Development of evidence-based, student-learning-oriented rubrics for pre-service science teachers' pedagogical content knowledge

Vanessa Kind
School of Education
Durham University, UK

Vanessa.kind@durham.ac.uk

An evidence-based rubric for pre-service science teachers' pedagogical content knowledge

Abstract

This paper offers pedagogical content knowledge (PCK) rubrics, that is, guides providing criteria for grading that are potentially applicable to a range of science topics and levels of teacher experience. Grading criteria applied in the rubrics are based on qualitative analyses of planned topic-specific professional knowledge (TSPK) and content knowledge (CK). Data for developing the rubrics were collected via three topic-specific vignettes from 239 pre-service science teachers (PSTs) starting a university-based, full-time, one year teacher education programme in England. The statements were analyzed for evidence of TSPK and CK. PSTs' statements proposed instructional strategies, which comprised demonstrations, explanations, illustrations and analogies. Some were classified as *Relevant* to the science topics, others *Irrelevant*. A proportion of *Relevant* strategies missed an aspect that may, if enacted, help students' learning, so were judged *Incomplete*. Statements were also analyzed for evidence of relevant and correct CK. CK and TSPK statements for each topic are aligned into grids, creating PCK rubrics. These demonstrate the precise nature of knowledge likely to lead to instruction that impacts positively on student learning. The rubrics present the possibility of developing PCK repertoires that contribute to clarity and precision when introducing PSTs to teaching. Although these findings cannot be generalized to all science teachers, the methodology offers a strategy for supporting out-of-field teachers establishing unfamiliar classroom practices, and / those seeking new instructional strategies to add to their existing repertoire.

An evidence-based rubric for pre-service science teachers' pedagogical content knowledge

Introduction

Effective educators develop a strong capacity to mediate students' learning, capitalising on a professional knowledge repertoire built on secure subject matter (hereafter, content) knowledge that is responsive to various learning needs (Windschitl, Thompson, Braaten and Stroupe, 2012). The ability to mediate learning and the professional knowledge of a teacher are embraced within pedagogical content knowledge (PCK, Shulman, 1986b). In their meta-review of research exploring teachers' professional learning, Coe, Aloisi, Higgins and Major (2014) identify PCK as the factor contributing most strongly to positive student achievement, defining "great teaching" as teaching "which leads to improved student achievement using outcomes that matter to their future success" (p 2). Coe et al (2014) explain the role played by PCK thus:

> "The most effective teachers have deep knowledge of the subjects they teach, and when teachers' knowledge falls below a certain level it is a significant impediment to students' learning. As well as a strong understanding of the material being taught, teachers must also understand the ways students think about the content, be able to evaluate the thinking behind students' own methods, and identify students' common misconceptions" (p 2).

Acquiring appropriate knowledge of content and a rich teaching repertoire that mediates learning effectively takes considerable effort on the part of individual teachers. Teacher education initiates and supports repertoire acquisition. However, most teacher education still comprises three components: an introduction to education "theory" and general pedagogy; "methods" courses relating to teaching a specific subject; and teaching experience in the "field", as a "student" or "trainee" teacher/intern teaching in one or more schools (Anderson and Mitchener, 1994). Programmes are packed with general information teachers "need" to know. Ball and Forzani (2010) argue that "after more than a century of organised teacher education, we still lack a well-defined curriculum of practice for prospective teachers" (p 11), noting that entering other professions such as medicine, law and aviation requires novices to learn component activities thoroughly before practicing for real. Similarly, Russell and Martin (2014) state that despite repeated calls for change and reform in teacher education, "inadequate subject matter preparation" and "haphazard education preparation" (p 881) remain long-standing themes. The most crucial aspect of teaching, that is, development of PCK that lies at the heart of a teacher's professional repertoire, relies mainly on chance encounters with effective experienced teachers via teaching practice. By common consensus, novice teachers learn "in the field", practicing on students who, to achieve their potential, require teachers who understand their potential difficulties and know how to handle these. Ball and Forzani (2010) argue this is unethical, and that teacher preparation must move towards identifying "key features of readiness for responsible practice" (p 12). From an English national perspective, the Carter review (2015) reports "considerable variability" in teacher education programmes across a range of areas, including content knowledge development and subject-specific pedagogy (p 6). In the US, in response to inconsistent teacher education practice across fifty states, National Board Certification (National Board for Professional Teaching Standards, 2016) offers a voluntary mechanism for teachers to accredit teaching experience judged against a set of standards, including passing a content knowledge test. Educating effective teachers whose practice mediates student learning consistently positively results from an often unpredictable process, rather than by design. Carter indicates, "…there may be a case for a better shared understanding of what the essential elements of good ITT [Initial Teacher Training] content look like" (p 6). This paper supports this aim and Windschitl, et al (2012) in establishing a shared, coherent language and resources to inform the foundations of secure, effective teaching practice.

This paper offers PCK rubrics, that is, guides providing criteria for grading teacher knowledge based on deductive and inductive analyses of pre-service teachers' (PSTs) written statements. The rubric structure and analyses are potentially applicable to other science topics and statements obtained from teachers of varied experience levels working in specific contexts. The analyses focus on knowledge quality, noting, as Coe et al (2014) indicate "high quality" is needed to mediate student learning. Adoption and presentation of the rubric to PSTs may enhance science teacher education and professional development practices by presenting exemplar PCK adaptable to teaching contexts.

The paper contributes to enhancing PCK within teacher education practice. Despite generating extensive research (Abell, 2007; van Driel, Berry and Meirink, 2014) and being identified as essential for student achievement, PCK exerts little impact on policy internationally. For example, PCK is not mentioned explicitly in the US K-12 Science Education Framework (National Research Council, NRC, 2011); the England and Wales' Teachers' Standards document (Department for Education, 2011); or the Australian Professional Standards for Teachers (Australian Institute for Teaching and Learning School Leadership, 2014). Coe et al (2014) imply this is because PCK is important, yet presents a structurally confused image. Shulman's (1986, 1987) original, simple proposals for a teacher's professional knowledge base have expanded into complex theoretical models varying in composition and application (Kind, 2009a), creating persistent lack of clarity about PCK. Also, Van Driel, Berry and Meirink (2014, p 865) observe a fundamental dichotomy in PCK studies. They note some adopt a descriptive "knowledge *of* teachers" standpoint, seeking to understand why teachers teach specific subject matter as they do, aiming to promote student learning; others work from a "knowledge *for* teachers" perspective, quantifying relationships between teacher and student variables, assuming standardisation and the possibility of distinguishing between "strong" and "weak" knowledge. Studies investigating "knowledge *of* teachers" often reveal rich, productive, flexible PCK. These small-scale studies are designed from researchers' preferred PCK models, presenting evidence from small numbers of teachers working in localised contexts. Thus, although convincing data adds detail to researchers' understandings of PCK, these studies may constrain impact on practice. This is because generalising from small-scale studies is methodologically problematic; and data from multiple sources results in a fuzzy" PCK image, so findings are difficult to disseminate meaningfully. This paper argues for and presents planned PCK organised in a generalizable, context-independent format that is "knowledge *for* teachers". From a policy perspective, PCK that identifies aspects of a professional repertoire that mediates student learning is valuable as a consistent, secure base from which advanced practice can build. Windschitl et al (2012) argue for creation of "…subject-specific high-leverage practices" that can "be articulated and taught during teacher preparation and induction" (p 878). The PCK rubrics proposed in this paper contribute to describing these.

Theoretical framework

The study is located within the teacher knowledge paradigm established through reviews (van Driel, Berry & Meirink, 2014; Abell, 2007). Teacher knowledge is the total knowledge a teacher has at his/her disposal at any one time. This knowledge underpins classroom-based actions (Carter, 1990). An effective teacher will select from a broad repertoire of practices developed through teacher education, classroom experience, self-study and professional development. Thus, this paper shares van Driel et al's (2014) view that teacher knowledge develops over time. The paper also attempts to address Abell's (2007) opinion that

> "…research in both subject matter knowledge and PCK has predominantly been at the level of description… The ultimate goal of science teacher knowledge research must be not only to understand teacher knowledge, but also to improve practice, thereby improving student learning." (p 1134)

Shulman (1986, 1987, Figure 1, Van Dijk and Kattman, 2007) proposed PCK as a component of a professional "knowledge base for teaching". PCK is teacher-specific knowledge that enables students to make sense of subject-oriented material such as science concepts, "that special amalgam of content and pedagogy that is uniquely the province of teachers, their own special form of professional understanding" (Shulman, 1987, p 8).

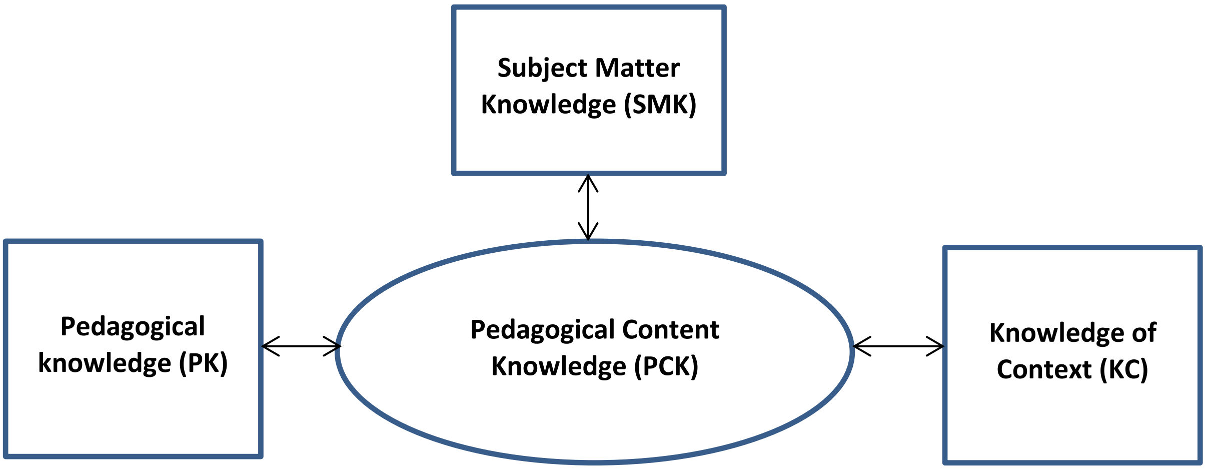

Figure 1: Shulman's teacher knowledge model (based on Van Dijk & Kattman, 2007)

PCK has been described as "transformative" or "integrative" (Gess-Newsome, 1999). "Integrative" PCK intersects subject matter, context and pedagogical knowledge, each retaining individual characteristics in classroom practice. Gess-Newsome likened this to a chemical mixture, in which individual components can be separated by physical methods. As an integrative structure, PCK relates to "traditional" teacher preparation, as knowledge bases can be taught separately (Anderson and Mitchener, 1996), allowing integration to occur on teaching practice. Gess-Newsome noted this may result in "transmission" mode teaching, as teachers may not actively integrate knowledge, resorting to rote learning practices devoid of instructional strategy and regardless of context. "Transformative" PCK inextricably combines subject matter, context and pedagogy. Gess-Newsome suggested this is akin to reactants in a chemical reaction forming a compound, that is, a new substance with unique characteristics. Teachers draw on knowledge bases creating PCK as new knowledge. This impacts student learning more than each independent resource. Gess-Newsome claimed a potential "danger" of this view is that "correct" practices exist for topics when taught to in specific contexts. Shulman viewed PCK as transformative, stating PCK constitutes "… the capacity of a teacher to transform the content knowledge he or she possesses into forms that are pedagogically powerful and yet adaptive to the variations in ability and background presented by the students" (p 15).

