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Probing the amalgam: the relationship between science teachers' content, pedagogical and pedagogical content knowledge

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ABSTRACT

This Special Issue aims to present evidence about the relationships between content knowledge (CK), pedagogical knowledge (PK) and pedagogical content knowledge (PCK); the development of these types of knowledge in novice and experienced secondary science teachers; and how CK, PK and/or PCK impact students' learning. Since Shulman's introduction of PCK as the feature that distinguishes the teacher from the content expert, researchers have attempted to understand, delineate, assess and/or develop the construct in pre- and in-service teachers. Accordingly, empirical findings are presented that permit further discussion. Outcomes permit post-hoc examination of a recent, collectively described, 'consensus' model of PCK, identifying strengths and potential issues. As we will illustrate, the relationship between CK, PK and PCK is central to this; that is, probing the hypothesis of pedagogical content knowledge as an 'amalgam' of content and pedagogical knowledge.

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Teacher education; teacher; teacher professionalisation; content knowledge; pedagogical knowledge; PCK

Introduction

There is international recognition that how teachers organise instruction impacts students' learning outcomes and thus their life chances (Education, Audiovisual and Culture Executive Agency [EACEA], 2012; Hattie, 2011). Providing teachers with the knowledge to organise high-quality instruction that helps students achieve their potential and sustaining this effort through lengthy teaching careers represents a challenge to teacher education systems worldwide (Furlong, Cochran-Smith, & Brennan, 2011). Identifying this knowledge is critical to understanding how best to prepare teachers who meet these criteria. Coe, Aloisi, Higgins, and Major's (2014) meta-review of research on teacher effectiveness identified pedagogical content knowledge (PCK) as the most significant factor impacting student progress. However, although its impact on students' learning is known, thirty years of research have yet to produce coherence about what constitutes such knowledge

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and how it is best developed (Berry, Friedrichsen, & Loughran, 2015). Consequently, as Settlage (2013) points out, the 'unsteadiness' surrounding PCK means the construct is noticeably absent from significant policy documents. Thus, a fundamental mismatch appears between the outcomes of PCK research and the premises on which the research is conducted and policy-makers' requirements for development of effective teachers.

Shulman's (1986) initial effort in describing teacher professional knowledge identified a range of knowledge bases, including content knowledge and (general) pedagogical knowledge. Significantly, he proposed PCK as uniquely the province of teachers, distinguishing them from content (or 'subject') specialists. He described PCK as 'that special amalgam of content and pedagogy that is uniquely the province of teachers, their own special form of professional understanding', encompassing how knowledge within a particular domain is organised and adapted to learners' diverse interests and abilities during instruction (Shulman, 1987, p. 8). Since Shulman's (1986, 1987) work, PCK has become widely accepted as a construct within educational research. However, there seems to be little agreement about how to model PCK (Berry et al., 2015). The extensive variation in models of PCK was the reason for an international researcher summit held in 2012 (Berry et al., 2015). The consensus model that emerged from this summit has been named a 'model of teacher professional knowledge and skill including PCK' (Gess-Newsome, 2015, p. 31). However, the model is also often simply referred to as the 'Consensus Model of PCK' (e.g. Ziadie & Andrews, 2018, p. 3)

This Special Issue offers an opportunity to evaluate this model in relation to Shulman's 'amalgam' metaphor, utilising the empirical evidence presented in five papers. As data presented were collected prior to the model being proposed, discussion is inevitably post-hoc evaluation, rather than new empirical testing. However, we believe this is valuable and necessary to test the model in an attempt to help raise the profile of PCK as a major contributor to teacher education policy and practice. This introductory paper sets out historical issues relating to PCK, highlighting why clarity is required, describes the Consensus Model of PCK and outlines rationales for the empirical papers. The closing paper reviews empirical evidence in the light of the model, drawing conclusions regarding its strengths and weaknesses and proposes future work.

