Eventually, the *Regard for student perspectives* dimension also closely involves the Detect module. Three of four indicators tap into very close ranges of modules (Detect, Align and Activity arrangement, Flexibility excepted), Student expression excepted, which uses Detect module and Conversation to elicit learners' expression.

The *Classroom organisation* domain, as depicted in Table 2, is related to the Detect and Align modules like the previous domain is, with an emphasis on knowledge and a greater involvement of the Arrangement-focused module, like in the Preparation dimension. The Instructional learning formats models show more important use of the Initiate module since pedagogical activities can be composed of actions pertaining to the exposition of content ("show" action).

The third and latest CLASS domain (see Table 3), *Instructional support*, is composed of Concept development and Quality of feedback, which are very complex and rich activities and use almost the whole range of abilities. Language modelling involves Conversation-based abilities, as well as Detect and Align abilities.

To what extent is the performance across the CLASS dimensions related to the module abilities? We computed a bilateral correlation between the CLASS dimension scores from a world-wide synthesis of the mean CLASS observation results (USA, Finland, the Netherlands, Portugal, France, Chile, Canada) computed by Cosnefroy et al. (2014) and the mean ability scores expressed by dimensions, as shown above. We found a significant correlation: $r = .70$, $p < .05$. This reveals a strong relationship between the current mean level of quality of teacher–student interactions in classrooms, and the complexity of natural or social skills likely involved in teaching. The more complex the latter are, the lower the corresponding CLASS dimension score involving them. In other words, it is noteworthy that classrooms in most countries score medium or high for Emotional support and Classroom organisation, and these dimensions tap into relatively low-level modules (see Table 1 and Table 2). Conversely, the Instructional support dimension involves modules at the highest level (see Table 3).

DISCUSSION

We attempted in this paper to describe what would be the set of *primary knowledge* involved in teaching, built on top of social skills that can in turn be used in building PCK, a more sophisticated and *secondary knowledge*-based set of knowledge. We also tried to validate the presence of these skills through the scores obtained from the CLASS, a widespread observation system. We set up a very rough grammar of actions to describe natural teaching processes. These actions were used as a framework to predict the complexity of the teacher–student relationships, as described in the CLASS observation system. This framework is more cognitively plausible than the evermore decomposition of knowledge components. The results showed a strong relationship between the raw description of the abilities involved in each CLASS dimension and the mean score the teachers commonly have in that dimension. This result may explain the fact that knowledge-related processing is more demanding for teachers because it involves higher-level module abilities.

This result is a first step toward a two-tier description of the teacher's knowledge-governing process: *primary knowledge*, involved in classroom management and social teacher–student interactions, and *secondary knowledge* for instructional design (planning) and didactical strategies. Historical, evolutionary or comparative approaches should help us understand the different possible weights of these two types of knowledge (e.g., Kline, 2015) and their relationships with human evolved adaptations (Balachandran & Glass, 2012). But, at this stage of our work, it seems much more prudent to follow dual-process theories and to consider that primary – and secondary – evolved teaching capabilities are always available, and that teachers can switch from one to another. Understanding the mechanisms underlying this switching is a main challenge.

We can list some consequences of the way to study teaching processes. First of all, this framework may be used in a descriptive way, as the basis of a diagnosis on how knowledge is used in teaching: – how k_1 and k_2 are actually used in daily classroom practice – how they are related to a measured amount of cognitive load, and – why and when a teacher can switch from the use of one type of knowledge

Table 1. Emotional support CLASS domain: Indicators tapping into the modules of our framework

Dimension	*Indicators*	*Detect*			*Align*		*Arrange*			*Initiate*	
		Face	*ToM*	*K Gap*	*Aff./Motiv.*	*Act.*	*Envir.*	*Act.*	*Show*	*Convers.*	*Feedback*
Positive Climate	Relationships	■	■		■	■					
	Positive Effect	■	■		■						
	Positive Communication	■	■		■					■	
	Respect	■	■		■					■	
Teacher Sensitivity	Awareness	■	■	■							
	Responsiveness	■	■	■							
	Addresses Problems	■	■	■							■
	Flexibility and Student Focus	■	■	■	■	■	■	■			
Regard for Student Perspectives	Supp. Autonomy/ Leadership	■	■		■	■	■	■			
	Student Expression	■	■	■						■	
	Restriction of Movement	■	■		■	■	■	■			

Table 2. Classroom organisation CLASS domain: Indicators tapping into the modules of our framework

Dimension	*Indicators*	*Detect*			*Align*		*Arrange*		*Initiate*		
		Face	*ToM*	*K Gap*	*Aff./Motiv.*	*Act.*	*Envir.*	*Act.*	*Show*	*Convers.*	*Feedback*
Behaviour Management	Clear Behaviour Expectations										
	Proactive										
	Redirection of Misbehaviour										
Productivity	Maximising Learning Time										
	Routines										
	Transitions										
	Preparation										
Instruction-al Learning Formats	Effective facilitation										
	Variety of Modalities and Materials										
	Clarity of Learning Objectives										

Table 3. Instructional support CLASS domain: Indicators tapping into the modules of our framework

Dimension	*Indicators*	*Detect*			*Align*		*Arrange*		*Initiate*		
		Face	*ToM*	*K Gap*	*Aff./Motiv.*	*Act.*	*Envir.*	*Act.*	*Show*	*Convers.*	*Feedback*
Concept Development	Analysis and Reasoning										
	Creating										
	Integration										
	Connections to Real World										
Quality of Feedback	Scaffolding										
	Feedback loops										
	Prompting Thought Processes										
	Providing Information										
	Encouragement and Affirmation										
Language Modelling	Frequent Conversations										
	Open-Ended Questions										
	Repetition and Extension										
	Self- and Parallel Talk										
	Advanced Language										

to another. Second, this framework may have a more prescriptive use by separating two kinds of knowledge to be built in teacher development. For example, one way to decrease cognitive load is to consider teaching as a joint activity (see Chapter 4, Section 1 of this book). Teacher and pupils work together to trigger and maintain joint activities (affect expression, joint attention) aligned with each other (Garrod & Pickering, 2004; Sahlström, 2001), facilitating their own activity. Another way is to reduce the cognitive load by routinising the first two domains (emotional support and classroom organisation), thereby devoting more cognitive resources to process instructional support-related situations.

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Philippe Dessus
LSE, Univ. Grenoble Alpes
Grenoble, France

Frank Tanguy
University of Bordeaux
Bordeaux, France

André Tricot
UMR 5263 CLLE (CNRS), University of Toulouse-2
Toulouse, France

SECTION 4

CONCLUSION

MICHEL GRANGEAT AND BRIAN HUDSON

12. A NEW MODEL FOR UNDERSTANDING THE GROWTH OF SCIENCE TEACHER PROFESSIONAL KNOWLEDGE

In the conclusion to this book, we aim to articulate the insights delivered by each chapter regarding the science teacher professional knowledge domain. In doing so, we aim to combine the outcomes of these chapters in responding to the questions that were raised in the introduction.

One of this book's main claims is that teaching is partly similar to other professional activities, and part of all human activities. Accordingly, the authors of this book have taken advantage of frameworks and theories that underline the exploration and understanding of diverse human activities and professions. The first part of this conclusion tackles these issues: teaching is a human activity that forms part of social and cultural contexts in which knowledge is continuously evolving.

Another crucial claim is that teaching is a specific activity since it refers to a topic with its contents, to teachers with their beliefs and orientations, and to students with their prior knowledge and skills. The second part addresses both the role of content knowledge and the epistemological and ontological reflections about it, and the balance between content and general pedagogical knowledge.

Finally, in order to contribute to the efforts to better understand teaching and improve learning, we propose a new model that aims to grasp the transformation of science teacher professional knowledge. This new model[1] largely draws on the PCK&S model that Gess-Newsome (2015) derived from the PCK summit (Berry, Friedrichsen, & Loughran, 2015). It needs to be referred to a theoretical framework that reinforces its validity. Envisioning a subject's professional actions and reflections as interacting with different contexts, the theoretical framework of activity theory is adapted to our purposes.

TEACHING IS A PROFESSIONAL ACTIVITY

Teaching is a professional activity. In this sense, it shares a lot of commonalties with other human activities, it is part of a social context, and it is continuously transformed. This section addresses these issues.