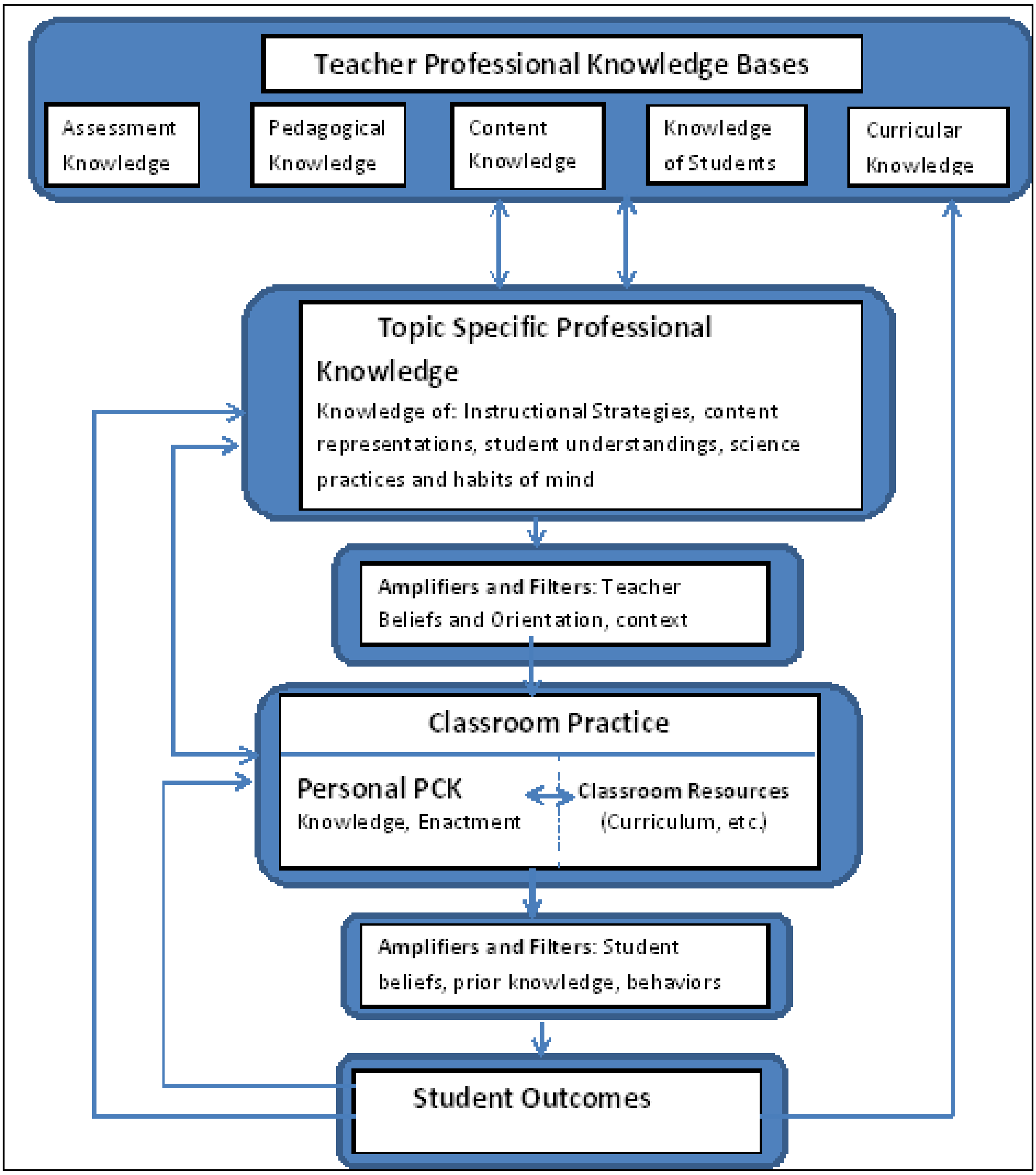

Figure 2: Model of Teacher Knowledge and Skill including PCK (Gess-Newsome, 2015)

Gess-Newsome (2015) updates PCK as “teacher professional knowledge and skill” (TPK&S, Figure 2). This complex model shows PCK as an amplified and filtered version of topic-specific professional knowledge (TSPK). TSPK derives from teacher professional knowledge bases, including pedagogical (PK) and content knowledge (CK). Figure 2 shows PCK as classroom-practice based, and involving “knowledge, skill and enactment”. “Amplifiers and filters” include individual teacher beliefs and orientations (views and stances about the purposes and possible outcomes of teaching) and context. Student outcomes emerge from PCK via student-based filters, and include teacher-mediated learning. PCK as transformative/ integrative is not discussed explicitly, although the model structure is consistent with a transformative standpoint. More importantly, Gess-Newsome moves discussion towards a need to define “the kind of knowledge” that comprises teachers’ professional knowledge bases, picking up Cochran-Smith and Lytle’s (1992) phrase “knowledge *for* practice”. This is generic knowledge codified and exemplified via research that can be utilised in teacher education programmes and professional development. This paper views “knowledge *for* practice” as “knowledge *for* teachers” (van Driel, et al, 2014). Further, the study views PCK as an amalgam of topic-specific professional (TSPK, Table X) and content (CK, Table X) knowledge. While not disregarding other components in the first line of Figure 2, this offers a simpler focus on two components that are regarded in extant literature as essential to high quality teaching. The rubrics (Tables 5 – 7) present exemplar, planned PCK generated from two professional knowledge bases, namely topic-specific professional (TSPK, Table X) and content (CK, Table X), obtained through the contextual “filter” of pre-service teachers (PSTs). The layout and knowledge classifications utilised in the rubrics are generalizable and context-independent. The interactions between TSPK and CK can be translated into practices that impact student achievement.

Questions the paper seeks to answer are:-

1. When responding to vignettes about topic-specific classroom events,
    a. What TSPK statements are generated by pre-service science teachers?
    b. What CK is exhibited by pre-service science teachers?
2. In what ways do pre-service science teachers’ TSPK and CK statements combine to support development of a rubric of pedagogical content knowledge for practice appropriate for use in teacher education?

Literature review

Learning to “think like a teacher”

The context for the study is supporting PSTs learning to “think like a teacher” (Hammerness, Darling-Hammond, Bransford, Berliner, Cochran-Smith, McDonald and Zeichner, 2005, p 382). Consensus on how teachers learn this from their personal starting points remains unresolved. Grossman, Smagorinsky and Valencia (1999) note teachers require pedagogically-based practical tools including instructional practices and resources that enable prompt action in a specific situation. This is consistent with Gess-Newsome’s (2015) view that “action is fast”, and instructional “moves” may be planned or intuitive responses to unanticipated events (p 36). Feiman-Nemser (2001) argues that teachers develop “as professionals” whose practice may strengthen over time along a continuum. An understanding or a vision of what is possible and desirable in teaching inspires and guides teachers’ development. Feiman-Nemser (2001) refers to a “beginning repertoire” of classroom-based enactment that supports PSTs in “transforming” their existing fractured knowledge into consistent “commitments, understandings and skills” (p 1048). She notes that PSTs are uncertain, so getting the nature of their initial repertoire correct is crucial to create an appropriate basis from which to become experts. Corrigan and Gunstone (2011) reflect on challenges to their professional understandings as academic teacher educators in the Australian Project to Enhance Effective Learning (PEEL). They suggest that although highly desirable, developing practical tools supporting teaching is not straightforward. Notwithstanding these challenges, a possible content of a beginning repertoire can emerge from Windschitl et al’s (2012) principle of “ambitious teaching”. These authors state that the term refers to "rigorous and equitable" teaching that should be achievable by a majority of practitioners, including novices/ new entrants. They argue for a limited number of research-based "core practices", that is, instructional strategies that foster engagement and learning. Jones and Cowie (2011) use the phrase "knowledge-as-action", pointing out that teachers need to know a strategy; understand how it functions and why it might be appropriate; have the necessary skills to use it; and be sufficiently flexible to recognise when it might be needed. These comments constitute factors that could characterise potential practices accessible to novice teachers, forming a basis for student-novice teacher interactions.

Teachers' Content Knowledge

Content knowledge (CK) comprises facts about concepts and information (Schwab, 1964). Teachers' CK is variable in quality. For example, Kind (2014a) shows that PSTs with "good" or "excellent" quality science degrees may have limited, poor quality or no content knowledge about basic science curriculum concepts. Teachers' limited knowledge may include misunderstandings and misconceptions about science topics similar to those of their students (Wandersee, Mintzes & Novak, 1994; Kind, 2014a, b).Evidence illustrates that CK is a distinct component of a teacher's professional knowledge (Kirschner, Borowski & Fischer, 2011). These authors established CK for physics teaching and PCK as different, but moderately correlated dimensions of teacher knowledge in a quantitative study of ninety-three German physics teachers. In a qualitiative study, Rollnick, Bennett, Rhemtula, Dharsey & Ndlovu (2008) counted CK as a "fundamental" domain of teacher knowledge, with knowledge of students, context and general pedagogy. These authors consider PCK as an "amalgam" of components, noting that teachers with similar CK may exhibit different PCK. These studies suggest CK and PCK retain distinct qualities.

Extant research also supports the notion that CK quality impacts on teachers' practices. When teachers' CK is poor, their lessons tend to rely on low-risk, text/seat-based activities, feature less whole-class discussion (reducing opportunities for student questions) and avoid cognitively challenging tasks (Abell, 2007, p 1119 – 1120). Abell's analysis draws on Carlsen (1993), who reports that when teaching unfamiliar topics, novice biology teachers tended to talk more often and for longer, asking frequent, low cognitive level questions; and Sanders (1993), who reports that teachers unwittingly acted as the source of students' misconceptions about respiration. More recently, Kaya (2009) found that novice teachers with higher quality understanding of the ozone layer better understood strategies that could diagnose students' preconceptions; and Käplyä, Heikkenen, and Asunta (2009) report that "expert" knowledge helped teachers handle content when planning lessons, as well as students' conceptual difficulties about photosynthesis and plant growth. Nelson and Davis's (2012) study reports that where CK was weak, teachers' evaluations of students' work lacked depth and richness, meaning leading to less success at promoting students' progress.

Collectively, research identifies CK as an initial source or basis for PCK development, consistent with Coe et al's (2014) statement (p 3) and supporting their relative positions in Figure 2. Research evidence also shows that where CK is weak, students' learning is not mediated, because PCK is also weak. For example, Johnson and Ahtee (2006) found that the physics knowledge of some pre-service elementary teachers was so poor that this prohibited their using PCK that mediated learning. This led to their recommendation that CK development is a precursor to PCK development. Developing CK is not straightforward. Spirandeo-Mineo, Fazio and Tarantino's work (2006), focused on "knowledge transformation" in twenty-eight pre-service physics teachers. They show that the process is not "one-way", but bi-directional, involving strengthening content knowledge *and* developing awareness of pedagogical practices. Similarly, Borko and Putnam (1996) state that learning how to teach is "an active, constructive process heavily influenced by an individual's existing knowledge and beliefs, and is situated in particular contexts" (p 674). These authors continue, "…for knowledge to be useful for teaching, it must be integrally linked to, or situated in, the contexts in which it is to be used" (p 675). Thus, research evidence suggests that presenting instructional strategies alone without also paying attention to good quality CK is unlikely to support development of effective teachers.

The role of "amplifiers and filters" (Figure 2) merits further consideration. Feiman-Nemser (2008) supports Spirandeo-Mineo et al (2006) stating that learning is "not a passive process of absorbing new information" (p 700): teachers interpret new knowledge through their existing beliefs and experiences. All novice, pre-service teachers were students, so learning "to teach" is filtered by prior experiences. Gess-Newsome (2015) refers to knowledge passing through the "lens of the teacher"; the teacher is free to accept, reject or modify new skills and knowledge (p 34). This is recognised in Figure 2 by inclusion of the "amplifiers and filters" box between TSPK and PCK. The nature of these amplifiers and filters will vary. Teacher education and professional development may act as "amplifiers", developing PCK (and/modifying TSPK) through engagement in specific activities and events. For example, Daehler, Heller and Wong (2014) found the largest improvements in physics teachers' PCK occurred when interventions emphasised science content situations in "activities and scenarios involving student curricula and instruction" (p 55). They recommend that professional development combines pedagogy, content and student learning, rather than one aspect alone.