Pedagogical content knowledge (PCK): the origins of a construct

Shulman's Presidential Address at the 1985 annual meeting of the American Educational Researchers Association in Chicago made a powerful case for teaching as a profession. Shulman acknowledged that the professional knowledge of teachers should include knowledge of subject matter as well as knowledge about teaching methods that have proven successful in terms of improving student learning (e.g. the use of focusing strategies such as advance organisers, Fraser, Walberg, Welch, & Hattie, 1987). However, Shulman (1986) argued that in this conception something was missing: the knowledge about *what to teach*, *how to teach it*, *how to engage students* and *how to deal with students' learning difficulties* (p. 8). In contrast to knowledge about subject matter (SMK) and knowledge about effective teaching methods, he referred to this as 'pedagogical content knowledge', characterised thus:

> …… for the most regularly taught topics in one's subject area, the most useful forms of representation of those ideas, the most powerful analogies, illustrations, examples, explanations,

> and demonstrations – in a word, the ways of representing and formulating the subject that make it comprehensible to others. Since there are no single most powerful forms of representation, the teacher must have at hand a veritable armamentarium of alternative forms of representation, some of which derive from research whereas others originate in the wisdom of practice. (p. 9)

He specifies that pedagogical content knowledge (PCK) includes knowledge about students' misconceptions and strategies to address these. More importantly, he elaborates on the knowledge bases that comprise PCK. These include propositional knowledge, that is, knowledge about (research-based) principles, maxims and norms of teaching; case knowledge, that is, knowledge of specific events (from practice) exemplifying principles, illustrating maxims and conveying norms for teaching; and strategic knowledge, that is, knowledge about how to align principles, maxims and norms to create high quality instruction on specific events.

Later, Shulman (1987) introduced the notion of teaching as a 'transformation' of an understanding of subject matter into content accessible to students. He identifies multiple additional knowledge bases needed by a teacher to realise this transformation (Figure 1). Besides content knowledge (CK) and (general) pedagogical knowledge (PK), these comprise knowledge of curriculum, learners and their characteristics, educational contexts, educational ends, purposes and values, and PCK. Shulman (1987) highlights PCK as knowledge that distinguishes a teacher from a content specialist, a 'special amalgam' (p. 8) of content and pedagogy. This includes understanding how a domain is organised, can be adapted to learners' interests and abilities and presented for instruction.

In a retrospective, 20 years later, Shulman emphasises two original features of PCK. First, PCK is the missing link between CK and PK; and second, PCK was intended to capture subject pedagogy as the main constituent feature of teaching, and of teaching a specific subject (Berry, Loughran, & van Driel, 2008). The idea of PCK as the central component of teachers' professional knowledge has received increasing acceptance (Berry, Depaepe, & van Driel, 2016). Nevertheless, there remains less agreement, however, about what PCK *actually is*.

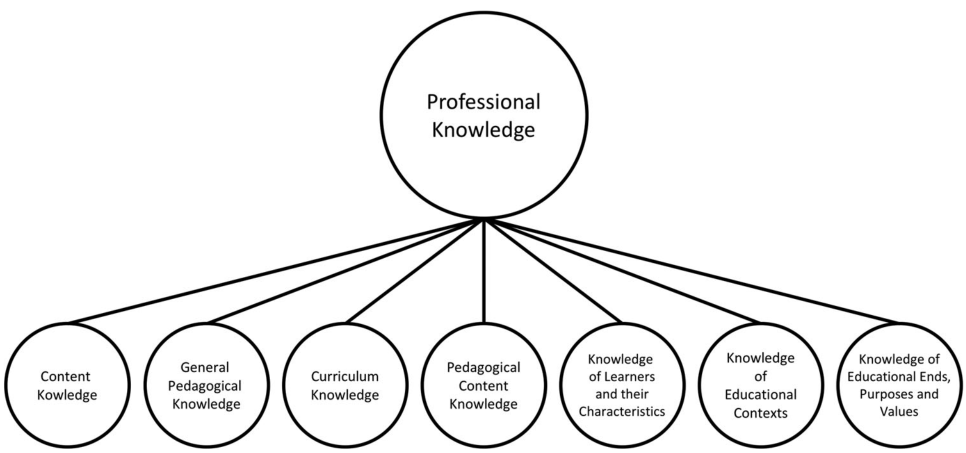

Figure 1. Teacher professional knowledge according to Shulman (1987).