M. Grangeat (Ed.), Understanding Science Teachers' Professional Knowledge Growth, 205–228.

Teaching is a Human Activity

Understanding human activity for improving both teaching and teacher education may appear a waste of time to some due to the apparently immeasurable distance between the two purposes. Nevertheless, any observer of any lesson has been affected at least once by noticing how teachers can encounter difficultly in managing low-achieving students when they are overloaded by contextual factors such as a new lesson, lack of institutional support, a large number of struggling students (Wallace, 2014), numerous classroom preparations, the assignment of responsibilities etc. (Gess-Newsome, 2015). Thus, even if the question seems difficult, we endeavour to include such an issue through two aspects: first, the distinction between "natural" and "rational" knowledge and, second, the interaction between teachers and teaching instruments through the construct of "affordance".

The chapter by Dessus, Tanguy and Tricot (Chapter 11) provides some insights into the issue. The authors distinguish two sorts of knowledge that are conversely related to the amount of cognitive load of the activity. Primary knowledge is part of human heritage and each individual acquires it through a simple adaptation to the environment. Secondary knowledge is the result of rapid and successive changes and has to be learned explicitly. They note that in many domains including teaching, particularly in the case of a high cognitive load, human activity is frequently underpinned by primary (natural) instead of secondary (rational) knowledge, even when available. According to this observation, they propose a distinction between pedagogical knowledge – seen as largely based on primary knowledge – and pedagogical content knowledge – termed as rational. That distinction is questionable since, at first sight, the upper levels of pedagogical knowledge are too complex to only be rooted in natural adaptation to the context. In fact, it raises crucial questions that should support an ontological reflection about teaching: is it a natural attitude of human beings to cope with low achievers, and to design adapted pathways, in order to allow them to achieve valued goals? Or is it a recently acquired behaviour that requires attention and reflection? According to the response, pedagogical knowledge will require a low or high cognitive load and will necessitate minor or large efforts during teacher education and continuous development programmes.

For the purpose of elaborating a renewed model of science teacher professional knowledge, we maintain that teachers may easily switch from "rational" to "natural" knowledge in the case of a significant cognitive load. As the practices required of teachers by the reformed curricula in the entire world are highly demanding, we assume that teachers encountering unexpected difficulties may adopt simplistic attitudes, for instance by denying all possibilities for performing learning-centred strategies and privileging methods focused on transmitting basic information to students to prepare them for the next level (Friedrichsen et al., 2009). The effort to achieve more "rational" practice is difficult but possible as reported by Nilsson (Chapter 9) and Kermen (Chapter 6). Consequently, in order to reduce the undesirable effects of the teacher "amplifiers and filters" identified by the PCK&S model, we assume that more attention has to be paid to the cognitive load required by certain teaching methods, and to the distinction between "natural" and "rational" knowledge underpinning all human activity.

If the nature of teaching depends on the cognitive load required by expected classroom practice, we can consider that the quality of teaching resources and instruments plays a major role in scaffolding teachers, and reducing the cognitive load during teaching. As the case study by Kapon (Chapter 10) shows, these instruments comprise 'hidden' opportunities and constraints which can be recognised and used by teachers and thus contribute to shaping their actions. These affordances can be directly perceived by the agent when interacting with these instruments, whereas others need to be recognised as specific potentiality of a tool and this is where education and experience come to the fore. This sensitivity and responsiveness to the potentiality of the environment is an important part of individual professional knowledge for teaching. Consequently, unlike the usual trends, teachers and teacher educators do not need to search only for applications but also for the recognition of affordances. Instructional methods courses should be transformed in a way that better empower pre- and in-service teachers, providing them with tools to design their students' learning and helping them to construct their self-efficacy.

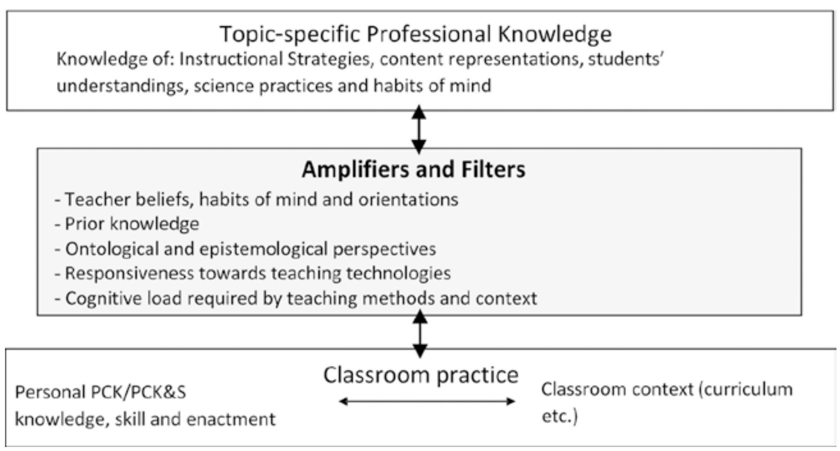

Figure 1. The teacher's amplifiers and filters with reference to the PCK&S model

Therefore, including in a renewed model the nature of knowledge that underpins human activity, and the role of the opportunities offered by technologies, stresses ontological and epistemological issues in teaching. This model needs to encompass these basic attitudes that underpin teaching and learning by unfolding the category of teachers' "amplifiers and filters" of the PCK&S model (see Figure 1). The next section explains why "context" is removed from this category.

Teaching is Part of Social and Instrumental Contexts

Within the PCK&S model, the teaching context is placed with "science teaching orientations and beliefs" in a specific amplifier or filter role that mediates teachers' actions and choices (Kind, 2015, p. 192). We argue that it is such a crucial element that it deserves a dedicated category since "teaching is a process that includes several components: the teacher herself, students within her classroom, the content, and the school environment" (Blonder, Benny, & Jones, 2014, p. 6). As shown by Kapon (Chapter 10), the technological environment contributes to shaping teachers' actions and choices. The studies by Grangeat (Chapter 7) and Kapelari (Chapter 8) demonstrate that the social context in which teachers are embedded influences their PCK growth. The two-year-long observation by Jameau and Boilevin (Chapter 3) highlights the alteration of teacher knowledge resulting from classroom feedback. Thus, the role of the teaching context needs to be explored.

This importance of the context cannot reduce the teachers' central role. The model we propose is clearly built on the fact that teacher professional knowledge makes a difference to students' learning outcomes. As stated by Hattie (2013), teachers are among the most powerful factors that influence learning since:

> The act of teaching requires deliberate interventions to ensure that there is cognitive change in the student: thus the key ingredients are awareness of the learning intentions, knowing when a student is successful in attaining those intentions, having sufficient understanding of the student's understanding as he or she comes to the task, and knowing enough about the content to provide meaningful and challenging experiences in some sort of progressive development. It involves an experienced teacher who knows a range of learning strategies to provide the student when they seem not to understand, to provide direction and re-direction in terms of the content being understood and thus maximize the power of feedback, and having the skill to 'get out of the way' when learning is progressing towards the success criteria. (p. 23)

Following this perspective, the renewed model is centred on individual teacher knowledge. Nevertheless, "effective practice such as providing feedback to students cannot spread just by describing them or advocating for their use" (Hargreaves & Fullan, 2012, p. 50). Conversely, cooperation and teamwork amongst teachers, teacher educators and experts – as researchers – have proved to be efficient. Understanding teacher professional knowledge growth therefore implies exploring the ways it may be developed through the collective creation or alteration of teaching material and artefacts, and the enrichment of the repertoire of instructional strategies that is available to teachers as individuals or as a group.

Parallel to this, relevant theoretical bases are necessary for designing a renewed PCK model. Within this book, several authors have based their research on the activity theory framework after Engeström (2000). According to this theory, subjects – teachers – attribute meanings to their choices and actions by evaluating the gap between the object that orientates their global activity and its outcome. As argued previously, these choices and actions are mediated by instruments, which comprise digital technologies, textbooks and all teaching resources such as pedagogical websites and, in an expansive meaning of "instruments", teacher education and continuous professional development programmes. All of these instruments contribute to shaping teachers' choices and actions. Accordingly, understanding the growth of teacher professional knowledge calls for diagnosing and exploring which instruments are available to teachers and to what extent do these instruments transform such knowledge.