CK– PCK interactions

Interactions between CK and PCK have been investigated. Note that these studies pre-date development and publication of the Figure 2 teacher knowledge model, so utilise teacher knowledge base components differently. Hillier (2013), for example, describes forty-nine science graduate PSTs' engagement in writing "narrative explanations" for scientific phenomena occurring in four demonstrations, namely, a peeled, hard-boiled egg being "sucked" into a conical flask; firing air pressure-fuelled rocket balloons; burning a graphite pencil; and melting ice. A consistent feature in PSTs' evaluation of the writing process was the way this forced organisation of their knowledge, including assessment and management of personal misconceptions. This led Hillier to develop the notion of "coherent internal accounts" (CIAs) that comprise individuals' "stories" explaining a phenomenon. She notes that developing such accounts would facilitate transformation of content knowledge and make PCK explicit, a particularly valuable strategy for novice teachers. Possession of a sound CIA for a phenomenon would help a teacher pose suitable questions to students, outline a discussion and permit development of an active learning experience.

Nilsson (2008) describes the CK – PCK intersection as "critical" in transforming physics content knowledge for teaching (p 1290) in her study of four Swedish elementary teachers teaching physics concepts. Like Nelson and Davis (2012), she notes the "gap" existing in teachers' CK that impacted their PCK, particularly, in this case, in handling children's questions and explaining phenomena. She recommends paying attention to pre-service teachers' "personal stories" (p 1296), while at the same time providing exemplar PCK that models good teaching, and opportunities to practice instructional processes in actual lessons.

An alternative perspective emerges from Kind (2009b). This study indicated that, when pre-service teachers teach an out-of-field/specialism topic, their lessons can be more successful in terms of achieving learning outcomes than those they teach on in-field/specialism topics. This suggests the counter-intuitive position that PCK may be easier to develop without strong CK. Out-of-field lesson preparation for these pre-service teachers often involved support from experienced mentors with strong PCK and CK in the topic. Transfer of this practice-based knowledge, coupled with the imminence of a forthcoming lesson, enabled the pre-service teacher to develop sufficient PCK to teach at least satisfactorily. In contrast, for in-field lessons, pre-service teachers were reluctant to seek preparation help, as they felt they were "expected to know" what to do. This resulted in poor selection of CK and PCK, and, ultimately, low quality lessons that were dissatisfying for the pre-service teacher and students. As Anderson and Clark (2012) suggest, PCK develops in conjunction with other knowledge base components, particularly CK, becoming an independent domain. This helps to explain Rollnick et al's (2008) findings, reported above. Overall, therefore, developing CK and PCK together, with acknowledgement of the teacher-based filters through which knowledge may pass seems a good option for moving towards high quality teacher education practices.

Context and sample

Data were collected from a convenience sample of PSTs on entry to a full-time, university-based initial teacher education programme of one academic year (September – June) duration. The programme, known as a "Postgraduate Certificate in Education" (PGCE), is available at UK universities and higher education colleges (Universities and Colleges Admissions Service, UCAS, 2014). PGCE programmes comprise twenty-four weeks of teaching practice in a minimum of two schools and twelve weeks academic study in a university or college. This PGCE provides initial teacher education for around 250 graduates annually, including approximately 45 scientists. The PGCE science programme provides initial teacher education for teaching physics, chemistry and biology to 11-14s, and a specialist, or "in-field" science to 14 -16s. PSTs' specialist or "in-field" sciences normal align with their Bachelor degree subjects, classified broadly as biology, chemistry or physics.

Besides meeting national entry requirements (Universities and Colleges Admissions Service, UCAS, 2014) applicants complete University-specific selection tests. These include: interviews about motivation for teaching and content knowledge; a written task about science education; and probing of skills such as team-working, flexibility, resilience in handling feedback and ability to work under pressure. PSTs were selected by the same faculty using identical, consistent procedures annually. Table 1 shows around two-thirds of successful applicants had prior experience of working with young people in a general, volunteer or science-specific capacity. More graduates with biology than physics or chemistry backgrounds apply. To retain a balanced cohort across three specialist sciences, higher academic standards tend to be applied to select biology graduates than chemists and physicists.

In practice, PSTs have diverse scientific backgrounds. Biologists hold degrees in biology and biology-related subjects including medicine, environmental and biomedical sciences. Chemists hold degrees in chemistry and chemistry-related subjects, including biochemistry and forensic science. Physicists hold degrees in physics, theoretical physics, astrophysics, astronomy or mechanical engineering. Table 1 presents background data about Bachelor degrees, possession of any higher degrees, age, gender, science teaching specialism and prior experience of teaching.

Methodology and data analysis

Data presented here form part of a mixed methods study (Merriam, 2002), findings from which are reported elsewhere (Kind, 2014a, b). Responses were collected from 239 PSTs in 2005 – 2007 (2005 n = 52; 2006 n = 44; 2007 n = 48) and 2009 – 2010 (2009 n = 48; 2010 n = 47) by written questionnaire (see *Context* and below) prior to science methods, teaching instruction or teaching practice. The questionnaire comprised closed questions and three vignettes. Closed questions requested information about PSTs' backgrounds. The closed questions and vignettes were completed in about 45 minutes in an examination-type setting. Annually two or three PSTs used additional time outside this session. Data were collected in accordance with the University's ethical procedures for research involving human subjects, which align with the British Educational Research Association (BERA, 2011). PSTs were informed that data were for research only; anonymity would be preserved in data storage, handling and publication; and responses were independent of any PGCE program assessment procedures. At the time data were collected, the author was a member of PGCE faculty, but reassurances were given and accepted that PSTs' responses were not associated with progress on the programme. No concerns about this have been expressed by any participant at any time.

Characteristic	Sub-characteristic	Biologists N=138	Chemists N=70	Physicists N=41	Whole sample N=239
		%	%	%	%
Gender	Female	**64.9**	**55.7**	**31.7**	**58.6**
	Male	**35.1**	**44.3**	**68.3**	**41.4**
Degree class [1]	1st	**6.3**	**12.9**	**19.5**	**10.5**
	2:1	**47.6**	**35.7**	**26.9**	**40.5**
	2:2	**35.1**	**32.9**	**39.0**	**35.1**
	3rd	**9.4**	**17.1**	**14.6**	**12.6**
	Not stated	**1.6**	**1.4**	**-**	**1.3**
Age	21-25	**67.2**	**38.6**	**70.8**	**59.4**
	26-30	**19.5**	**24.3**	**14.6**	**20.1**
	31 or over	**13.3**	**37.1**	**14.6**	**20.5**
Higher degree	PhD / Masters	**11.7**	**27.2**	**7.3**	**15.5**
	Other, e.g. Diploma	**3.1**	**2.8**	**4.9**	**3.3**
	None	**85.2**	**70.0**	**87.8**	**81.2**
Prior experience of school/teaching	Science specific	**18.8**	**25.7**	**19.5**	**20.9**
	General school-based	**32.0**	**30.0**	**31.8**	**31.4**
	Non-school based	**17.2**	**10.0**	**14.6**	**14.6**
	None	**32.0**	**34.3**	**34.1**	**33.0**

Table 1: PSTs' background characteristics

---

[1] UK undergraduate degrees are awarded in five grades: "First" (Equivalent to secured marks 70+ / US GPA 4.00 /German "Outstanding" /Australian "High Distinction"); "2:1" (60-69/ GPA3.3-3.9 /Substantially above average/ Distinction); "2:2" (50 – 59 / GPA 3.0 – 3.2 / Good average / Credit); "Third" (40-49/GPA 2.3 – 2.9 / Average / Pass); and "Ordinary" (35 – 40 / 2.0 – 2.2/ Barely meets requirements/ Fail)

Vignette design and completion

The vignettes (Veal, 2002) were described classroom teaching situations about one topic each in chemistry, biology and physics taught to 12 – 13 year old students (Science National Curriculum, DfE, 2013) selected to minimise repetition possibilities. The topics were: explanations for plant growth (generation of biomass); a chemical reaction producing a new substance (magnesium oxide); and constant current flow in a simple electric circuit. Vignettes presented students' misconceptions or incorrect ideas documented in literature, identified the correct answer, and asked PSTs, "What would you do as the classroom teacher to help students learn the correct answer?"

Vignettes were presented on separate pages, allowing approximately two-thirds of an A4 (210 x 297mm, 8.3 x 11.7 inches) page length for responses, although PSTs could use extra space if desired. No constraints on type or length of response were applied. In practice, all PSTs answered one or more vignettes in 10 to 200+ words using only the space provided. The response rate was around 95% during the five years data were collected.

Vignette response analysis

PSTs' responses were examined for evidence of pedagogical strategies and CK statements using content analysis procedures (Denzin & Lincoln, 2011) described in detail below. Each statement was considered twice: once for evidence of planned pedagogical strategies, and a second time for evidence of science content knowledge (Table 2).

Table 2 shows that some responses (line 1) proposed more than one pedagogical strategy. Where this occurred all applicable codes were applied. This double/ triple coding showed greater complexity in the response. Line 2 in Table 2 indicates that some PSTs wrote content knowledge statements, without proposing any pedagogical strategy. Line 3 illustrates that some pedagogical strategies were embedded within CK statements: this example refers to use of Lego® building bricks to illustrate a chemical reaction, coded as a "relevant illustration" even though the CK within the statement is incorrect. Line 4 is an example of a relevant explanation, implying that a teacher would invite a class to engage in discussion about the chemical reaction and add clarification. Line 5 exemplifies an irrelevant demonstration that is beyond the scope of the constant current concept. Coding CK from the same responses illustrates two examples coded "complete relevant correct" (Lines 1 and 2). Both show understanding of the science concepts, provide accurate chemical equations and a means of showing how this connects to a mass increase. Lines 3 and 5 are examples of incorrect CK, suggesting that respondents held misconceptions about the science concepts. Line 4 illustrates CK that is correct, but extends beyond the scope of the science concept.

Reliability was established by engaging science subject faculty experts in coding a random set of about 25% of responses. Inter-coder comparability was consistently 82 – 85%. Differences were discussed, resulting in refinement of responses to fit categories shown in Tables 3 and 4. Quotations from PSTs' responses are referred to by three letters. The first letter indicates the PSTs' in-field/specialist science teaching subject (B, biology; C, chemistry; P, physics). The second pair indicates the vignette (BV, Biology; CV Chemistry; PV Physics).

Planned instructional strategy	Exemplar responses	Subject matter knowledge
Relevant demonstration and analogy	Set up an experiment to show photosynthesis. [Diagram of apparatus] Show gas being collected. Explain its O_2. Then explain $CO_2 + H_2O \rightarrow$ glucose + O_2 If glucose is made – think of it like making bags of sugar – bag gets heavier. (C)	Correct reaction identified with a correct equation and notion of mass increase
SMK statement only	Plants absorb carbon dioxide from the air and minerals and water from the soil. This is called photosynthesis. $H_2O + CO_2 \rightarrow$ (sun) carbohydrate $+O_2$. Energy from the Sun is used to convert these into carbohydrates, which are stored in cell walls, creating new cells, hence more mass. (C)	**Correct relevant complete**
Relevant Illustration	…the actual original components have changed in the reaction. Magnesium and oxygen went in and reacted, producing magnesium oxide (the white powder and hence the smoke…) So the powder is really what magnesium and oxygen look like when they are added together. You could use … yellow Lego blocks [as] the oxygen and red the magnesium and put them together in a new shape to show that they are still really there but now look different. (P)	**Incorrect** – implies element identities are retained in a compound
Relevant explanation	Ask the class what has taken place. Establish that oxygen is needed for things to burn (remind them that TV adverts say to keep windows shut if their (sic) in a burning building as extra air will cause the flames to burn more). Let them know that magnesium will combine with the oxygen – use drawings to make it clear. (B)	**Irrelevant** – beyond the scope of the concept
Irrelevant demonstration	Put more lamps in the circuit to show the current [is] unchanged with them so the current doesn't get used up even with more. Change number of batteries to increase current with one lamp to show current (amps) is battery-dependent (power source) not use[d] in the circuit. (C)	**Incorrect** – implies electrons disappear

Table 2: Dual coding of PSTs' vignette responses

Initial Topic-Specific Pedagogical Knowledge coding: using Shulman's components as categories

Initial coding of PSTs' topic-specific pedagogical knowledge (TSPK) utilised Shulman's (1987) PCK components (Figure 3, Table 3) deductively. Note that in Figure 2, Shulman's typology of instructional strategies appears under topic-specific pedagogical knowledge. For coding purposes, TSPK comprises *Instructional strategies*, sub-coded as "demonstrations", "explanations", "analogies" or "illustrations"; and *knowledge of students' learning difficulties,* which includes "students' prior knowledge" and "misconceptions". Responses giving only CK statements without an indication of a planned pedagogical strategy were coded "CK only" (Table 3). These categories were applied consistently to written statements. Responses that did not fit any of these categories were coded "Un-coded response". In practice very few responses could not be coded.