Early years: conceptualisations of PCK

Early adopters of the idea of PCK closely followed Shulman's (1986, 1987) original descriptions. Geddis (1993), for example, highlighted the significance of PCK as a *resource* for the transformation of subject matter content into content accessible to students. He includes within PCK knowledge about student misconceptions, strategies for altering misconceptions and representations that support altering misconceptions. These aspects are research-based and according to Shulman's (1986) descriptions comprise 'the heart' of PCK (p. 10). Bromme (1997) similarly perceived PCK as the knowledge needed to transform subject matter content into content for instruction. He notes that the subject matter structure alone cannot guide the design of instruction. Content-specific pedagogical knowledge is a necessary pre-requisite to finding adequate representations of subject-matter content, and deciding about the selection and sequencing of ideas, that is, to enable transforming subject-matter structure into an instructional structure. Wilson, Shulman, and Richert (1988) characterised PCK as knowledge developed as a *product* of the transformation of subject-matter content into information accessible to students, instead of a resource for the transformation process. Grossman (1990) picks up the concept of PCK as a product, describing PCK as the result of teachers transforming subject matter knowledge for teaching.

van Driel, Verloop, and de Vos's (1998) conceptualisation of PCK as a form of craft knowledge driving teachers' actions in classroom practice highlights the role of PCK in *action* (see also Loughran, Milroy, Berry, Gunstone, & Mulhall, 2001). Magnusson, Krajcik, and Borko (1999) develop this conceptualisation further, explicitly defining PCK as the result of a transformation of knowledge from other domains and emphasising its role in the planning and conducting of and reflecting on teaching.

Gess-Newsome (1999b), in a first major review, identified two fundamentally different conceptualisations in the work on PCK that had emerged. The first conceptualisation corresponds to Shulman's original *transformative* perspective, in which other knowledge bases combine to form new, distinct knowledge. The second adopts an *integrated* perspective, in which PCK is knowledge generated when teachers draw on other knowledge bases and connect knowledge from these knowledge bases in new ways. Both perspectives have been adopted by researchers internationally, as the following discussion indicates.

More recently, Kind (2009) identified nine PCK conceptualisations, some going substantially beyond and/or not building on Shulman's (1986, 1987) original work (Banks, Leach, & Moon, 2005; Cochran, DeRuiter, & King, 1993). All these conceptualisations are highlighting different, yet important aspects of PCK. However, the multitude of conceptualisations, each representing considerable intellectual effort, also serves to illustrate the continued need to achieve consensus about PCK and its different components.

Growing up: models of PCK

In their efforts to model PCK, researchers have disagreed about PCK components. For example, an early adopter, Grossman (1990), identified four components: knowledge of students' understanding of subject matter; curriculum materials available to teach a subject; strategies and representations for teaching topics; and beliefs about the purposes for teaching a subject at different grades. Although presented as research-based knowledge, Grossman (1990) characterises these as personal to teachers. Subsequent research building on Grossman's work added and removed components depending on the respective conceptualisation of PCK employed. Marks (1990), for example, removed knowledge and beliefs about purposes; while Fernández-Balboa and Stiehl (1995) included knowledge about educational contexts. Thus, different models of PCK entailing different components in quantity and quality became apparent in research literature.

One widely-adopted model is that of Magnusson et al. (1999). These authors collapsed Grossman's first and third components into 'knowledge and beliefs about science curriculum', to include knowledge (and beliefs) about science goals and objectives and about science curricula. They added 'knowledge and beliefs about assessment'. More importantly, however, they also added 'orientation to teaching science' as the one component of PCK that in turn shapes and is shaped by the other four components; namely knowledge of science curricula, knowledge of students' understanding of science, knowledge of instructional strategies, and knowledge of assessment of science literacy. The 'Magnusson' model adopts a strongly *transformative* perspective of PCK, in that it understands PCK as the way in which teachers conceptualise science teaching, emphasising the personal nature of teachers' orientations. These orientations serve as a conceptual framework determining how teachers' knowledge (of science curricula, students' understanding of science, instructional strategies and assessment) shapes teachers' actions in practice. As such, Magnusson et al. (1999) highlight the importance of PCK for classroom practice and the role that teachers' orientations play in how teachers' knowledge shapes this practice.

An alternative is proposed by Hashweh (2005). She adds subject matter knowledge (or CK) and pedagogical knowledge to emphasise how PCK originates from interaction of these (p. 279). Thus, Hashweh (2005) leans towards an *integrative* perspective on PCK that implies teachers draw on knowledge bases in constructing PCK for classroom use. Although Loughran, Berry, and Mulhall (2006) include similar components to Hashweh (2005), they describe PCK as an 'amalgam' of knowledge developed through experience. This implies PCK is transformative, that is, a separate type of knowledge created from other knowledge bases. Hence, ten years after van Driel et al.'s (1998) and Gess-Newsome's (1999b) reviews of PCK literature, Park and Oliver (2008) find extensive variance in the components researchers include in their models of PCK. Abell (2007) noted this variation in calling for more research on the essence of PCK and in turn more coherent (i.e. clearly defined) conceptualisations of PCK. She pointed out inconsistent and vague models of PCK that depend on specific methodological approaches utilised to represent it.