In addition, activity theory sees professional activity as always underpinned by a community, governed by a certain division of labour and shaped by certain rules. From this perspective, a community is merely a group of people responsible for a shared object; in this way, teachers are always part of a community (Engeström, Kajamaa, Kerosuo, & Laurila, 2010). As stated by Plakitsi (2013), "the framework provided by activity theorists is a coherent theoretical framework which establishes science education as participation in the community" (p. 5). Thus, exploring the fundaments of teacher knowledge leads us to portray the role of teachers' groups, and the rules shared within these groups.

Further, the culture of each subject teachers' community is crucial for understanding their professional knowledge base; for instance, the habit of caring for students' safety in chemistry classrooms may reduce the level of autonomy below which teachers feel comfortable. In addition, it is well known how head teachers' styles impact on teachers' objects, choices and actions.

Consequently, the classical activity theory triangle is adapted for understanding teaching. The central sequence subject-object-outcomes is changed in the sequence teacher-classroom practice-student outcomes. This sequence represents the core of teaching, and is shaped by both instruments and social context (see Figure 2).

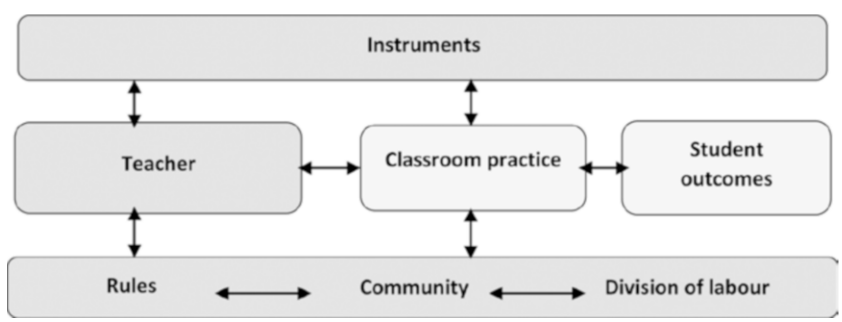

Figure 2. The activity system of teaching

Understanding Teacher Knowledge in Contexts

The activity theory model does not take account of the fact that, in some professions, the objects of the action are other subjects. In education, the students are part of the system since they interact with the teachers' action by sending feedback that helps shape the choices and actions of the teachers. For instance, the case study by Cross and Lepareur (Chapter 4) demonstrates that teachers need to learn how to recognise, interpret and cope with students' behaviour: if the teacher's professional knowledge is too stable and strong, it impedes the teacher's recognition of the students' feedback. As stated by Gess-Newsome (2015), "student outcomes are the 'downstream' products of educational research" (p. 39). From this perspective, we consider that student outcomes are part of the classroom context.

Within this book, key features of scientific learning are mentioned. These are split into three parts, as outlined by Jameau and Boilevin (Chapter 3), Nilsson (Chapter 9), and Kermen (Chapter 6): knowledge of the content, knowledge of scientific methods, and understanding of scientific thinking, comprising argumentation. The studies by Cross and Lepareur (Chapter 4) and Grangeat (Chapter 7) show three complementary elements: motivation regarding scientific issues, self-regulation, and cooperation within peer groups. These elements are partly included in the classroom context since student outcomes are transferred outside the school.

Therefore, the teaching context is seen as threefold and consists of instruments, social organisation, and interaction in the classroom (see Figure 3):

- The mediation of instruments: teachers' knowledge is transformed by the use of instruments. This instrumental context comprises teaching artefacts (textbooks, resources as guidelines or syllabus, concrete material like the disposition of the tables in the classroom), digital technologies (applications and devices) and teacher education (formal or informal, like participating in a joint project with external partners). Teacher education forms part of the instruments because it often provides teaching material that aims to transform classroom practices.
- The action of a specific social context: teachers' knowledge is related to the group in which each teacher is involved or committed. The quality of this social context depends on the nature of the division of labour (hierarchical structure, school leadership, collective organisation), on the community (orientations and purposes, professional culture, habits of mind) and on the rules that underline the teachers' group (habits and repertoires of actions used by or available to members of the group).
- The nature of the classroom context: this third context interacts directly with the subject – with the teacher. The way classroom practices unfold and students perform directly interacts with teacher professional knowledge.

These interactions are constant during the different phases of teaching: planning, performing, assessing and reflecting.

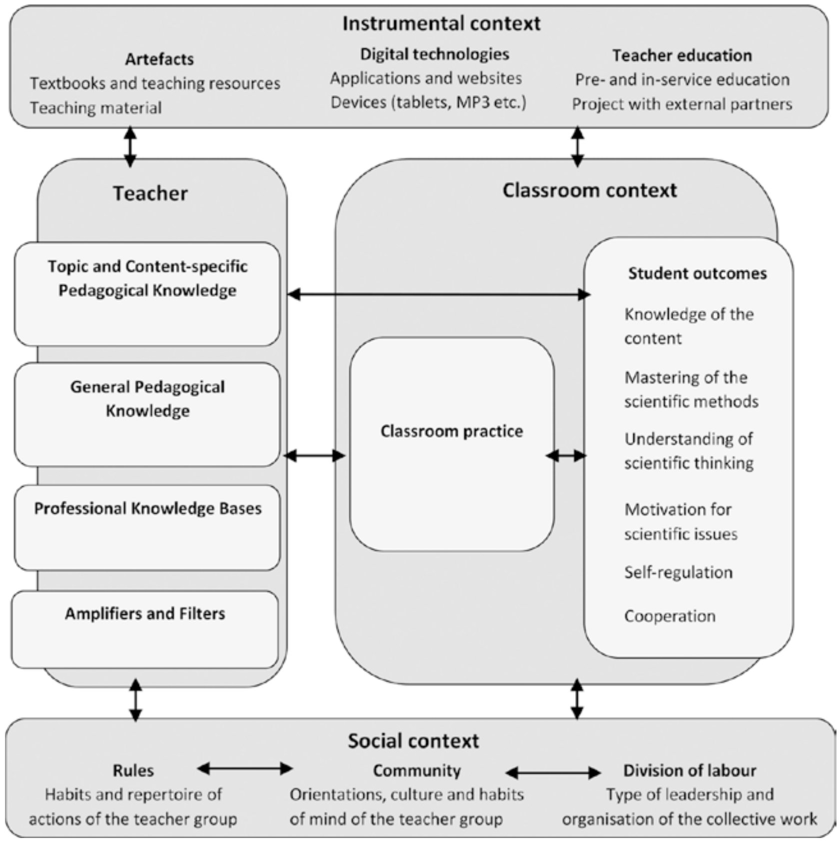

Figure 3. Teaching contexts that shape teacher knowledge

Teaching Is an on-Going Process

As with other professional fields, teacher knowledge is constantly evolving during education and the work process. This evolution depends upon the subject's reflection in and on the action, and upon the cycles between the development of tacit and explicit knowledge.

Studies in various professional fields have shown that actors' professional knowledge is a synthesis arising from: the habits of mind and know-how that are shared through the community; information collected from the Internet or specialised documentation; education or training programmes; and lived experiences (Fischer & Boreham, 2004). These sources of knowledge are consistent with the contexts interacting with teacher knowledge (see Figure 3). This synthesis not only concerns the specific activity carried out by an individual, but also the whole work process and the collective way of handling it. It emerges from contradictions between standards and instructions, theoretical knowledge, and perceptions of professional reality. That implies that professional knowledge is dynamic since it evolves when new professional problems and dilemmas are overcome (Grangeat & Gray, 2007). That is consistent with the relations represented by the different double arrows inscribed in both the model outlined above (see Figure 3) and the PCK&S model (Gess-Newsome, 2015). The question is to specify the meaning of these double arrows, and thus the processes that interact between teacher knowledge and the three contexts.

Insights are gained from studies in ergonomics exploring this question through a twofold regulation loop (Rogalski, 2004; Grangeat & Gray, 2008). The first part of the loop derives from the results of the subject's action and transforms the situation, the context of the action. In our case, the student outcomes transform the classroom practice. The second part of the loop results from a reflection by the subjects about the effects of their activity that, in turn, transforms the subjects' professional knowledge. These are respectively the short and long regulation loops emphasised by Jameau and Boilevin (Chapter 3), with the first transforming the practices during the lesson and the second the repertoire of instructional strategies (see Figure 4). In this sense, these empirical results reinforce the PCK&S model presented by Gess-Newsome (2015) and endeavour to respond to Kind (2015) who regrets that "the model is complex, with connecting arrows and components layers. Nothing indicates what these arrows are or mean" (p. 193).