Descriptions of experimental work were coded *Demonstrations*. These were teacher-led to a whole class, or students-led under teacher direction, for example:-

> "…*show the children the same type of plant grown* in different conditions for the same amount of time. In this demonstration you could ask them which plant looks healthiest…" (Biologist (B), Biology vignette (BV))
>
> "*Get the pupils to plant seeds* and each week, spend 5 [minutes] talking and having a class discussion about their growth…" (B, BV)

Discussion or questioning activities were coded *Explanations*, for example:-

> "I would *advise* the children that plants are different to animals… they … make their own food… this process is called 'photosynthesis'…." (B, BV)
>
> "Ask: 'how do plants/trees get water/nutrients from soil?' … *Explain* photosynthesis… Dismiss/explain suggestions air – without soil, would the plant grow?" (B, BV)

Responses coded *Analogies* used "like" or stated the word "analogy", for example:-

> "Give some simple examples of the chemicals involved in growth and what they are used for … extend it to [an] *analogy* of human growth by eating…" (Chemist (C), BV)
>
> "Think of [the circuit] *like* a circular river turning a water wheel…" (Physicist (P), Physics vignette (PV))

Statements proposing visual media, models or role plays were coded *Illustrations,* for example:-

> "[The children] could be given a picture of a tree, and boxes, one labelled 'air' and one labelled 'soil'. In it they would … remove pieces of paper from the boxes which corresponded to the things taken from the air and soil used by the plant. These pieces of paper would be stuck on to the tree diagram…" (B, BV)
>
> "Get the class to stand in a circle, each holding [a] ball[s]. Ask them to pass the ball[s] around. One person is the bulb, one the ammeter. If the 'bulb' stands on the other side of the circle, will it change the ball being passed? No." (P, PV)

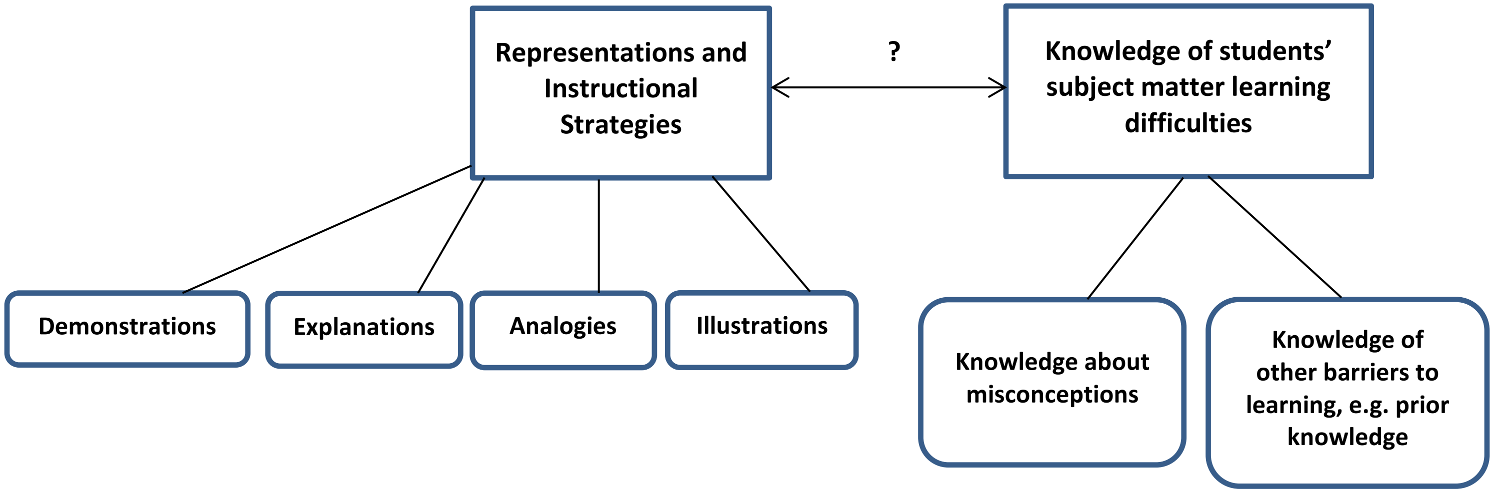

Figure 3: Shulman's Pedagogical Content Knowledge model (Shulman, 1987)

Where *Knowledge of students' learning difficulties* was apparent, responses referred to students' misconceptions and acknowledge prior knowledge:-

> "*Explore the answers the children gave* [given in the vignette] and use the information they should know about photosynthesis…." (B, BV)

> "I would ask pupils for *all three answers [given in vignette] why they think that*… I would try to cover all the areas the children had mentioned previously. I would try and demonstrate the fact that electricity is not 'used up'…" (B, PV)

Responses coded for evidence of students' prior knowledge referred explicitly to students' knowing more than the information provided in the vignette, but did not mention misconceptions. For example:-

> "Ask questions *why they believe it is just (a) air, (b) soil… relate question back to them*… what experiences have they had – helped parents in garden… any observations they've made of plants…" (B, BV)

Responses proposing multiple strategies were considered holistically to best resolve the author's intention, for example, this response:-

> "I would get the class to look closely at some plants and discuss the purpose of different parts of the plants. I would then describe photosynthesis, the purpose of different parts of the plant and draw analogies and highlight differences between plants and animals." (C, BV)

The PST proposes demonstration ("…look closely at some plants…") and analogy ("…draw analogies…"). The purpose of looking at plants is to examine different parts, not to teach photosynthesis. Also, no precise analogy is stated. The photosynthesis aspect of the response is based on oral description ("I would … discuss …. I would then describe…"). Thus, this response was coded as "explanation".

Refining the coding scheme to emphasise the quality of planned pedagogical strategies

These vignettes asked PSTs what they *would do* to "help students learn the correct answer". The initial, deductive coding scheme described and categorised responses that proposed strategies with potentially contrasting student learning outcomes in the same way. For example, both of these responses were coded "*Demonstrations"*:-

> "Demonstrate the growth of a plant in a bell jar, or just a window sill.[I] could have 3 actually, give 1 H_2O and air => it will grow; 2nd H_2O but no air (sealed glass system); 3rd air but no H_2O. Pupils would see for themselves that over time plants 2+3 would visibly die, while 1 would flourish." (C, BV)

> "Set up an experiment to show photosynthesis. [PST provided a diagram]. Show gas being collected. Explain [it is] O_2. Then explain $CO_2 + H_2O \rightarrow$ glucose + O_2…" (C, BV)

The first example describes an experiment *illustrating* plant growth, but this does not address *what photosynthesis is* and *how plant growth occurs*. In contrast, the second example proposes an experiment focused on learning the photosynthesis reaction. This response, if enacted, is more likely to develop student learning about plant growth than the first example. The same contrasts between student-learning-oriented and non-student-learning-oriented responses is apparent in *Explanations*, for example:-

> "Discuss if plants could live and grow without air and soil. Are the plants made of air or soil? What has happened to the air and soil? They have been converted to more useful things that the plant can use." (C, BV)

> "Explain photosynthesis + transport of water + minerals via xylem + phloem vessels. Explain that these products are used + converted into mass" (B, BV)

The first response raises rhetorical questions, is vague and does not explain plant growth. The second uses precise language focusing on plant growth concepts and information. Although photosynthesis is not explained in detail, the second is more likely to generate student learning than the first response.

To account for quality difference within each category, inductive sub-categories were devised that analysed whether proposed *Demonstrations* and *Explanations* were *Relevant*, *Relevant Incomplete* or *Irrelevant* (Table 3, Column 1) to students learning the correct answer. A *Relevant* response was closely allied to the vignette topic, and thus, likely to impact students' learning positively, for example,

> "[Give a] brief description of photosynthesis $CO_2 + H_2O \rightarrow O_2 + C_6H_{12}O_2$ [Arrow labelled "Light" joins the reaction arrow] CO_2 from atmos[phere], light collected by leaves, H_2O from roots, CHO [carbohydrate] made in leaves (O_2 by-product). CHO used to make more leaves, branches, roots. All that comes from soil is micronutrients…" (B, BV; *Relevant Explanation*)

> "Show them the same occurs in lots of different circuits, using different components and power supply, putting the ammeter at various points around the circuit. Show that it is voltage that is used up not current by putting a voltmeter across the load. If you were to say the bulb does not use up electricity they'll wonder how it works at all so show them how it does." (C, PV; *Relevant Demonstration*)

> "Word equation 'Magnesium + oxygen -> magnesium oxide' Explain that you start off with magnesium and oxygen which react together. In a chemical reaction you get a new product. Give other examples of reactions where a new product is formed." (C, CV; *Relevant Explanation*)

Relevant Incomplete responses avoid mention of the central scientific idea in the vignette, for example:-

> "I would ask them what they noticed about the experiment (looking for 'there was a bright light or smoke given off') I would try to make them understand that the light was energy from the reaction. I would … ask what they thought the smoke was. I would ask… where they thought the magnesium had gone – was it the smoke or was it the ash? I would ask… if they thought I could reverse the reaction and get back what I started with." (C, CV; *Relevant Incomplete Explanation*)

This is *relevant* because the features described (light, smoke, energy, ash) are all characteristic of the magnesium /oxygen reaction. The response is incomplete because the chemical elements themselves are not named and there is no reference to a product, magnesium oxide, being formed in a chemical reaction between magnesium and oxygen.

> "I would get pupils to make circuits of their own with different numbers of bulbs and get them to investigate different ammeter positions." (P, PV; *Relevant Incomplete Demonstration*)

This is *relevant* because students making their own electric circuits is a sensible strategy to help them understand that electricity flows through a complete circuit. The response is *incomplete* because the statement does not explain how using different numbers of bulbs would help students understand electricity flow is constant throughout a circuit and is not used up.

> "Grow plants in different conditions and ask them to evaluate the different growing conditions compared to their growth." (B, BV; *Relevant Incomplete Demonstration,*)

This is coded *relevant* because growing plants in different conditions could help develop understanding of photosynthesis. The response is *incomplete* because details of the conditions are absent, together with an explanation of how each growth condition would assist in developing understanding of the origins of biomass.

Irrelevant responses offer information unrelated to vignette concepts and/or do not support learning for other reasons. For example:-

> "Show them an example where it wouldn't work. Trying (sic) to do the experiment under CO_2 so showing them how important oxygen is to the process." (C, CV; *Irrelevant Explanation*)

This suggestion is *irrelevant* because using carbon dioxide gas does not illustrate the importance of oxygen to the magnesium/oxygen reaction. The statement refers to the reaction between carbon dioxide and magnesium, which results in the formation of magnesium oxide and carbon. This is not the reaction described in the vignette.

> "Let them see the answer. Show them the result on the ammeter." (B, PV; *Irrelevant Demonstration*)

This is *irrelevant* because simply showing students the result on the ammeter would not help develop understanding of constant current in a circuit.

> "I would unearth the plants and let them feel the roots…I would then show a video projection of the undersides of the leaves showing the stomata. The pupils could then see how the plant obtains chemicals from both air and soil, helping them to learn." (B, BV; *Irrelevant Explanation*)

This is *irrelevant* because plant roots and stomata are aspects of plant anatomy. Photosynthesis reagents in air and soil are not mentioned and no explanation is provided of how knowing about plant anatomy supports understanding of photosynthesis and development of biomass.