Reaching teenage years: two lines of research on PCK

The transformative and integrative perspective on PCK are seen in two independent lines of research, exemplified below. The transformative perspective is represented by a previous Special Issue (SI, IJSE Volume 30, Issue 10) which revisited 'the roots' of PCK. The integrative perspective is illustrated by research prominent in German-speaking communities and arises from the organisation of teacher education in these nations.

The previous SI focused on articulation and development of science teachers' PCK (Berry et al., 2008). In their introduction to the previous SI, Berry et al. (2008) described PCK as 'the amalgam of a teacher's pedagogy and understanding of content such that it influences their teaching in ways that will best engender students' learning for understanding' (p. 1272) suggesting a transformative perspective on PCK.

Nilsson (2008) and Loughran, Mulhall, and Berry (2008) investigated the articulation and development of student teachers' PCK during pre-service education at elementary (Nilsson, 2008) and secondary levels (Loughran et al., 2008). Nilsson (2008) noted student teachers' reflections on having 'their knowledge bases as a transformed unit' (p. 1295), concluding that moving from individual knowledge bases to the complex interaction between them was crucial for improving teachers' practice. Loughran et al. (2008) introduced pre-service teachers to PCK through novel data collection methods, namely, 'Content Representations' (CoRes) and 'Pedagogical and Professional-experience Repertoires' (PaP-eRs). They observed that participants attempted to align subject matter content with pedagogy such that content would be better understood by students (p. 1317). Both papers implement a transformative perspective in which PCK is an amalgam of CK and PK (Gess-Newsome, 1999a).

Four of the papers in previous SI examined the development and articulation of experienced science teachers' PCK. Henze, van Driel, and Verloop (2008) identified two types of teachers, or types of teacher PCK: the first develops PCK in four components (similar to Magnusson et al., 1999), with few links between them, and a strong focus on content. The second develops PCK so components are consistently and dynamically inter-related. Padilla, Ponce-de-León, Rembado, and Garritz (2008) reported two PCK profiles among university chemistry teachers, one characterised as 'rationalist' and the other 'empiricist'. Padilla et al. (2008) view PCK as knowledge about teaching subject-matter that develops through *repeated* transformation of subject-matter content into content for teaching.

Rollnick, Bennett, Rhemtula, Dharsey, and Ndlovu (2008) investigated the role teachers' SMK plays in the transformation of content and suggested that teachers with poor SMK express PCK in domains that reflect theoretical assumptions like knowledge of students or context. Teachers with good SMK exhibited PCK consistent with high-quality teaching, that is, topic-specific instructional strategies or representations. This is confirmed by Nilsson's (2008) and others' (Stender, Brückmann, & Neumann, 2017) findings.

The final paper in the previous SI, Lee and Luft (2008), investigated teachers' articulations of their PCK, finding teachers conceptualise PCK as 'knowledge for teaching science'. Although all teachers referred to the same PCK components (namely, goals of science education and students' understanding of science), their linking of individual components and subsequent impact on teaching differed. Lee and Luft (2008) concluded teachers hold various forms of PCK simultaneously that evolve throughout a professional career. This elegantly explains concurring conceptualisations discussed in the field.

Thus, the previous SI investigated PCK from a perspective of transformed knowledge driving teachers' teaching practice: Berry et al. (2008) set off by noting how PCK is often tacit and that further PCK research linking with teachers' practice is required (p. 1277). Abell's (2008) concluding piece highlighted how the papers in the previous SI demonstrate consensus on conceptualising PCK as a transformative construct: the authors agree that PCK is not an independently acquired knowledge base but represents a special amalgam of CK and PK (Lee & Luft, 2008; Loughran et al., 2008; Nilsson, 2008) developed from other knowledge bases (Henze et al., 2008; Loughran et al., 2008; Rollnick et al., 2008). This effectively implements a *practitioners*' perspective on PCK.