The process of transformation between tacit and explicit kinds of knowing provides important support for professional education. As stated by Henze and Van Driel (2015), teacher knowledge is largely tacit since, to express it, it is necessary for teachers "to be aware of this knowledge, and to have the ability to articulate it" (p. 132). We claim that it is also a question of opportunity. The studies by Nilsson (Chapter 9) and Kapelari (Chapter 8) demonstrate how tacit knowledge can be transformed into explicit knowledge shared by a community. They point out that this process relies, on one hand, on the interactions amongst the community and between individual professionals and expert observers and, on the other hand, on teacher reading, on sharing information through the Internet, on education programmes, and on joint projects with partners. Nevertheless, during the cycle, the new knowledge again becomes tacit since it is internalised by teachers involved in the programme or project.

This cycle provides opportunities for capturing teacher professional knowledge. An external observer can collect and make explicit the set of professional knowledge of a group of teachers involved in a project that comprises focus groups, leading teachers to express their conceptions about a particular topic or content or about a specific pedagogical issue – for instance, the combination of formative and summative assessment. In addition, as shown by Jameau and Boilevin (Chapter 3), Kermen (Chapter 6) and Grangeat (Chapter 7), a researcher or a teacher educator can collect individual professional knowledge by asking a teacher to express her or his choices and goals during an interview underpinned by a video of this teacher performing in the classroom. The interview can focus on the content, topic-specific or general pedagogical knowledge.

Despite this, as clearly demonstrated by Cross and Lepareur (Chapter 4), what is at stake is not the extent of declarative professional knowledge but the realisation by teachers in the classroom. A large discrepancy may exist between teachers' professional knowledge that is tacit, that may be made explicit, and that is performed with students. Thus, in the classroom context, what counts is the enactment of teacher professional knowledge – the teacher's skills. Nevertheless, part of this knowledge can be inferred from this performance by researchers.

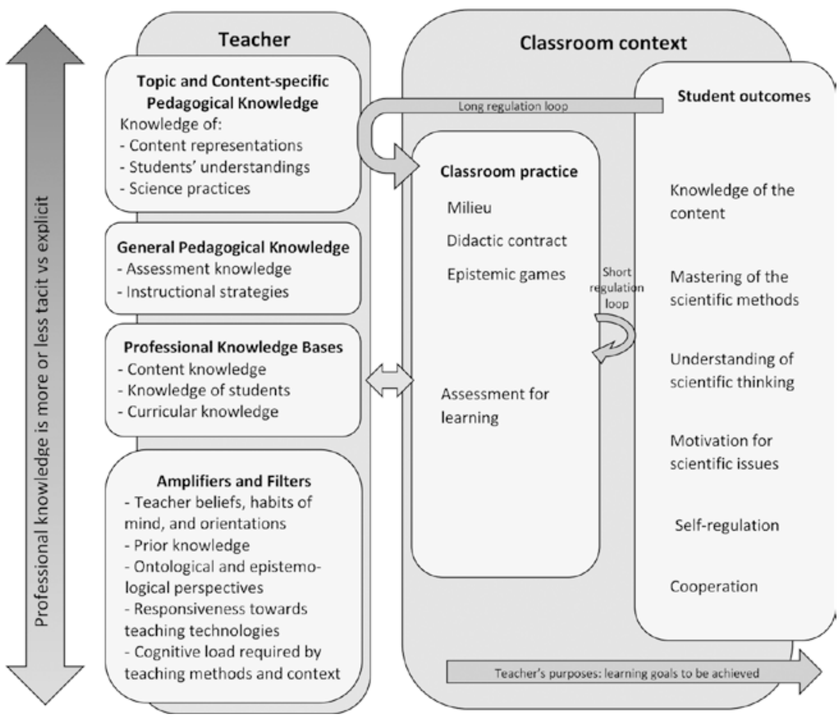

Figure 4. Interactions between teacher professional knowledge and the classroom context

In his chapter, Sensevy (Chapter 5) argues that what is enacted in the classroom depends on the knowledge and behaviour of both teachers and students. This idea reinforces the proposition of including in the same "classroom context" category of the model both classroom practice and student outcomes. This emphasises, in a renewed way, the crucial role of the short regulation loop that transforms classroom practice during the lesson regarding student outcomes. This results in investigating two components of the classroom context: first, the "milieu" that is the whole environment designed by the teacher in order to promote learning for all the students; second, the "didactic contract" – in other words, the "instructional agreement" – that is the set of habits and procedures shared by the teachers and the students regarding both the usual organisation of the work and the content-specific tasks that relate to the specific notion being learned in the current lesson. The balance between the two underscores the quality of the "epistemic games" in which teachers and students are involved. If the milieu is poor or the didactical contract is unclear, the quality of the epistemic games is weakened and the students cannot really benefit from the lesson. Sensevy's framework provides meaningful insights for understanding three crucial components of classroom practices in the model: milieu, didactic contract, and epistemic games.

Finally, even if any chapter of this book stressed this issue, the category "classroom practice" needs to include assessment for learning. Most research studies about PCK skip it but, as Harlen (2013) argues, this kind of assessment "is not something that happens occasionally; it is integral to the process of making decisions that is happening all the time in teaching" (p. 17). It is thus part of the decision-making process that shapes the classroom practice (see Figure 4).

TEACHING ENTAILS A SCHOOL, A DOMAIN, A TOPIC AND SPECIFIC CONTENT

This section pursues the reflection by addressing the nature of the teacher professional knowledge that is related to a topic and specific content, and the balance between content and general pedagogical knowledge. It stresses the role of epistemological and ontological reflection on this aspect.

Distinguishing CK, PK and PCK

The studies that make up this book address diverse types of science teacher professional knowledge. Such knowledge concerns the bases that are necessary for teaching, namely, general pedagogical knowledge, and the topic and content-specific knowledge.

Content knowledge. This knowledge is the foundation of teaching activity. It addresses all phases of a teacher's career but particularly their first years of teaching, when the limitation of experience does not allow new teachers to rely on effective pedagogical methods.

The mastering of the content is one of the key issues regarding the first steps in teaching, but it may be not the main concern. McCormack (Chapter 2) stresses the crucial role of awareness about the content that is known or uncertain. Being able to distinguish between certain and uncertain assertions represents a basis of scientific thinking. Pre-service teachers' and students' educational experience needs to provide opportunities to make this kind of epistemological reflexion usual for all learners. We assume that these habits of mind would be more widespread among teachers if, during undergraduate studies, the content is not transmitted as an amount of discrete facts. The necessity to be aware of the weakness of some part of the human knowledge and of his/her own mastery of this content may be more generalised if this content is introduced as a system of knowledge aiming to respond to human questions and intended to be shared by scientists and civil society. We assume that undergraduate students and pre-service teachers may improve their reflection about what they know related to a specific content if all of them are regularly involved in disseminating projects aiming to explain this content to people who are novices in the field.

Regarding experienced teachers, content knowledge remains an issue. Nilsson (Chapter 9) emphasises how collaboratively designing efficient teaching units results in deepening both the understanding of the notion to be taught and the way to make it understandable to students. By exploring the interactive process between content and pedagogical content knowledge, her study demonstrates that the momentum resulting from the collaboration between teachers and experts about a lesson design triggers a deepening of the content mastery by experienced teachers. We assume that this kind of collaboration deserves to be more widespread.

General and content pedagogical knowledge. This knowledge represents the core of classroom practice and shapes students' outcomes. The issue is to make it visible by being aware of the cycles between the development of tacit and explicit knowledge.

The studies in this book provide criteria for distinguishing the two types of pedagogical knowledge. They demonstrate that teaching relies on such general and specific knowledge and skills. The issue is to enlarge the repertoire of instructional strategies – general and specific – available to teachers as individuals and as a community in a school. We assume that students' outcomes would be improved if teachers in a school gained the opportunity to address what they know, individually and collectively, about:

- general teaching strategies (assessment for learning, ways for differentiating teaching regarding students' needs and expectations);
- domain or topic instructional practice (developing students' autonomy in scientific inquiry, allowing students to argue in a scientific way); and
- content that is relevant to a topic or to crosscutting concepts.

Classroom practice. Nevertheless, the main issue resides in the enactment of this general or content pedagogical knowledge during teaching.