Illustrations were categorised as *Relevant* or *Relevant Incomplete*. No illustrations that were irrelevant to vignette topics were found, hence this sub-category was not applied. *Relevant* illustrations connected the model/ image and vignette topic explicitly, for example:-

> "Use the children to set up a human circuit. Standing them around the room to represent the circuit, elect one child to be the light, one to be the ammeter and the teacher as battery….the teacher provides a current of electrons (sweets!) which can be passed around the room to show movement of electrons.." (B; PV; *Relevant Illustration*)

> "Simple particle models could be done show[ing] oxygen and carbon and that carbon would be left in plant from photosynthesis…"(P, BV; *Relevant Illustration*)

> "I could use Lego bricks to show that when 2 substances undergo a chemical reaction, bonds are broken and reformed to make new products (reassemble the Lego as appropriate)." (B, CV; *Relevant Illustration*)

Relevant Incomplete illustrations did not explicitly connect the model/image and vignette topicand/lacked detail about what was illustrated. These were found for Biology and Chemistry vignettes only:-

> "Draw a diagram of the reaction and give a verbal explanation." (C, CV; *Relevant Incomplete Illustration*)

> "Visual aids – for example I would draw what takes place on the white board as well as verbally explaining it." (B, BV; *Relevant Incomplete Illustration*)

The actual reaction or drawing and verbal explanations are not specified, hence these examples must be incomplete.

Analogies were re-categorised as *Relevant* or *Irrelevant*. This binary sub-categorisation reflects that analogies cannot of themselves be incomplete: they either support or do not support a description of the vignette concept. These proposed analogies showed explicit connections, indicated by italics:-

> "Photosynthesis *is like* making bags of sugar." (B, BV; *Valid Analogy*)

> "*Think of [the circuit] like a* circular river (electrons) turning a water wheel (lamp). Water does not get used up, but it flows more slowly after passing through the wheel." (C, PV; *Relevant Analogy*)

Irrelevant analogies are consistent with misconceptions or misunderstandings for example:-

> "Relate plant growth to our growth. A child who doesn't eat enough or healthily will be weak gaunt and slight…." (B, BV; *Irrelevant Analogy*)

This is irrelevant because a child does not make his/her own food as a plant does; and reasons for poor health emerging from dietary deficiencies are beyond the scope of the vignette topic.

> "Maybe use an analogy – mixing paint -> colour purple is from mixing red + blue paint -> haven't got the colour purple from anywhere else" (C, CV; *Irrelevant Analogy*)

		Vignette		
Potential learning impact	**PCK sub--component**	**Biology**	Chemistry	**Physics**
Relevant	**Demonstration**	Do experiment to show photosynthesis	Repeat experiment, discuss MgO product	Show the circuit, move ammeter
				Use two ammeters
	Explanation	Show [equation for] photosynthesis/ energy transfer	State magnesium oxide is formed	Show $V = IR$ / ammeter role / energy conservation /electron flow
	Analogy	It's like making bags of sugar	None	Water flowing in pipes / Runners in an obstacle race
	Illustration	Use /draw pictures of plants grown in different conditions	Draw particle diagrams/ diagram of reaction	Use children to model a circuit
		Use visual aids, model of plant, tree poster	Model reaction/show new products / conservation	
	Awareness of misconceptions /Prior Knowledge	Explore children's answers	Use children's responses in demonstrations	Use children's responses in demonstrations
		Ask about past experiences	Find out what they already know	Find out what they know about circuits
Relevant Incomplete	**Demonstration**	Compare growth with/without water, air	Show mass increases	Let students try it themselves / Set up the circuit
		Grow plant from seed, weigh as you go	Show involvement of oxygen / combustion	
		Do an investigation (unspecified)	Show magnesium /oxygen /carbon as elements	
		Remind about historical/ classic experiments	Do other reactions to show products form	
		Investigate factors influencing plant growth		
	Explanation	Burning a tree releases carbon, which comes from air /Fertilisers /"Ask why they think this…"	This /all reaction(s) produce (a) new product(s)	Tell them the correct answer
			Equation for reaction (without explanation)	
			Burning produces oxides	
	Illustration	Model the reaction / diagrams (no explanation of the reaction)	Use Lego® bricks to model reaction (no explanation of reaction)	None
Irrelevant	**Demonstration**	Compare growth in different media/ with/without fertiliser/ nutrients	Repeat experiment with another gas /in a vacuum	Add more bulbs to the circuit
		Look at different plants/ leaves/ plant parts		
	Explanation	None	Discuss CO_2 not supporting combustion	Energy is emitted as heat and light
	Analogy	Humans are like plants	It's like mixing paint / making a cake	River dividing in two/Circulation system

Table 3: PSTs' topic-specific pedagogical knowledge (TSPK)

Making a mixture in which components retain their original structure, electron arrangements and bonding is fundamentally different from making a new substance via a chemical reaction. Hence this analogy is irrelevant to the vignette topic.

> "Use an analogy – use the circulation system -> heart pumping red blood cells. Always the same number before and after an organ." (C, PV; *Irrelevant Analogy*)

The circulation system is a double-pump system comprising two interlinked circuits. This is entirely different from the simple electrical circuit illustrated in the vignette. Thus this analogy is irrelevant.

Table 3 shows PCK graded by quality for all three vignettes.

Coding content knowledge

This was coded inductively by generating a coding network (Bliss, Ogborn and Grize, 1979). Statements were classified as *Correct* or *Incorrect* (Figure 4 and Table 4). A correct statement was scientifically accurate and free of any potential misconceptions or misunderstandings. An incorrect statement expressed faulty science, and/or a potential misconception or misunderstanding. "*Incorrect*" statements were not further sub-divided, because incorrect CK statements would, if enacted, negatively impact student learning, so whether these can be sub-categorised is not important. Correct statements were sub-divided as *relevant* to the vignette topic or *not relevant*. A relevant statement is directly related to the vignette topic. An irrelevant statement, although correct, gives information that is outside the scope of the vignette topic. Correct relevant statements were further analysed for *completeness*. "*Correct relevant complete*" statements described photosynthesis accurately using symbols or a word equation (Biology), and connected this to mass increase; referred to magnesium oxide as the product /new substance, and identified oxygen and magnesium as elemental reactants (Chemistry); and noted the ammeter role in measuring current, and constancy of current and electron flow (Physics). "*Correct relevant incomplete*" statements omitted a vital point that would enable students to understand the science concepts. For example, stating "photosynthesis", "metals produce oxides", "conservation of mass", or noting "energy is transferred" are insufficiently detailed, and too general to mediate learning.

Rubrics combining PSTs' CK and planned TSPK

Tables 5 – 7 connect CK and planned TSPK statements. To create the rubrics, twenty-square grids were formed by setting PCK gradings *Relevant*, *Relevant Incomplete*, *Irrelevant* and *CK only* as column headings and CK gradings *Correct relevant complete*; *Correct relevant incomplete; Correct irrelevant; Incorrect* and *PK only* as row headings. In each table, one square represents an individual response with the specific CK and TSPK qualities shown. This categorisation means the maximum theoretical number of possible CK - planned TSPK combinations is nineteen, as the lowest right-hand corner square combination represents "no response". The response pool was examined for examples coded in each CK and PCK combination for the three science concepts. Nineteen, sixteen and fourteen combinations were found for biology, chemistry and physics respectively. "No example" in Tables 5 – 7 indicates where none was found from this response pool. Responses are quoted verbatim where possible, including original minor spelling and syntax errors. Colloquialisms and abbreviations are amended or removed. Insertions in square brackets clarify meaning and/ or abbreviate lengthy phrasing. Ellipses indicate textual omissions such as "I would ask/tell…" or "The children/ students would/should…"

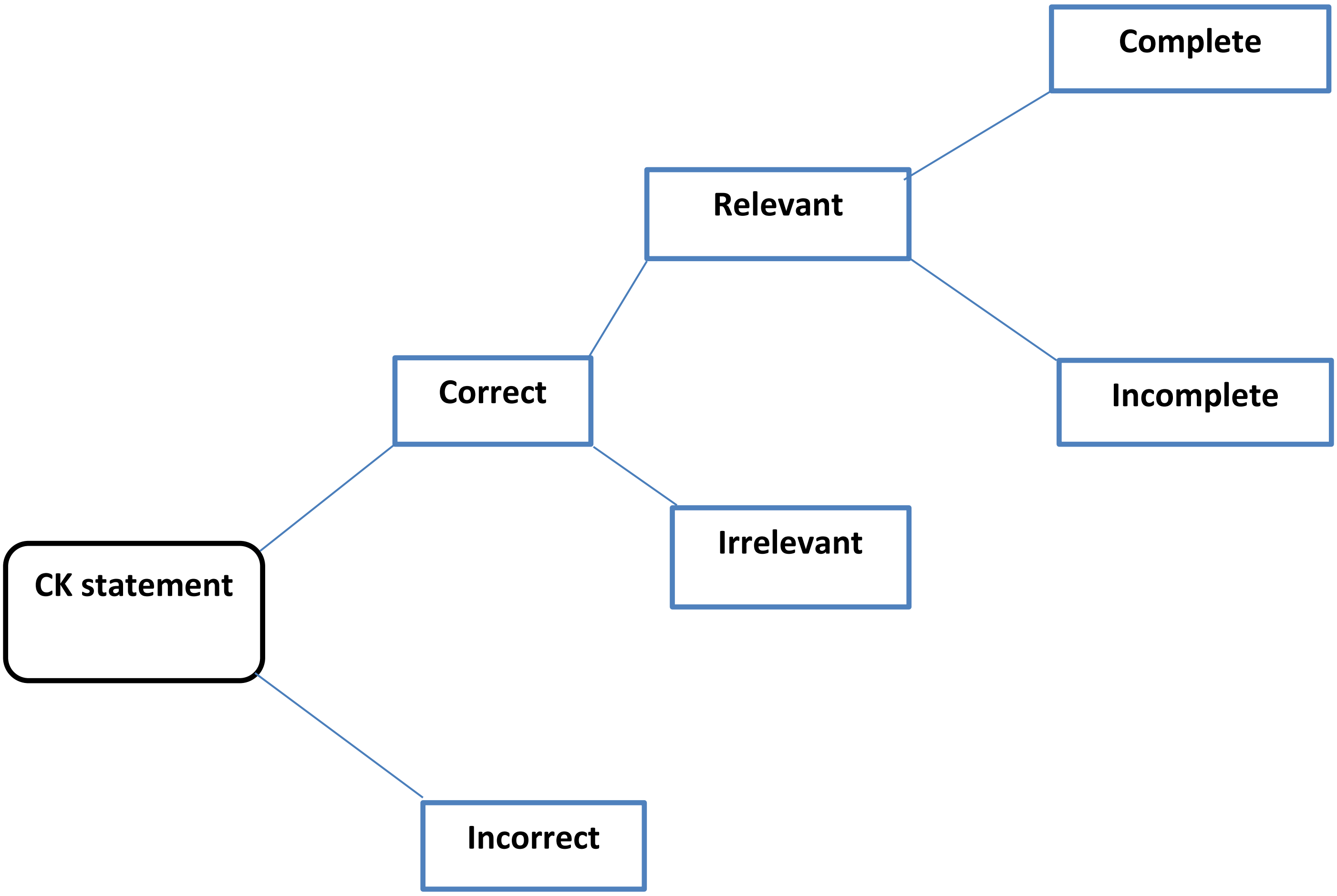

Figure 4: Content knowledge coding network

Findings

PSTs' planned topic-specific pedagogical knowledge

A majority of planned TSPK statements (Table 3) were demonstrations or explanations suggesting PSTs' initial teaching proposals are based on showing, telling, describing or explaining. A greater variety of instructional strategies was observed in response to chemistry and biology vignettes, compared to physics. PCK statements *relevant* to vignette topics divided between including instructional strategies and a relatively small proportion showing awareness of students' learning difficulties.