Research in the German-speaking communities incorporates an integrative perspective on PCK. This perspective has its origins in the organisation of teacher training in these countries (e.g. Neumann, Härtig, Harms, & Parchmann, 2017). In the German-speaking countries teacher education is organised in three strands: (1) education in the subject (e.g. physics) aimed at providing teacher trainees with the necessary subject matter knowledge, (2) education in the respective subject education (i.e. physics education) dedicated to teaching students the theoretical knowledge about teaching the subject, and (3) education in educational sciences (i.e. pedagogy, pedagogical psychology, general education) aiming at developing general pedagogical knowledge about teaching. That is, teacher education in the German-speaking countries aims at developing the triplet of CK, PCK and PK in dedicated classes. These classes mainly cover theoretical, research-based knowledge, there are few opportunities to develop practical experiences organised in the form of practical studies in schools of a duration no longer than a few weeks (for details see Neumann et al., 2017).

The triplet of knowledge bases forms the central components of a teachers' professional knowledge in Baumert and Kunter (2013) approach to defining a teachers' professional competence within the 'Professional Competence of Teachers, Cognitively Activating Instruction, and Development of Students' Mathematical Literacy' ('COACTIV') research programme (Figure 2). In addition to the triplet of knowledge bases, Baumert and Kunter (2013) include organisational and counselling knowledge (Figure 2). These authors consider professional knowledge represents the core of teacher competence, and envision this to additionally comprise beliefs, values and goals, motivational orientation and self-regulation abilities.

The COACTIV research programme investigated mathematics teachers' professional competence and its impact on instruction quality, particularly students' cognitive

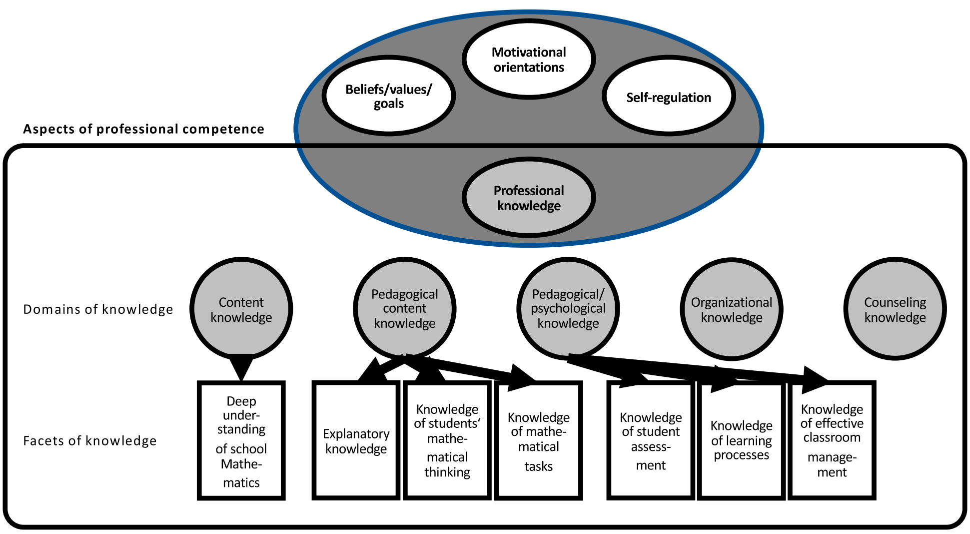

Figure 2. Teacher professional competence according to Baumert and Kunter (2013).

activation (Kunter et al., 2013). Findings show that CK, PCK and PK represent distinct constructs; teachers' CK is an essential precondition for development of PCK; and PCK is most important for cognitively activating instruction in class (Baumert et al., 2010).

Similarly, the 'Professional Knowledge in the Natural Sciences' (ProwiN) project in science education investigated biology, chemistry and physics teachers' professional knowledge and its impact on instruction quality (Borowski et al., 2010). ProwiN conceptualised PCK in line with Magnusson et al.'s (1999) four components. Findings corroborate those of COACTIV, in that CK, PCK and PK represent distinct but correlated knowledge bases for biology (Jüttner & Neuhaus, 2012; Großschedl, Mahler, Kleickmann, & Harms, 2014), chemistry (Tepner & Dollny, 2014) and physics teachers (Kirschner, Borowski, Fischer, Gess-Newsome, & von Aufschnaiter, 2016). Further, Riese and Reinhold (2010) confirmed that pre-service physics teachers' CK, PCK and PK are distinct, strongly correlated knowledge bases