Sensevy (Chapter 5) introduces the notion of counterfactual strategies that are the various virtual ways of acting that an analysis can propose as alternatives to a given actual teaching practice. This enables the researcher to focus on the concrete teaching-learning praxis. In this perspective, teacher PCK can be seen as a particular skill, specific to a given system of knowledge, which relies on the repertoire of counterfactual strategies a certain teacher is able to envision relating to this system of knowledge, through the joint action he/she is involved in with the students. We assume that teacher PCK "in action" is necessarily grounded on knowledge-related generic principles and strategic rules, but needs to also take account of the (more or less) contingent features of a situation nested in a given institution.

Parallel to this, Grangeat (Chapter 7) raises the issue of teachers' collective work. Teachers are involved in a school community and share professional knowledge with colleagues in other subjects. They need to elaborate strong professional knowledge that enables them to engage "in activities that require creativity to solve complex problems and that make a real difference" (Hargreaves & Fullan, 2012, p. 151). Depending on the colleagues they work with, teachers need general knowledge that contributes to the school's effectiveness, or topic or content-specific knowledge that improves student outcomes in a domain. We assume that these exchanges were more productive if teachers share common teacher professional bases about the curriculum, the cognitive and affective process which underlies learning, and about the crosscutting content (art, creativity…).

Consequently, there is a need to explore the elaboration of teacher professional knowledge that refers to the school, the domain, the topic and the content. There is also a need to develop a linkage among these parts of teachers' education that are often artificially separated.

Reflecting on Epistemological and Ontological Questions

The model stresses the importance of epistemological and ontological issues. Within the literature, three factors that influence science education are commonly addressed: competence in the use of scientific enquiry processes, confidence in handling the emotional and psychological states associated with the subject, and understanding the content to be taught. The previous sections highlighted how the last of these needs to be handled in a more effective way than usual by being linked to instructional strategies that will allow this content to underpin students' or other people's education. Here, we want to pay more attention to the first two. This addresses the question of the nature of science and the importance of developing scientific thinking in the science classroom.

For example, in his analysis Lakatos (1976) compares and contrasts the deductivist approach and the heuristic approach to mathematics and describes the latter as the logic of proofs and refutations. He presents the perspective of mathematical fallibilism based on a view of mathematics as human activity and on the proposition that it is this human mathematical activity that produces mathematics. However, Hudson et al. (2015) argue that it is not simply the dominating influence of this deductivist approach which is a problem for the teaching and learning of mathematics in schools today, but the way in which this can become distorted in the process of 'didactic transposition'. The concept of 'didactic transposition' relates to the school context in which the knowledge in question is not knowledge for acting and solving problems in the social contexts in which it was created and where it is used, but is instead transposed into knowledge to be taught and to be learned. The concept of didactic transposition is based upon recognition that there is a 'rupture' between daily life and school, which changes the knowledge profoundly. It is further argued that this rupture can lead to the epistemic quality of the subject becoming degraded as it is transposed into school mathematics. This high epistemic quality is seen to involve an approach which presents mathematics as fallible, refutable and uncertain and which promotes critical thinking, creative reasoning, the generation of multiple solutions and of learning from errors and mistakes. In contrast, low epistemic quality is seen to be characterised by an approach that presents the subject as infallible, authoritarian, dogmatic, absolutist, irrefutable and certain and which involves rule following of strict procedures and right or wrong answers.

It is further argued that high epistemic quality is promoted through an approach based on assessment for learning involving low-stakes formative and self-assessment which is engaging and motivating for individual learners and leads to a sense of enjoyment and fulfilment of mathematics as a creative human activity. In contrast, the excessive pressure from high stakes external testing and inspection and the associated heavy emphasis on drill and practice lead to the degradation of epistemic quality into a form of mathematical fundamentalism and to an experience for learners of mathematics that is fearful and anxiety inducing, boring and demotivating and leads to alienation from the subject itself.

This reflection stresses the importance of paying attention and evaluating the epistemic quality of prior didactic analysis – during the planning phase – and of classroom practices. In our model, these factors are represented in the categories "amplifiers and filters" and "epistemic games".

METHODOLOGICAL ISSUES

Our reflection also comprises methodological issues that may complement the field. Two main issues are addressed: how to capture and portray teacher professional knowledge, and how to spur this knowledge development.

Four components for portraying professional knowledge are proposed by Grangeat (Chapter 7): goal, clue, repertoire of action, and reference knowledge. The goal represents the specific purpose that sustains teaching with regard to a particular topic or content. The clue is each event, expected or unexpected, that leads the teacher to choose, more or less consciously, to act in a specific way, to initiate a specific classroom practice. As these clues are often rapid and trigger the adjustment of instruction, they play a central role in teacher knowledge. The repertoire of actions encompasses the different instructional strategies available to a teacher in a specific context, to particular students, for a given content. The reference knowledge is what is used by the teacher for explaining and justifying the choices that are actualised during the planning stage of the courses or the act of teaching in order to enhance student outcomes. These four components concern the different types of professional knowledge whereas this knowledge is explicit for the teacher or made explicit through a research method or a teacher education programme.

Criteria for distinguishing general or content-specific pedagogical knowledge are provided by Jameau and Boilevin (Chapter 3), Kermen (Chapter 6), and Grangeat (Chapter 7). General pedagogical knowledge may be shared by teachers from different disciplines. Teachers of a same school or a same team may share the same set of knowledge regarding instructional strategies and assessment – inquiry-based learning, differentiation based on students' needs, assessment for learning, or tests. Consequently, if the teacher does not refer to topic or content-specific issues for explaining or justifying her/his choices, the pedagogical knowledge is general. Conversely, if the teacher refers to a particular topic, or specific content, she/he makes explicit a piece of topic or content-specific pedagogical knowledge.

Metacognitive issues about mastering the content are emphasised by McCormack (Chapter 2). The test she presents provides an opportunity, among other tests, for evaluating this content knowledge and the level of awareness that teachers and mainly pre-service teachers have of their possible weaknesses. Such a reflective attitude is crucial for new teachers since it is clear that they cannot master all the contents of all the topics for all students in their entire domain. This is similar for experienced and veteran teachers in the case of curriculum changes. Thus, evaluating teachers' metacognitive attitude complements the usual ways of testing content knowledge.

Developing general and content pedagogical knowledge through collective settings and iterative design-based programmes is proposed by Nilsson (Chapter 5) and Kapelari (Chapter 8). These approaches meet the CoRes (Content Representations) and PaP-eRs (Pedagogical and Professional-experience Repertoires) methods developed by Cooper, Loughram and Berry (2015). These representations – on which in-service teacher development programmes rely – address a specific topic and endeavour to make explicit the big ideas, the key content, shared by the teachers engaged in the programme, the students' alternative conceptions or areas of confusion they know, and their ways of framing ideas and testing for supporting student learning. Pa-PeRs are narrative accounts by teachers regarding how the ideas that had been expressed in CoRe have been put into classroom practice. Focusing teacher continuous development programmes on a specific professional problem, and engaging a group of teachers in overcoming them, seems a way to effectively spur professional knowledge growth. When the programme allows teachers to organise several trials of the teaching unit or instruments that they had designed in a cooperative way, teacher knowledge growth seems more sustainable. Nevertheless, all of our examples concern a group of teachers who cooperate with experts, teacher educators or researchers. It would be a mistake to believe that a group of teachers may improve their practice without the insight of any external actor.

A NEW MODEL FOR EXPLORING THE GROWTH OF SCIENCE TEACHER PROFESSIONAL KNOWLEDGE

This section summarises the key points from this conclusion, and presents a renewed model of science teacher professional knowledge growth in contexts.

Teaching as an Activity Influenced by Its Contexts

The first point we stress is that teaching is underpinned by the contexts in which it is enacted. In this sense, teaching shares commonalities with other professions.

The nature of the professional community, at least of the teacher group, strongly contributes to the quality of teacher knowledge. When the community is oriented towards the constant enhancement of teaching practice, individual teachers are supported in their efforts to transform their practice and knowledge; this is particularly the case for new teachers. This orientation of the community is influenced by the way the school is organised. When heads of school, inspectors, ministry and local authorities highly value teaching quality, then the teacher community gains more opportunities for sustaining individual efforts. This kind of virtuous circle transforms community rules and individual repertoires of actions. When the community is supportive, teachers are more able to share their teaching material and practice, and to enlarge and deepen their repertoire of instructional strategies.