About one-third of statements were coded "*Relevant incomplete*". These instructional strategies may be interesting, and/or propose a stimulating classroom or laboratory experience, but if enacted, would provide inadequate support for students' learning. For example, the response "Let students try it themselves" (Table 3, Relevant incomplete, Physics) implies students will learn current is constant by experience. This answer omits that students require an *explanation for* constant current. Similarly, "showing involvement of oxygen" does not explain the formation of magnesium oxide (Table 3, Relevant incomplete, Chemistry); and "Growing a plant…" (Biology) fails to explain processes occurring to generate additional plant mass.

Some TSPK statements were *Irrelevant*. Table 3 shows irrelevant explanations, demonstrations and analogies, indicating some PSTs had limited ideas about how to teach the vignette topics. The proposal "add more bulbs to the circuit" (Irrelevant, Physics) was the most frequent irrelevant demonstration response. If enacted, this would show electricity flow through a more complex circuit than that shown in the vignette, but would not help students learn that flow is constant in a complete circuit. The analogy "humans are like plants" (Irrelevant, Biology) would not help students learn how plants accumulate mass via photosynthesis.

Table 3 shows different response patterns between vignettes. A frequent response to the biology vignette was a *relevant explanation* for plant growth, by-passing the fact that the topic is well-suited to an investigation (inquiry) or experiment. Suggested demonstrations were mainly *relevant incomplete,* implying that knowledge of a relevant demonstration is highly specific. These *illustrated* plant growth only, and ignored photosynthesis. *Valid* analogies for plant growth were rarely proposed. Much more frequent than a valid analogy was the *invalid* suggestion that "humans are like plants" although 14% of responses to the biology vignette gave the. Very few responses featured knowledge of students' difficulties. This response type was least frequent in response to the biology vignette. PSTs may have considered students' subject matter learning difficulties indirectly, as aspects of misconceptions feature in *relevant incomplete* demonstrations / explanations.

Explanations comprised the most frequent type of TSPK statement in response to the chemistry vignette. About one-third were coded *relevant*, as these explained magnesium oxide is the reaction product. Most of the remainder were coded *relevant incomplete*. These described aspects of the reaction, such as the mass increasing and the chemical elements involved only, or stated that a product was formed but did not identify it. A small proportion gave explanations using *irrelevant* material, such as repeating the experiment in carbon dioxide (a reaction producing magnesium oxide and carbon); or analogies involving making mixtures not compounds. Knowledge of students' difficulties featured more frequently in response to the chemistry vignette compared to biology and physics. Statements noted students' misconceptions explicitly, and suggested strategies to address them, such as cutting magnesium strips open to show its elemental nature.

About half of Physics responses included *relevant* instructional strategy statements, a higher proportion than found in response to the Biology and Chemistry vignettes. The relevant Physics TSPKK statements comprised demonstrations, explanations, analogies and illustrations in roughly equal numbers. Valid analogies included references to water flowing in pipes and runners on an obstacle course. A small number of responses proposed relevant illustrations, such as students role-playing components of a closed circuit: suggestions included students "acting" as electrons, or passing a ball or piece of paper representing an electron around a "circuit" comprising students standing in a circle. Fewer Physics TSPK statements were coded *relevant incomplete* or *irrelevant* compared to the Biology and Chemistry contexts. *Relevant incomplete* responses proposed students investigating "for themselves." *Irrelevant* proposals included changing the circuit by adding more bulbs, ammeters or switches likely to prompt students' confusion rather than learning the concept.

Between-subject comparisons of TSPK statements indicate that the more than half of responses to the physics topic were *relevant* to compared to about one-quarter of responses for the biology chemistry topics. This suggests these PSTs understood constant electricity flow in a simple circuit better than the other two topics. However, many more biology and chemistry vignette responses compared to physics responses were *relevant incomplete*. This may arise because the physics topic is relatively well-defined with few connections to other conceptual areas, reducing possibilities for diversion. The biology topic invites variation, leading this PST population (comprising a high proportion of biologists) to draw on wider knowledge. The physics topic may illustrate PSTs' knowledge limit, explaining the reduced response range and short response length. The chemistry vignette generated a higher proportion of responses showing awareness of students' difficulties, compared to the biology and physics contexts. Most responses in this category mentioned misconceptions.

PSTs' content knowledge

About two-thirds of PSTs' responses included CK statements (Table 4). However, only a small proportion of these were *correct* and *relevant*, with a limited number of these being coded *complete relevant*. The most common type of correct CK statement provided evidence of general, substantive (Schwab, 1964) knowledge, such as statements about the conservation of matter, rather than topic-specific content knowledge.

CK Quality	Vignette		
	Biology	**Chemistry**	**Physics**
Correct Relevant Complete	Photosynthesis explanation / equation and link to growth	Magnesium oxide (MgO) identified as new substance; oxygen from the air and elemental magnesium	Ammeter role; current constant; electron flow constant
	Air / gas has mass	Chemical reactions produce new substances	Conservation of energy statement
	Plant growth statement	Conservation of matter / particles	
		Metals react with oxygen to produce oxides	
Correct Relevant Incomplete	Photosynthesis explanation / equation; no explicit link to growth	Product named as magnesium oxide / equation for reaction stated without explanation	Reference to ammeter / current / electrons alone
	Photosynthesis named, no explanation/ equation	Reaction is oxidation / oxide formation	Particles in circuit
	Photosynthesis reactant(s) identified	An un-named new substance is produced	Electricity description
	Photosynthesis product/ products identified	Macro-scale observation statement, e.g. white ash / smoke / light / heat produced	Energy transferred
	Plants make their own food	Magnesium and oxygen are chemical elements	
	Conservation statement	Thermodynamics statement	V= IR
Correct Irrelevant	Plant parts named (no other statement)	Experimental procedure description	Circuit description
	Alternative plant growth system, e.g. hydroponics	Heat provides energy for the reaction	Changing circuit
		Use other metals /reactions	Measure voltage
Incorrect	Human-plant analogy	A mixture forms	Energy/electricity is used up
	Incorrect source(s) of reactants identified	Product is magnesium oxide – incorrect formula	Electron speed constant
	Reactants / products not identified	Atoms 'hold hands'	Amps = electron speed
		Non-conservation response	Battery supplies charge
		Incorrect energy source	Voltage constant
		Endothermic reaction occurs	
		No reaction between Mg and N_2	
		Incorrect chemical element properties	

Table 4: PSTs' topic-specific content knowledge

		PCK			
SMK		Relevant	Relevant Incomplete	Irrelevant	None: SMK only
Correct	Complete Relevant	Set up an experiment to show photosynthesis. [Diagram of apparatus] Show gas being collected. Explain its O_2. Then explain CO_2 +H_2O -> glucose + O_2 If glucose is made – think of it like making bags of sugar – bag gets heavier. (C)	Process of photosynthesis. Describe. Carbon dioxide +water -> (light) glucose + oxygen. Say how the area that the plants have grown will affect the amount of water + light that they receive so will affect the plants growth rate. [Picture of plant provided] (P)	Ask children how they grow – what do they need to grow? Relate this to plants – ask what they think plants need to grow. Explain how plants use sunlight in photosynthesis to make carbohydrates for growth + storage – use of CO_2 also. Conditions for growth. Explain that they also need to take nutrients from soil – like we need to eat a variety of goods to get all of the nutrients we need. (B)	Plants absorb carbon dioxide from the air and minerals and water from the soil. This is called photosynthesis. H_2O + CO_2 -> (sun) carbohydrate +O_2. Energy from the Sun is used to convert these into carbohydrates, which are stored in cell walls, creating new cells, hence more mass. (C)
	Incomplete Relevant	I would ask one of the pupils why they think this. I would then try & expand on this. I would explain photosynthesis… chemicals have to be taken from the air and soil. I would try to use visual aids and examples to demonstrate this. (B)	Weigh a plant + soil over time to show increase in mass. Suggest this can't just be from soil as the level has not fallen. Must be air. Explain basically plants make 'food' from CO_2/air (B)	Elicit what they know/ remember from KS2 science about what plants need to make 'food' and grow. Remind them / tell them about historical 'discovery' experiments that led to an understanding of plant nutrition. Help them to plan series of investigations? (B)	Plants require components from the soil – water and air, CO_2 because they make their own food. Food provides energy as nutrients for the cells to grow. A plant with less nutrients and chemicals will not progress as well. (B)
	Irrelevant	Explain to the class that the two plants were grown from seeds from the same packet planted at different times. Ask children why they may differ in size. Record the observations… Give prompts about where the plants have been left and the environment they were in. Ask if there are other examples? E.g. new born animals given different foods. Set up experiments with cress or other fast-growing plants. Keep them in different environments. (C)	Using differing fertilisers and light levels devise an experiment with the children to show that the varying amounts of chemicals in soil and air result in varying size plants. Provide a prize for the best grown plant and explaination (sic). (B)	Hydroponics – plants grown without soil still grow. Burning a lamp in greenhouse => faster grown because increases CO_2. Growing plant in a completely sealed box => no growth. (C)	In chemical reactions there are the same number and type of atoms in the reactants as in the products. Chemical reactions take place between the air/soil/water and the plant therefore these reactants masses are added together. (C)
Incorrect		Relate the topic to cross-curricular topic on mass and make reference to	Give a practical explaination (sic) – this could involve using humans as	Relate it to humans. Ask them what makes them get bigger. Hopefully they	Energy => CO_2 + nutrients (P)

	chemicals causing growth. Ask for suggestion to what chemicals make a plant 'grow'. Get the class to decide where the carbon/ hydrogen and oxygen come from. Make reference to photosynthesis and describe the equation related to this. Maybe point out it is the reverse of respiration. Reinforce with a questionnaire… (B)	examples such as how we need to grow. Building blocks / Lego could be used having different colours for the essential items required for growth. Provoke questioning on the children – why did the plant grow? Etc. (C)	will say from food. Ask where plants get their food from -> photosynthesis. What are raw materials? -> Water + nutrients from soil taken up by roots. (C)	
None: PK only	They could be given a picture of a tree and 2 boxes, one labelled air and one labelled soil. In it they would work as a group to remove pieces of paper corresponding to things taken from the air and soil used by the plant. These would then be stuck onto the tree diagram to extend the branches showing growth. (B)	Demonstrate the growth of a plant in a bell jar, or just on a window sill… give 1 H_2O + air => it will grow; 2nd H_2O but no air (sealed glass system); 3rd air but no H_2O. Pupils would see for themselves that over time plants 2 and 3 would visibly die while 1 would flourish. (C)	As the teacher I would unearth the plants and let them feel the roots. If equipment was available I would then show a video projection of the undersides of the leaves under a microscope, showing the stomata. The pupils could then see how the plant obtains chemicals from both air and soil, helping them to learn. (B)	