These two lines of research generate similar insights into PCK, despite adopting different models for the construct. Van Driel, Berry, and Meirink (2014) described these lines of research as investigating the knowledge *of* teachers and research investigating the knowledge *for* teachers (see also Fenstermacher, 1994). The transformative perspective, in which, PCK is viewed as an amalgam of knowledge that develops through transforming subject matter content into content for teaching during teaching practice, represents knowledge *of* individual teachers. The integrative perspective, in which PCK is considered to include separate components each representing knowledge about different aspects of the amalgam of content and pedagogy, represents knowledge *for* teachers to develop during (formal) teacher education. Each teacher makes connections in new ways that make subject matter accessible for students. Hence, although both lines make contributions to our understanding of teacher knowledge, an outcome for the field remains an inconsistent conceptualisation of PCK (Smith & Banilower, 2015; Van Driel et al., 2014). Lee and Luft's (2008) findings offer an elegant solution, suggesting that the models are not contradictory, but are simply different types of PCK that teachers can hold simultaneously and develop over time.

Approaching maturity: the consensus model of PCK

To address variation in conceptualisations of PCK, a model of teacher professional knowledge and skill including PCK has been proposed by a summit of international researchers (Berry et al., 2015). The model, also known as the Consensus Model of PCK, combines features of earlier PCK configurations in a multi-layered, flow-chart structure (Gess-Newsome, 2015; Figure 3).

The model places teacher professional knowledge bases at the top, with a flow down to 'student outcomes'. Interlinking arrows suggest inter-dependencies of the knowledge layers. The top level comprises 'knowledge *for* teachers' (Gess-Newsome, 2015, p. 32) that is, generic knowledge prepared by, for example, curriculum developers and assessment experts. Topic-specific professional knowledge (TSPK) is next. This equates broadly to Shulman's original PCK definition. The Consensus Model acknowledges this, noting the critical difference that TSPK is 'codified by experts' and 'is available for study and use by teachers' (Gess-Newsome, 2015, p. 33). Thus, utilising earlier definitions (see above), TSPK is shaped by but is also itself a knowledge base on which teachers can

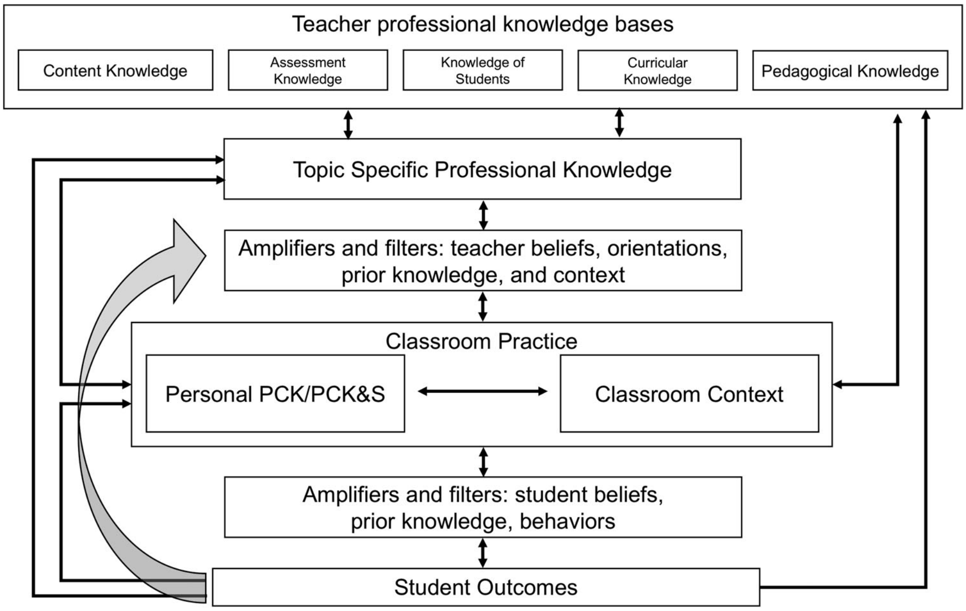

Figure 3. Teacher Professional Knowledge according to Gess-Newsome (2015).