In addition, students' behaviour constitutes part of the teaching context that contributes to shaping teacher knowledge. When a teacher is trying a new method, if the students enjoy it, if they are more engaged, and if they achieve the teacher goal in a better way, this teacher is supported in deepening this method, and transforming her/his pedagogical content knowledge. When a student is asking a challenging question about a specific content, if the teacher is supported by a community that values actual scientific thinking, this teacher may search for complementary information and challenge her/his content knowledge.

Finally, classroom practice and teacher professional knowledge are transformed by the tools and signs that are available to teachers regarding a specific content, topic or method in a specific school and community, and for specific students. This instrumental context consists of artefacts (textbooks, teaching material, guidelines and other resources for teachers), of digital technologies (websites, applications, and devices), and of teacher education programmes since they all provide teachers with new instruments and ways of thinking about instruction.

Therefore, the model includes these three types of contexts that interact with teacher professional knowledge and classroom practice. In this sense, it differs from the PCK&S model that merely includes them in the category "amplifiers and filters". This difference consists more in an improvement than opposition since both models recognise the role of the context in shaping teacher knowledge and skills. For these reasons, we propose calling this renewed model the Teacher Professional Knowledge in Contexts (TPKinCs) model (see Figure 5).

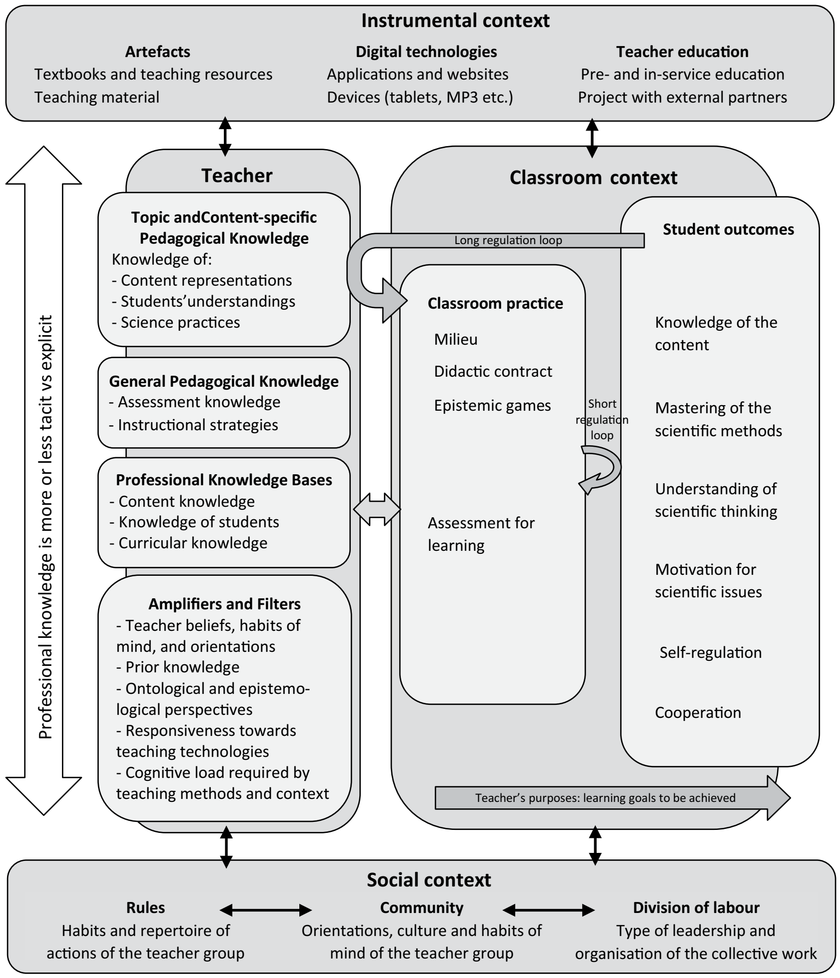

Figure 5. Model of science teacher professional knowledge in contexts (TPKinCs)

Teaching as a Human Activity

The second point we stress is to keep in mind that the nature of teaching practice depends on processes shared by all human beings.

The cognitive load implied by the teaching methods and the context alters the activity. When the cognitive load required by the instructional strategies expected from teachers is too strong, or when the school context is too disturbing, teachers tend to overuse simple methods, often merely transmitting a content.

In addition, teachers' goals, choices and actions that underline classroom practice are mediated by instruments that shape teacher performance. Through the Internet, a lot of teaching material is exchanged among teachers' and schools' networks. Many applications and digital tools are made available to teachers. Teacher education programmes promote new teaching methods. Participation in joint programmes with external partners like scientific centres transforms classroom practice. All of these instruments may enrich teacher professional knowledge if they are not seen as recipe providers but as habits of mind transformers. Such an opportunity depends on the teacher sensitivity and responsiveness in recognising possible affordances in these instruments, and using them. An affordance is a modality inscribed in an instrument for allowing the users to transform their way of thinking of, engaging in, and overcoming problems that are addressed by this instrument. For instance, affordances are created in a lesson plan displayed on the Internet if it contains the principles that had underlined its design; if not, it might be merely a recipe.

Moreover, teachers' reflections and perspectives about learning alter classroom practices and professional knowledge. For instance, teaching depends on the teachers' awareness regarding the accuracy of their content knowledge.

Therefore, the TPKinCs model emphasises the category "amplifiers and filters". Like the PCK&S model, it includes teacher beliefs, habits of mind, orientations, and prior knowledge. This is complemented by ontological and epistemological perspectives, the responsiveness to teaching technologies, and the cognitive load required by teaching methods and the context.

Teaching as a Specific Activity

The specificity of teaching as a professional activity is that its purpose consists in transforming students' thinking, understanding and acting by bringing them into a specific environment. The classroom practice is the locus of teacher professional knowledge enactment. For some researchers, the classroom could be the only opportunity to evaluate teacher PCK. This point is questionable since the classroom and the social contexts may alter such an enactment. Nevertheless, classroom practice remains of greater importance for validating teacher professional knowledge. For understanding this practice, we suggest four criteria.

First, the nature of the "milieu": when the learning environment had been designed in order to allow students to gain autonomy in judging whether they are progressing towards the goal that was elaborated by or with the teacher, these students are more able to develop a deep understanding of the content at stake.

Second, the clarity of the "didactic contract": when teaching and learning are visible, in other words when the teacher's goals and expectations are made explicit, the students become more able to self-regulate their own learning and to support other students.

Third, the quality of "epistemic games": when the teacher and students are tuned towards shared objectives, the teaching practice is more oriented towards deep understanding for more students.

Fourth, the role of assessment: when assessment is a means for learning, teachers and students may join their activity for improving achievement for all. Students are equipped for self-regulating their activity and progress towards goals that are shared by the students' and teachers' groups.

Teaching as a Profession That Necessitates Specific Knowledge

The TPKinCs model comprises three types of teacher professional knowledge. They concern each part of teacher activity.

The professional knowledge base concerns all the educational actors in a school. It consists of three elements:

- Knowledge of the curriculum is needed for understanding the role of each actor in the learner career and for gaining a clear idea of what had to be taught during each grade.
- Knowledge of students allows the actors to share the same conceptions of students' needs and capabilities regarding their specificities, and understanding of affective and cognitive processes that underlie learning.
- Knowledge of content is a base for teaching and educating. The content is relative to a subject, and to a domain through crosscutting concepts.

General pedagogical knowledge mainly concerns the teacher community. It consists of two crucial elements:

- Assessment knowledge is needed by all teachers regardless of their subjects in order to improve the coherency of classroom practices for the same student group.
- Instructional strategies are necessary for dealing with students' needs and expectations, and with specific social and cultural contexts.

Topic and content-specific pedagogical knowledge concerns teachers of the same domain or subject. The content represents the basis of this kind of knowledge, not forgetting that this content concerns both specific and crosscutting concepts. It consists of three elements:

- Content representations allow teachers to propose multiple representations of the same content, and to use specific examples adapted to particular students to support them in building relevant ideas.
- Students' understanding consists in dealing with misconceptions, and prior knowledge for enabling them to elaborate better understanding of a particular content in a particular grade.

- Science practices consist in being capable of integrating content in teaching in a way that motivates the students and allows them to understand the nature of science and the meaning of overarching ideas and crosscutting concepts.

Teacher Professional Knowledge Evolves between Being Tacit and Explicit.

These professional knowledge categories are formalised by researchers and experts, but are also elaborated by teachers through their education and experience. Consequently, a large part of this professional knowledge is tacit.