Table 5: Rubric of PSTs' planned PCK focusing on plant growth

		PCK			
SMK		Relevant	Relevant Incomplete	Irrelevant	None: SMK only
Correct	Relevant Complete	The white stuff is magnesium oxide Explain that the oxygen in the product comes from the air. Say “If I cut open the Mg strip, will there be oxygen in there?” Answer, “No, only Mg” Mg strip contains only Mg atoms, so when it burns the product will contain Mg and atoms from the other reactant. The other reactant is oxygen. Ash/soot comes from burning carbon containing species (C)	Ideally get them to carry out an experiment in the absence of oxygen and hope no ‘white ash’ is was produced… As a second option test the ‘white ash’ to rule out possibility of carbon/ ash and perform some kind of test to show it was magnesium + oxygen. Ideally demonstrate white ash behaved the same as pre-prepared magnesium oxide. (B)	No example	2Mg(s) + O_2 (g)-> 2MgO (s) (C)
	Relevant Incomplete	Weigh the reactant and product and show a mass increase. Ask where the mass increase comes from. Guide them towards gas from air if necessary. Discuss reactions. (B)	I would do the experiment again. Prior to the experiment discuss/write on board exactly what is being added to the reaction (i.e. magnesium, and oxygen from air). Then re-ask question and if need be steer pupils that what goes in, must be what comes out, even if in a different form, to show that mass is conserved. Then show it is magnesium and oxygen. (P)	Try an experiment where Mg was burnt in different pure gases, e.g. N, O, He. Pupils could compare products with original experiment to see if there was (sic) any comparable results. Pupils could also be taught about the principles of combustion with oxygen, e.g. burning other materials in the gases to reinforce this idea. (B)	The ‘white stuff’ comes from a result of magnesium reacting with oxygen to produce MgO. The fire has created enough energy for the magnesium ribbon to react with the air. (C)
	Irrelevant	Ask the class what has taken place. Establish that oxygen is needed for things to burn (remind them that TV adverts say to keep windows shut if their (sic) in a burning building as extra air will cause the flames to burn more). Let them know that magnesium will combine with the oxygen – use drawings to make it clear. (B)	Describe the difference between physical and chemical changes. Give them an idea of what was involved in the reaction and see if they could work it out. Explain that the effects they see are consequences of energy being released. (C)	Burn Mg in presence of air and without air. Do not burn Mg with/without air. The oxide should form on outside, thin layer. Try also with other metals, oxide should form quite quickly, e.g. 2Cu + O_2 -> 2CuO (C)	Compare to how wood burns (something they will probably understand). Say about how 2 elements can react together to form one compound – the “white stuff” (P)
Incorrect		I would ask them to question their own ideas + prove how it could be that. I would explain that the only “ingredients” going into the reaction are	… the actual original components have changed in the reaction. Magnesium and oxygen went in and reacted, producing magnesium oxide (the white powder and	Discuss with them how air is made of different particles. Talk about reaction, how white stuff is created, not found.	No example

	Mg and O_2 so isn't it likely that the white soot left over is from the reaction between Mg + O_2. Maybe use an analogy -> mixing paint -> colour purple is from mixing red + blue paint -> haven't got the colour from anywhere else.(C)	hence the smoke…) So the powder is really what magnesium and oxygen look like when they are added together. You could use … yellow Lego blocks [as] the oxygen and red the magnesium and put them together in a new shape to show that they are still really there but now look different. (P)	Show day to day example of this such as cooking break to proof (sic) point. As bread mass changes when cooked. (P)	
None: **PK only**	Initially I would show the children the piece of Mg ribbon. I would ask what would they expect to see if the Mg was burned in air. I would carry out the experiment and ask them to write down their observations. Give 1 min to discuss quietly with their neighbour what they think happened. Then bring the group together and ask several to explain what they saw. Then ask them what in air the Mg may have reacted with and working with the group conclude that the white ash was actually a compound and the compound was [PST then writes ….]" (C)	Ask what was in the magnesium, what was in the air, what the Mg reacted with in the air. Draw out a chemical equation with blanks. Have class fill in the blanks. If they still didn't manage, go through the 3 options [listed in the vignette] then best/discard answers. (B)	No example	

Table 6: Rubric of PSTs' planned PCK focussing on a chemical reaction

SMK		**PCK**			
		Relevant	Relevant Incomplete	Irrelevant	None: SMK only
Correct	Relevant Complete	Let the children do the process themselves using a variety of bulbs/ resistors to satisfy themselves that the statement is true. Explain how electricity is a 'flow' of electrons, that if the circuit was broken neither bulb nor ammeter would 'work'. (C)	The electron flow is back to back like a tyre spinning round. Although the energy of the electrons may be changed the flow isn't (unless resistors => heat). Questions from text. Try to set position of other things. Look at results, what effected (sic) current? Conclude. (B)	Use an analogy -> maybe use the circulation system -> heart pumping red blood cells. Always the same number before and after an organ. (C)	The battery output remains constant. The ammeter measures current flow, the rate of which will not change throughout the closed circuit. The voltage will be reduced as it energy (sic) is converted to heat and light in the bulb, but the flow of electrons in the wire remains the same. (C)
	Relevant Incomplete	I would explain that the current was travelling through the bulb to go from the negative to the positive and that it is not retained in the bulb. I would disconnect the circuit after the bulb to show that when a circuit is not complete the bulb does not light, and that the current needs to run through the bulb for it to light. (B)	Experiment. Allow the students to set up a simple circuit and experiment with the positioning of the ammetre (sic). Following this I would go through the theory of current being constant around the circuit. (P) The current flows through the whole circuit. Current flows round the circuit. Set up circuit and draw diagram (C)	Do the experiment again without a bulb in the circuit to get an initial reading of the circuit. Explain what the ammeter is reading for, charge, resistant, etc. (B)	The voltage will be given by the power supply in this case the battery. This is the energy used up by the lamp. Also a current will be supplied by the battery so will remain the same around the circuit. A current is the flow of electricity around a circuit. This will remain unchanged around a closed circuit. Therefore the current will be the same either side of the bulb. Voltage = energy used by lamp given off as heat + light energy. (P)
	Irrelevant	I would tell them about the equation $I = V/R$ where I is the intensity of the current, V is the voltage across the circuit and R the resistance. A bulb is a form of resistance but here we're assuming its resistance is very small therefore there is no voltage drop across it. Because the battery (the source of power) hasn't changed either then the reading of the ammeter is the same. (C)	No example	No example	No example

Incorrect	The 2nd ammeter reading should be taken so the children could see that there is no change in the reading. When this reading is seen we can explore why… If it was higher, the bulb would have to produce energy. If it was lower the bulb would have to use energy. As we see it is the same it shows the bulb simply utilises the energy rather than altering it. (B)	No example	Put more lamps in the circuit to show the current [is] unchanged with them so the current doesn't get used up even with more. Change number of batteries to increase current with one lamp to show current (amps) is battery-dependent (power source) not use[d] in the circuit. (C)	Introduce idea of current/ voltage through a circuit. How ammeter works. No loss of voltage around a circuit, i.e. the lamp does not "use up". (B)
None: PK only	[Ask] what the class thinks current is. ..I then ask the class to place a bulb in the circuit at various points and ask whether the position would affect whether or not it would work….then ask if the current flow would be affected by placing a bulb in the circuit. Get them to write down their ideas. Then place an ammeter after the bulb in the circuit. Then ask why the reading is the same – then conclude from their observations that the bulb does not use up energy. (C)	Get the class to set up the ammeter at different points in the circuit and see for themselves that the reading stays the same. Get them to add extra bulbs etc to prove this point. (C)	No example	

Table 7: Rubric of PSTs' planned PCK focussing on constant current in a simple electric circuit

About one-quarter of all responses were coded *correct relevant incomplete*. These feature a variety of types of information, including macro-scale observations (Chemistry); statements about photosynthesis with no reference to plant growth (Biology) and a description of energy transfer (Physics). *Irrelevant* responses were rare. These occurred most frequently for physics, describing changing the circuit, or measuring voltage. Irrelevant chemistry statements described reactions other than the one featured in the vignette; and those for the biology context described features of plant anatomy or referred to hydroponics. A small proportion of CK statements were incorrect. The most frequent incorrect answer was the analogy "plants are like humans". This analogy attempts to focus on growth, but is incorrect because, unlike plants, humans do not make their own food via photosynthesis. The chemistry vignette prompted the widest range of incorrect CK statements, as Table 4 indicates. Overall, these data may under-estimate levels of correct CK in the PST sample, and over-estimate incorrect knowledge. This point is considered when discussing limitations. Nevertheless, this qualitative coding scheme distinguishes precise, accurate CK that is free of ambiguities and focusing on the topics under discussion from statements that tend describe rather than explain concepts and/ introduce irrelevant material or faulty scientific ideas.

The CK - planned TSPK rubrics

The rubrics (Tables 5 – 7) combine CK and TSPK statements. The three the top left-hand corner squares show that the potential to mediate student learning about a specific concept requires correct relevant CK and appropriate TSPK. In Table 5, this response specifies exactly knowledge students need to learn about photosynthesis, describes an experiment and an appropriate analogy; in Table 6, the "white stuff" is explicitly identified as magnesium oxide, and misconceptions mentioned in the vignette are dismantled systematically; and in Table 7, the physics response includes the correct CK statement "Explain how…", and TSPK based on students' experiments.

The rubrics show that compromising CK and/ or planned TSPK quality reduces the chances for mediating student learning. Responses comprising *PK* only (lower left-hand corners) show that instructional strategies *without* relevant CK are meaningless for learning. In Table 5, the *PK only* response describes a lively activity students may enjoy, but as this lacks CK, engaging in this activity alone would not enable them to learn the origins of plant mass. In Tables 6 and 7, *PK only* responses are good descriptions of whole class strategies. Students experiencing these would have pleasant classroom experiences, but would not learn the scientific knowledge relevant to the vignette topics. Contrastingly, top right-hand corner responses featuring CK alone are sterile and unhelpful for student learning. These may be closest to a rote learning strategy in which students are instructed to learn information without explanation, experimentation or questioning. CK only statements do not "transform" knowledge for students' benefit.

The potential negative impact of incorrect CK on students' learning is particularly potent where *relevant* PCK pairs with *incorrect* CK. In Table 5 the response in this square states a misleading reference to photosynthesis as the "reverse of respiration"; Table 6 includes a proposal to work through students' answers, but explaining these using a "mixing paint" analogy; in Table 7 the response explains that the bulb "utilises the energy", showing poor understanding of energy conservation. If these examples were enacted, students would engage in meaningful activities, but learn incorrect information.

Other columns illustrate the possibility for lessons to divert on to un-related topics. For example, in Table 5, *irrelevant CK* may result in students learning about hydroponics (*Irrelevant PCK*) or fertilisers (*relevant incomplete PCK*) but not photosynthesis. In Table 6, students may be distracted by burning magnesium in other gases (*Relevant incomplete CK/ Irrelevant PCK*); information about handling a house fire (*Irrelevant CK/Relevant PCK*); or exothermic reactions generally (*Irrelevant CK/Relevant Incomplete PCK*). In Table 7, fewer examples of irrelevant CK are apparent, but distractors include the suggestion of adding more bulbs to the circuit (*Incorrect CK/ Irrelevant PCK*) and doing calculations using Ohm's law (*Irrelevant CK/ Relevant PCK*). These (and other) examples would leave students without specific basic knowledge of the topics, potentially creating gaps in understanding.