draw. This is consistent with an integrative perspective on PCK. The Consensus Model places PCK lower in the flowchart, within classroom practice, with the qualifiers 'personal' and 'skill'. Personal PCK is defined as the 'knowledge of, reasoning behind, and planning for teaching a particular topic in particular way for a particular purpose to particular students for enhanced outcomes' (p. 36), and 'PCK and skill' is defined as 'the act of teaching a particular topic in a particular way for a particular purpose to particular students for enhanced student outcomes' (p. 36). This implies PCK is formed from knowledge bases presented higher in the structure but avoids indicating is this as an integrative or a transformative process. The 'personal' / 'skill' labelling aligns with Berry et al.'s (2008) emphasis on PCK as a unique teacher's 'product' developed for and applied in specific instructional situations.

Two sets of 'amplifiers and filters' are identified as moderators or mediators respectively between the knowledge layers: (1) teacher beliefs, orientations, prior knowledge and context and (2) student beliefs, prior knowledge and behaviours. Like in previous models, these sets of amplifiers and filters acknowledge the relevance of affective aspects of teachers' and students' experiences for the development of and efficacy of teachers' knowledge. More specifically the first set, teacher-related amplifiers and filters, acknowledges Grossman's (1990) and Magnusson et al.'s (1999) teacher orientations and beliefs PCK component. Placing these as *influencing* rather than as *a component of* PCK acknowledges the contribution these make on practice, as discussed by Coe et al. (2014). However, by excluding this component from lying within PCK the Consensus Model is making a statement about the relative impact of orientations and beliefs on actual teacher's practices, moving away from these as an essential aspect of transforming subject matter or CK. Thus, the Consensus Model notes only an alignment with teachers' beliefs (Kind, 2016). The second set, student-related amplifiers and filters, acknowledges the extensive research indicating the role of for example student motivational orientations (Schiefele, Krapp, & Winteler, 1992) or prior knowledge (e.g. West & Fensham, 1974) for students learning. Finally, the inclusion of student outcomes roots in the expectation about PCK as a pre-requisite for effective instruction and learning (Committee on Science and Mathematics Teacher Preparation, 2000), which aligns with findings from the integrative research line (as discussed above). Overall, the Consensus Model embraces many aspects of teacher knowledge revealed by successive eras of research on the topic. All knowledge layers inter-connect with TSPK being informed by teacher professional knowledge bases, and TSPK becoming personal PCK through enactment in classroom practice (van Driel, de Jong, & Verloop, 2002). This classroom-based knowledge determines student outcomes, subject to their prior knowledge, behaviours and beliefs.

Hence, overall, although the Consensus Model of teacher professional knowledge and skill includes PCK, it is not a model of PCK itself. In fact, the Consensus Model does not indicate explicitly what PCK may comprise. This point is left open: instead the model shows PCK as teachers' personal knowledge that drives their planning for, implementation of, and reflection on instruction. While this may be intriguing, and indicative of further research on the nature of PCK, we see little value in this. A major reason is that we believe a more relevant, current discussion lies in exploring how PCK develops and plays out in teaching. Insights from this are more likely to inform improvements to teacher education and professionalisation than pursuing continued debate about PCK's components.

Critically, however, the Consensus Model exhibits but does not make claims about the nature or extent of interactions between knowledge types and how these impact the quality and/or development of PCK over time. That is, although the model provides guidance for researchers about teacher professional knowledge components, more research is needed to further inform teacher education and professionalisation (policy). Research that tests the Consensus Model in terms of how components interact and relate to PCK development would be beneficial.

Aim and structure of this special issue

Shulman's (1987) original description of pedagogical content knowledge (PCK) as an 'amalgam' is simultaneously helpful and frustrating. Imagining PCK as an amalgam centres teacher education and professionalisation on pedagogical strategies for presenting content from a specific subject or topic to learners. This emphasises a 'need' for a special knowledge as unique to teachers, in contrast to content specialists or educators in other fields (p. 7). However, PCK as an 'amalgam' is open to multiple interpretations, allowing different understandings to emerge. Over time, regardless of components, two have become well-established: PCK as an amalgam of content knowledge and pedagogical knowledge developed from transformation of subject matter to content for teaching; and PCK as knowledge about content and pedagogy as a pre-requisite to transformation of subject matter to content for teaching.