Therefore, neither teacher professional knowledge nor student outcomes reside uniquely in the teachers' or students' heads. Teacher knowledge is partly tacit and explicit, thus this professional knowledge is owned both by teachers as individuals and as members of a community, and by experts and researchers. It is the reason that, in the model, the grey box representing the teacher does not totally contain the boxes representing the types of professional knowledge. This results from our initial stance regarding the three metaphors of professional education (Grangeat, & Kapelari, ibid.): professional knowledge growth is an on-going process that depends both on the rules and repertoire of instructional strategies that are available within the community, comprising experts and researchers, and on the instruments and resources that exist in the professional environment, comprising teacher educators and teacher development programmes.

This stance does not imply that the professional knowledge created by teachers as individuals or in groups is always efficient. The implication consists in altering experts' and researchers' activities: since teachers, like other professionals, are transforming the content of teacher development programmes and the rules of the school, thus experts in the field have to design teacher education and school organisation that commit teachers to collectively elaborating efficient professional knowledge.

Through two regulation loops the model aims to capture some ways by which teacher professional knowledge is elaborated, enacted and transformed. The short regulation loop takes place during the lesson: by trying new practice and reflecting on what occurs in the classroom (reflection in action), teachers change their beliefs and knowledge about their own skills. The long regulation loop acts from one term, semester or year to another: by noticing what occurs with student outcomes, teachers may change their teaching plans and repertoire of instructional strategies (reflection on action). It is important to keep in mind that these changes may result from the two other contexts; for instance, from the use of new material, from teacher education, and from educational bodies' objectives (changes in school organisation or the curriculum).

The transformation of teacher professional knowledge is located in the centre of the TPKinCs model. This complements the PCK&S model by deepening the different relationships it contains, and notably the relationship represented by the bold arrow between student outcome and classroom practice.

Implications of the TPKinCs Model

The TPKinCs model aims to contribute by stimulating the reflection of teachers, teacher educators, training providers and school authorities. It also aims to nourish further research.

The first role of the criteria included in the model is to inform school authorities and teacher training providers. It proposes a means of leverage for teacher educators (e.g., how to shorten the long regulation loop in order to maximise the elaboration of new pedagogical knowledge) or educational authorities (e.g., how to transform the school organisation in order to enhance teacher cooperation with scientific partners). It is aligned with the claim that the more effective teacher education programmes are those that focus on a concrete professional problem and emphasise the role of the teacher community. As shown in this book, teacher professional knowledge growth is boosted by programmes that bring teachers, teacher educators, scientific partners and researchers together in order to overcome a specific teaching challenge. These programmes are mid-term ones, lasting for at least one year with multiple sessions allowing trials, analyses and improvement of the new practice that is targeted.

These criteria are also dedicated to underpinning further research. Each part of the model raises questions for researchers (e.g., to what extent does strong pedagogical content knowledge result in efficient classroom practices?). There is a need to better explore: the congruency of the "milieu" with the learning and teaching purposes; the visibility of the "didactical contract" both for teachers and students; the richness of "epistemic games"; and the climate created by assessment for learning on learning outcomes in the science classroom. For instance, we need to better understand the linkage between students' regulation and self-regulation, and the nature of formative assessment in science teaching.

Commonalities and Differences with Other Models

This model is designed upon a teacher perspective in order to help teacher educators and teacher professional development providers design more efficient programmes. It aims to be a reference for researchers in order to better understand the transformation of science teacher professional knowledge. It challenges the canonical model by Schulman and shares differences and commonalities with the PCK&S model (Gess-Newsome, 2015).

The exploration conducted in this book results in thoroughly altering the seminal model by Shulman (1986) since, today, the professional knowledge required from subject teachers in a school is threefold: parallel to the knowledge linked to specific content and subject, complementary knowledge has to be elaborated and shared amongst teachers from a same domain (e.g., science, technology, engineering and mathematics) or from a school team. Further, effective teaching is no longer constrained by the school boundary and considerable deep learning outcomes result from partnerships between the school and other bodies – such as scientific centres.

Consequently, the fact that teachers need to cooperate implies that researchers should combine, with the same respective levels of importance, professional knowledge related to a topic, a subject, a domain, a school, and the social, cultural and economic environment of the school. The TPKinCs model attempts to combine the knowledge required by these successive fields of teachers' action. It is the reason we identify three categories of teacher professional knowledge. The more general are the professional knowledge bases shared by all actors of education. The more specific is the topic and content-specific pedagogical knowledge that is shared by teachers from the same subject, and to some extent within the same domain (e.g., science, technology, engineering and mathematics). Between the two, general pedagogical knowledge is a common repertoire of the teacher community. These categories of knowledge are also shared and elaborated by external experts, such as teacher educators or researchers in the field.

This exploration also results in raising the importance of epistemological and ontological knowledge since, when teachers have to work together, they need to be sure of the nature of their discipline, to know at least a little about the nature of the close topics in their domain, and to be interested and excited in sharing conceptions with teachers and partners from other domains (e.g., biology and art, economics and drama, physics and physical education, and so on). Therefore, Shulman's model needs to be updated regarding the current evolution of scientific disciplines and the organisation of schools: the lesson is no longer the best unit for understanding teacher knowledge. For instance, addressing student competencies like modelling necessitates a sequence of lessons, and the content is less at the centre of teaching since it is merely a basis for overcoming complex problems, often through inquiry.

The biggest difference with the PCK&S model is that the TPKinCs model is based on theoretical and methodological frameworks that are shared through the research community. According to the activity theory framework, our model stresses the importance of the contexts – instrumental, social and classroom contexts – on the elaboration and enactment of science teacher professional knowledge. It is the reason these contexts are removed from the category "amplifiers and filters". This theoretical framework also results in considering three kinds of professional knowledge: topic and content pedagogical knowledge, general pedagogical knowledge, and bases.

Another difference lies in emphasising the role of teachers' "amplifiers" and "filters". The professional knowledge is transformed by the teacher's approaches to ontological and epistemological questioning regarding the content, the pedagogy and the learning. It also depends on the teacher's responsiveness to technologies, and of the cognitive load required by instructional strategies.

Finally, the model differs by more precisely explaining the elements that constitute classroom practice and their relationship with student outcomes. The classroom is the locus of pedagogical knowledge enactment, whereas it is general or content-specific. The double regulation loop with its short and long duration is not really a difference with the PCK&S model but our theoretical framework allows us a better understanding of their functions.

In parallel, the two models share important commonalities. Both adopt the "amplifiers and filters" category that contains "Teachers beliefs and orientations". This is a simplification of more ancient models. Both adopt similar definitions for the different forms of science teacher pedagogical knowledge. They both focus on the teaching system that articulates teachers with their professional knowledge, classroom practices in their context, and student outcomes that are both the result of teachers' activity and the mirror sending feedback to teachers' professional knowledge. Both are underlined by the purpose of teaching, that is to allow all students to achieve relevant learning goals.

ENACTING THE FUTURE

We conclude by providing recommendations for teacher education, and highlighting further research perspectives.

The main insight arising from this book's contributions is that teacher development is a cooperative issue relying on iterative processes trying to overcome very precisely defined professional problems. These problems should be topic-specific (e.g., electric circuits), domain-specific (e.g., scientific inquiry at secondary school) or general (e.g., assessment for learning in grade 10). The programmes should be based on horizontal cooperation among teachers and experts (i.e., teacher educators, researchers, scientific centre educators, inspectors etc.). The programme should allow multiple trials and iterative adjustments of teaching units or instructional instruments (e.g., a matrix for scaffolding self-regulated learning). We assume that teachers will be better engaged in these programmes if they are oriented to the dissemination of teaching units and instruments that have been designed, tested and validated. That is our recommendation regarding teacher education.

Regarding further research perspectives, parallel to testing the validity of our model, we raise three issues.

The first issue results from the fact that "research on effective instructional practices often fails to take into account important individual student characteristics or school contextual differences that may differentially impact their relative effectiveness" (Waxman, Dubinski Weber, Franco-Fuenmayor, & Rollins, 2015, p. 21). We assume that individual professional knowledge developed by teachers in urban, suburban or rural schools should be partly different.

The second issue consists in noticing that the "lesson has never been the unique unit of teaching" (Hargreaves & Fullan, 2012, pp. 53–54). Most research draws on one lesson, and we assume that the teacher professional knowledge needed for carrying out a complete teaching sequence, from the first moment to the correction of the final test, should differ from the knowledge usually explored in the literature.