Many researchers have implicitly or explicitly built towards this distinction. Park and Oliver (2008), for example, referred to this distinction as 'knowledge-in-action' and 'knowledge-on-action'. Gess-Newsome (1999b) distinguished between 'transformative' and 'integrative' perspectives, although as extreme ends of a continuum. van Driel et al.

(1998) acknowledged that while PCK is developed through teaching practice, aspects of PCK are also developed through formal education. Later, Van Driel et al. (2014) distinguished between a 'knowledge *for* teachers' and the 'knowledge *of* teachers' (p. 848). The definition employed depended on what researchers were looking for or valued with respect to teacher professional knowledge. For example, researchers focusing on PCK as a prerequisite for (quality) teaching practice adopted a transformative or knowledge-in-action perspective. In contrast, researchers focusing on PCK as a result of in-school activities employed a knowledge-on-action or integrative perspective.

The Consensus Model combines both perspectives into one: PCK as knowledge about an amalgam of content and pedagogy, shown as TSPK (Figure 3); and as personal knowledge and skill of a teacher, produced through transformation of knowledge bases such as CK, TSPK or PK, creating personal PCK or PCK and skill (pPCK /PCK&S). Underlying these conceptualisations are ideas about the nature of this knowledge and how it develops. TSPK is likely to be acquired through formal in-school or teacher education activities, whereas pPCK/PCK&S are developed through classroom-based teaching practice. The development of TSPK and pPCK/PCK&S involves other components of teacher professional knowledge, such as students' abilities and behaviour, curriculum, assessment, school/college context and culture. As a consequence, the model summarises knowledge components that research evidence identifies as influencing and/or comprising PCK. However, in common with all other models, the Consensus Model does not make specific claims about the extent or nature of interactions between knowledge types, how these impact PCK quality and quantity and how PCK may develop over time.

An aim of this Special Issue is to examine the Consensus Model with respect to how teachers' PCK (both TSPK and pPCK/PCK&S) develops, how it plays out in teaching, and the role that other aspects of teachers' professional competence contribute to these processes. Specifically, our aim is to offer evidence that explores:

- relationships between content knowledge (CK), pedagogical knowledge (PK) and pedagogical content knowledge (PCK),
- the development of these types of knowledge in novice and experienced secondary science teachers and
- how CK, PK and/or PCK impact students' learning.

Methodologically, these papers present evidence from quantitative (Sorge, Kröger, Petersen and Neumann, Liepertz and Borowski), qualitative (Kind) and mixed-methods analyses (Pitjeng-Mosabala and Rollnick, Gess-Newsome et al.). The two quantitative papers used paper-and-pencil instruments to assess PCK in terms of TSPK, investigating the relationship between CK, PK and PCK (Sorge et al.), and the impact of PCK on student learning outcomes respectively (Liepertz and Borowski). These suggest that CK and PK play a major role in development of PCK in terms of TSPK, with CK becoming the more dominant factor over time. An implication arises of a missing link between PCK in terms of TSPK and student outcomes: quality instruction requires more than TSPK, namely pPCK/PCK&S. Pitjeng-Mosabala and Rollnick's and Gess-Newsome et al.'s and mixed-methods research illustrate outcomes of professional development interventions on the quality of teachers' PCK, in terms of TSPK and pPCK/PCK&S. Pitjeng-Mosabala and Rollnick note the impact that high-quality professional development has on raising the quality of teachers' PCK by developing their CK. Gess-Newsome et al.'s findings suggest CK and PK strongly effect PCK in quality instruction and thus student learning. These studies confirm once more the central role that CK in addition to PK for the development of PCK. Kind presents evidence that homes in on the significance of content knowledge more precisely. Kind's paper concludes with a straightforward model representing connections between teacher knowledge base components.

As a whole, these papers offer quantitative and qualitative data for investigating the development of PCK, how PCK influences teaching and the role that other knowledge bases – especially CK and PK – play in these processes. Data show that to achieve the desired outcomes, that is high-quality science teachers, professional education and development systems are required that teach teachers necessary knowledge bases. Specifically, teachers require content and pedagogical knowledge, and (topic-specific professional) knowledge about the amalgam of content and pedagogy. The SI argues for providing teachers with support to create their amalgams from these knowledge bases, generating personal PCK and PCK and skill to ensure quality instruction and positively affect student learning outcomes.

Disclosure statement

No potential conflict of interest was reported by the authors.

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