The third issue is that "although crosscutting concepts are fundamental to an understanding of science and engineering, students have often been expected to build such knowledge without any explicit instructional support" (National Research Council, 2012, p. 83). Most studies focus on one topic, although crosscutting approaches are required in many actual scientific questions. We may assume that exploring teacher professional knowledge regarding cross-disciplinary activity in different compositions (e.g., science and art, science and sport) should provide a useful insight for the whole profession.

In order to improve learning for all students, such comparative studies might be meaningful

NOTE

[1] The TPKinCs model results from symposia and exchanges during international conferences (ECER, ESERA) and from a two-day seminar held at University Grenoble Alpes in March 2015.

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Michel Grangeat
Univ. Grenoble Alpes
Educational Science Laboratory
Higher School for Education and Teaching

Brian Hudson
University of Sussex
Centre for Teaching and Learning Research
School of Education and Social Work

ABOUT THE CONTRIBUTORS

Jean-Marie Boilevin is a professor of science didactics at the University of Western Britany – France. He is the co-director of the CREAD laboratory. His research topics are: the study of school organisations and transmission; the appropriation of scientific knowledge systems, including the study of didactic teacher-student interaction(s) instrumented or not; inquiry-based science teaching in primary and secondary school; the disaffection for scientific studies; the science teacher's resources and teacher professional development.

David Cross is an associate professor of science education at the Faculty of Education, University of Montpellier, France. He was a member of the research team involved in the European projects S-TEAM and ASSIST-ME.

Philippe Dessus is a professor of educational sciences at Université Grenoble Alpes, and head of the Educational Sciences Laboratory of the same university. His research focuses on cognitive tools for teaching and learning, mainly using natural language processing techniques like Latent Semantic Analysis. He was involved in the LTfLL (EU FP7) project. He has co-edited several books and is the (co-)author of about 40 academic articles.

Michel Grangeat is a professor of educational science at the Université Grenoble Alpes in France. His research focuses on teacher knowledge development in collective settings, mostly in science. As part of the European expert group on science education, he contributed to the report "Science Education for Responsible Citizenship" recently published by the European Commission. He has supervised many research projects at the Educational Science Laboratory of Grenoble. One of his main last projects was the S-TEAM European project about science teacher education towards inquiry-based learning. He has produced a model aiming at a better understanding of science teacher practices and approaches. Currently, he is part of the management board of the European research project ASSIST-ME that is evaluating the linkage between formative assessment and inquiry-based learning. Before his commitment in higher education, he was a primary school teacher and a teacher educator for 20 years.

Brian Hudson is a professor of education and head of the School of Education and Social Work at the University of Sussex. He is currently the main organiser of the World Education Research Association (WERA) International Research Network on Didactics – Learning and Teaching, and associate editor of the Journal of Curriculum Studies. He was Chair of the Teacher Education Policy in Europe (TEPE) Network and represented the Scottish Educational Research Association (SERA) on the

WERA Council until early in 2014. He was a professor of education and associate dean for research in the School of Education and Social Work at the University of Dundee from 2009 to 2012 and, prior to that, was a professor for ICT and Learning in the Department of Interactive Media and Learning at Umeå University in Sweden, and a professor of education at Sheffield Hallam University. Before entering higher education, he was a secondary school teacher of mathematics for 15 years working in comprehensive schools, including 5 years as Head of Mathematics in an 11–18 high school.

Alain Jameau is an associate professor of science didactics at the University of Western Britany – France. He is part of the CREAD laboratory. He is also a member of the council in charge of the "committee of training teacher research" His research topics are: professional knowledge mobilised by teacher in their lesson preparations and implementation in class; inquiry-based science teaching in primary and secondary school; building of a theoretical model for the acquisition of professional experience; the science teacher's resources. Before entering higher education he was a secondary school teacher for ten years.

Suzanne Kapelari is an assistant professor of science education at the University of Vienna in Austria. Her research focusses on the professional knowledge and knowledge development of teachers and science educators working in and outside the classroom. In terms of students' learning, she focusses on design-based research applied to study learning inside and outside the classroom. She was the founder and head of the Plant Science Education Centre at the University Botanic Gardens in Innsbruck, Austria for 15 years and coordinator of the European educational projects "INQUIRE, Inquiry-based teacher training for a sustainable future" and PLASCIGARDENS. Currently, she is a partner in the European project "MASCIL, Mathematics and Science for Life". Before entering the domain of higher education studies, she taught biology and environmental education at secondary and high school level for 5 years.

Shulamit Kapon is an assistant professor at the Department of Education in Science and Technology at the Technion – Israel Institute of Technology. She is interested in sense-making processes in which people gradually change the way they interpret situations; processes in which people adapt, appropriate and start to think independently through disciplinary-based models, representations and technology; the internal standards people use to assess their sense of understanding; and in explanations and instructional designs that influence these processes. She has explored these themes in physics education, and more recently also in mathematics education, and teacher education. She was a physics teacher for many years and was involved in and led many curriculum development and in-service teachers' professional development projects, many of which involved state-of-the-art educational technology. This experience constantly feeds into her research and academic teaching.

Isabelle Kermen is an associate professor of chemistry in the Science Department of Artois University in Lens, France, and a researcher in chemistry education in the LDAR (laboratoire de didactique André Revuz) team, a mathematics and science education research team based in Paris Diderot University, Paris, France. She has been teaching chemistry at university level since 1992 after having been a physics and chemistry teacher in various secondary schools. She earned her PhD in Chemistry Education in 2007 (Paris Diderot University). Her research interests include learners' understanding of models in chemistry (e.g. chemical change and chemical reaction) and about chemical representations of molecules (semiotics), learners' understanding of special relativity in a 3D virtual environment, chemistry teachers' practices and chemistry teachers' professional knowledge.

Céline Lepareur is a PhD student in educational science and involved in the research team of the Education Science Laboratory in Grenoble. She was also part of the S-TEAM and ASSIST-ME European projects about science teacher education towards inquiry-based learning.

Lorraine McCormack joined Brunel University London in May 2014 as a lecturer in science education. Prior to this, she held the post of lecturer in science education and subject leader for science at Plymouth University since 2010. She also worked as a post-doctoral researcher in the European FP7 funded project entitled ESTABLISH (European Science and Technology in Action: Building Links with Industry, Schools and Home). Lorraine was awarded a PhD in 2009 from Dublin City University for her work on the study of the cognitive development levels of pre- and post-second level transfer students. She researched the effect of the CASE (Cognitive Acceleration through Science Education) on students' cognitive development and academic attainment.

Pernilla Nilsson is a professor of science education at Halmstad University, Sweden. In 2002, she initiated work on building up a science learning centre at the university which since then has been the context for her research as well as teaching practices for pre-service and in-service teacher education. During the last decade, she has focused her research on teachers' and student teachers' development of pedagogical content knowledge (PCK) in both primary and secondary science education. She has worked with different tools and activities such as Content Representations (CoRe), Learning Study, video and digital portfolios to stimulate reflection and to help teachers and student teachers engage in their own professional learning. She has also been working on scientific literacy, formative assessment and self-study. She has a genuine interest in teacher professional learning and aspects within teachers' practice that make a difference for students' engagement and learning in science. Recently, her research has been acknowledged at a governmental level and she has been participating as an expert on education in a scientific council of the minister of education.

Gérard Sensevy is a professor of educational sciences at the Brittany School of Education (University of Western Brittany). The main focus of his research consists of studying teaching and learning processes, and their relationship. In his current work, he has developed the Joint Action Theory in Didactics in which he notably tries to link Didactics with other disciplines in social sciences (Cognitive Sciences, Philosophy, Anthropology, Sociology, Psychology, Linguistics, History). He is also the co-editor of the Journal *Education & Didactique* and co-director of the Series *Paideia* (Presses Universitaires de Rennes).

Franck Tanguy is a professor of psychology at the School of Education at the University of Bordeaux in France. His main research topics concern primary and secondary knowledge, instructional guidance in connection with cognitive load theory.

André Tricot is a professor of psychology in the CLLE-LTC lab and School of Education at the University of Toulouse in France. He is also the head of the research federal structure "Learning, Teaching, Training" in Toulouse (20 labs, 5 other institutions, 250 members). His main research topics are: learning and information-seeking with digital documents, from cognitive and ergonomics perspectives; document use, human computer interaction, applied psychology, cognitive load theory.