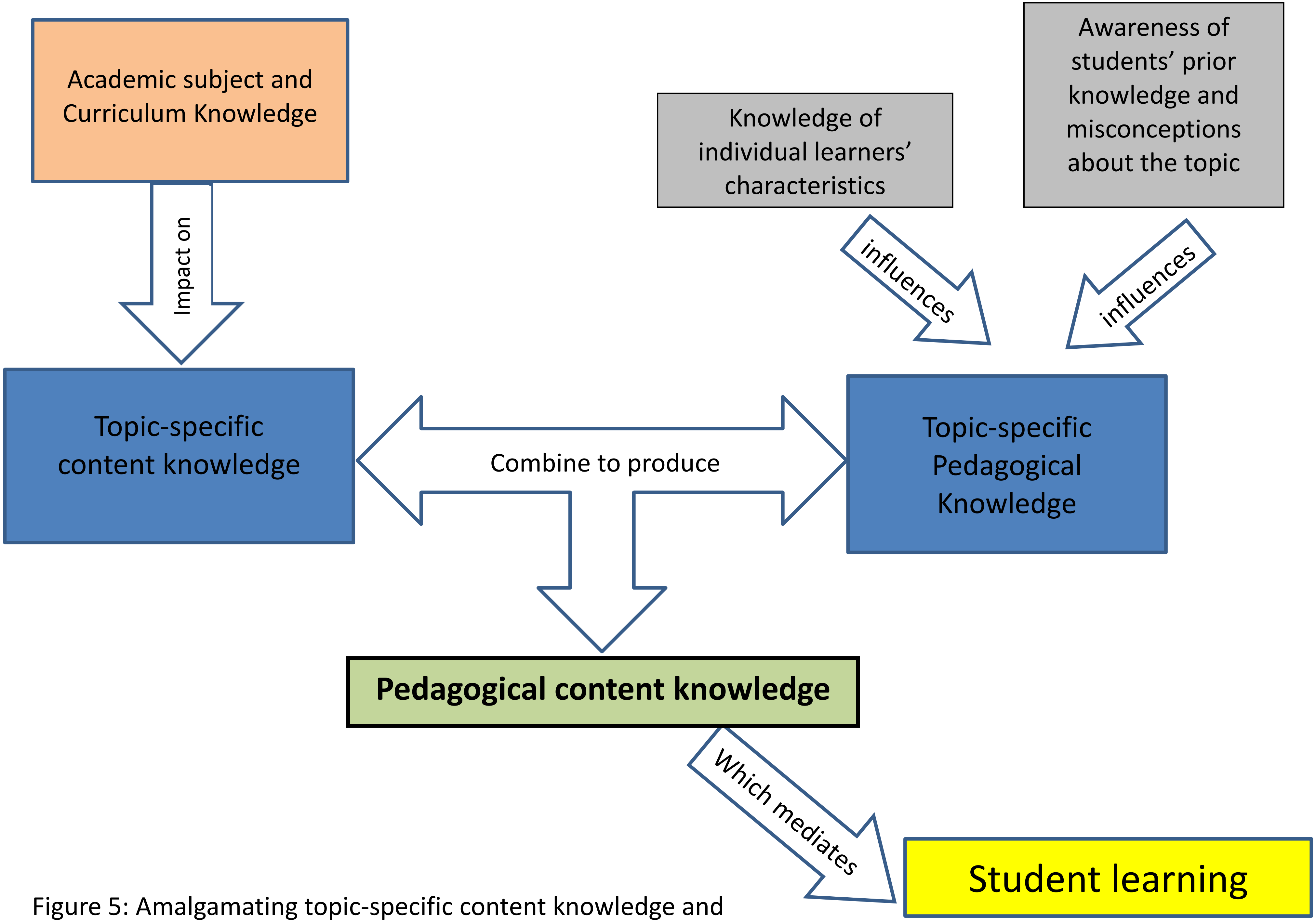

Figure 5: Amalgamating topic-specific content knowledge and pedagogical knowledge

Discussion and conclusions

The rubrics stratify topic-specific pedagogical knowledge and content knowledge by quality, and show examples of how these combine. The author's view is that the combined statements represent PSTs' planned PCK, filtered via prior knowledge gained mainly through personal (school) experience of science. The rubric structure offers a means of identifying variation in knowledge quality, and exemplifying how CK and TSPK may interact and influence each other producing planned PCK likely to generate variable outcomes for students. The stratification illustrates potential for mediating students' learning if teachers hold and utilise high quality, that is, relevant and, for CK, correct, knowledge, as well as lower quality irrelevant and / incorrect knowledge. This contributes to understanding the intersection between CK and TSPK showing that good quality knowledge of both are required to ensure students learn science topics correctly. The few examples of high quality PCK cannot claim to be equal to possible statements that "expert" teachers may provide, or those based on, say, observations of expert teaching. Nonetheless, the classification *method* permits identification of best available knowledge within a context ("filter", Figure 2), and permits negative implications for learning from weak or incorrect knowledge to be highlighted.

Selecting precise*,* relevant knowledge from all knowledge a teacher holds is essential for teaching a specific curriculum topic. In a classroom, students given pleasant tasks that distract, or create confusion will learn little; teachers with good pedagogical knowledge may be able to control students' behaviour very well, but this in itself is not a guarantee that their learning will be mediated (Tobin and Fraser, 1987). Also, PSTs must support individual learners, rather than build classroom monocultures. From a science perspective, knowing that students are likely to hold a range of misconceptions and appropriate / incorrect prior knowledge is valuable. PSTs must learn to select precise CK from extensive academic knowledge. Initially, subject-specialists may struggle to select sufficiently precise CK (Kind, 2009b) as examples in Tables 5 – 7 confirm. Although this study has not examined or investigated assessment, this is likely to influence a teacher's choice of instructional strategy. Evidence reported elsewhere (Kind, 2009b) showed that where PSTs made errors in their instruction, this was identified by assessment of students' learning outcomes, resulting in prompt correction of future action.

An aim for the study was to characterise "knowledge for teachers" in a way that can support novice teachers as they take steps becoming experts (Feiman-Nemser, 2001). The high quality PCK examples shown in Tables 5 – 7 may be adapted as "high-leverage practices" (Windschitl et al, 2012), that is, recognised TSPK strategies backed up by accurate, correct CK. If identifying these is repeated for more topics, based on exemplars from expert teachers, a practice portfolio can be developed for PSTs, out-of-field practitioners, and others needing to refresh or develop their teaching. Other components in the top line of Figure 2, including pedagogical knowledge, knowledge of context and assessment as well as "filters" play a role: where a teacher holds strong, well-developed PK, knows the students well, utilises assessment effectively and has utilised his/her "filters" productively, s/he is likely to be mediating student learning. Nevertheless, however strong, vital and developed these additional components may be, without precise, accurate CK and TSPK a teacher will not impact positively on student learning outcomes *in science*. The importance of these components within PCK is summarised by Figure 5. Developing effective science teachers, from PSTs possessing mixed, often fractured knowledge and diverse backgrounds requires a solid foundation of professional knowledge for science teaching.

The paper is, naturally limited. Data were generated by PSTs, not expert teachers. To raise these responses to a really high quality professional knowledge would require further refinement and input from recognised "expert" teachers. Further, only three topics are presented here, whereas science curricula comprise many. The process of developing a meaningful repertoire comprising topic-specific instructional strategies and SMK for a range of science topics may be laborious and labour-intensive. The vignettes themselves are a constraint: the question posed in each focuses on "learning the correct answer", which is naturally limited. Other vignette structures would of course generate perhaps a more extensive range of TSPK and CK statements. However, even with these limitations, the value of generating a secure repertoire of introductory practices that PSTs know are effective could have impact on science teacher education practice. This would reduce PSTs' uncertainty, and by indicating clearly the nature of the TSPK and CK required would go some way to meeting the challenge of understanding great teaching and how to create great teachers.

References

Anderson, D. & Clark, M. (2012). Development of syntactic subject matter knowledge and pedagogical content knowledge for science by a generalist elementary teacher. *Teachers and Teaching: Theory and Practice*, 18, 315 – 330.

Anderson, R.D. & Mitchener, C.P. (1994). Research on science teacher education. In D. Gabel, (Ed.) *Handbook of Research on Science Teaching and Learning* (3 – 44). New York: MacMillan.

Ball, D.L. & Forzani, F.M. (2010). What does it take to make a teacher? *Phi Delta Kappan*, 92, 8 – 12.

Bliss, J., Ogborn, J. & Grize, F. (1979). The analysis of qualitative data. *European Journal of Science Education,* 1, 427-440.

British Educational Research Association (BERA, 2011). Ethical Guidelines for Educational Research. Retrieved from https://www.bera.ac.uk/wp-content/uploads/2014/02/BERA-Ethical-Guidelines-2011.pdf October 2016.

Borko, H. & Putnam, R. T. (1996). Learning to teach. In D.C. Berliner & R.C. Calfee, (Eds.) *Handbook of Educational Psychology (*673 – 707). New York, NY: Simon & Schuster.

Carlsen, W.S. (1993). Teacher knowledge and discourse control: Quantitative evidence from notice biology teachers' classrooms. *Journal of Research in Science Teaching,* 30, 471 – 481.

Carter, A. (2015). Carter review of initial teacher training (ITT). London: Department for Education. Retrieved from
https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/399957/Carter_Review.pdf

Coe, R., Aloisi, C., Higgins, S.E. & Major, L.E. (2014). What makes great teaching? Review of the under-pinning research. Retrieved from http://www.suttontrust.com/wp-content/uploads/2014/10/What-Makes-Great-Teaching-REPORT.pdf

Corrigan, D. & Gunstone, R. (2011). An approach to elaborating aspects of a knowledge base for expert science teaching. In D. Corrigan, J. Dillon, J. & R. Gunstone (Eds.), *The Professional Knowledge Base of Science Teaching* (83 – 106). London, UK: Springer.

Daehler, K.R., Heller, J.I. & Wong, N. (2014). Supporting growth of pedagogical content knowledge in science. In A. Berry, P. Friedrichsen & J. Loughran (Eds.) *Re-examining Pedagogical Content Knowledge in Science Education* (45 – 59). London, UK: Routledge.

Denzin, N.K. & Lincoln, Y. S. (2000). *Handbook of Qualitative Research (2nd Ed.)*. London: Sage Publications Ltd.

Department for Education, DfE (2013). National Curriculum in England Science Programme of Study. Retrieved from https://www.gov.uk/government/publications/national-curriculum-in-england-science-programmes-of-study/national-curriculum-in-england-science-programmes-of-study#key-stage-3

Feiman-Nemser, S. (2001). From preparation to practice: Designing a continuum to strengthen and sustain teaching. *Teachers College Record*, 103, 1013 – 1055.

Feiman-Nemser, S. (2008). Teacher learning: how to teachers learn to teach? In M. Cochran-Smith, S. Feiman-Nemser, D.J. McIntyre & K.E. Demers (Eds.) *Handbook of Research on Teacher Education* (3rd Ed.) (697 – 705). Abingdon, UK: Routledge.

Gess-Newsome, J. (1999). Pedagogical content knowledge: an introduction and orientation. In J. Gess-Newsome and N.G. Lederman (Eds.) *Examining Pedagogical Content Knowledge* (3-17). London, UK: Springer.

Gess-Newsome, J. (2015). A model of teacher professional knowledge and skill including PCK: Results of the thinking from the PCK Summit. In A. Berry, P. Friedrichsen & J. Loughran (Eds.) *Re-examining Pedagogical Content Knowledge in Science Education* (28 - 42). London, UK: Routledge.

Grossman, P., Smagorinsky, P. & Valencia, S. (1999). Appropriating tools for teaching English: a theoretical framework for research on learning to teach. *American Journal of Education*, 108, 1 – 29.

Hammerness, K., Darling-Hammond, L., Bransford, J., Berliner, D., Cochran-Smith, M., McDonald, M. & Zeichner, K. (2005). How Teachers learn and develop. In L. Darling-Hammond, & J. Bransford, J. (Eds.) *Preparing Teachers for a Changing World* (358 – 389). San Fransisco, CA: Wiley.

Hillier, J. (2013). How does that work? Developing Pedagogical Content Knowledge from Subject Knowledge. *Teacher Education and Practice*, 26, 323 – 340.

Kind, V. (2009a). Pedagogical content knowledge in science education: potential and perspectives for progress. *Studies in Science Education*, 45, 169 – 204.

Kind, V. (2009b). "A conflict in your head": An exploration of trainee science teachers' subject matter knowledge development and its impact on teacher self-confidence. *International Journal of Science Education*, 31, 1529 – 1562.

Kind, V. (2014a). A degree is not enough: A quantitative study of pre-service science teachers' chemistry content knowledge. *International Journal of Science Education*, 36, 1313-1345.

Kind, V. (2014b). Science Teachers' Content Knowledge. In H. Venkat, M. Rollnick, J. Loughran, & M. Askew (Eds.), *Exploring Mathematics and Science Teachers' Knowledge (*15 – 28). London, UK: Routledge.

Kirschner, S., Borowski, A. & Fischer H.E. (2011). Physics Teachers' Content Knowledge and Pedagogical Content Knowledge: Developing Test Scales and Measuring the Relation. *Proceedings for the National Association for Research in Science Teaching 2011* Orlando, FA. Retrieved from https://www.researchgate.net/publication/257418805_Physics_Teachers'_Content_Knowledge_and_Pedagogical_Content_Knowledge_Developing_Test_Scales_and_Measuring_the_Relation

Johnson, J. & Ahtee, M. (2006). Comparing primary student teachers' attitudes, subject knowledge and pedagogical content knowledge needs in a physics activity. *Teaching and Teacher Education,* 22, 503 – 512.

Jones, A. & Cowie, B. (2011). Moving beyond deconstruction and reconstruction: Teacher Knowledge-As-Action. In D. Corrigan, J. Dillon, J. & R. Gunstone (Eds.), *The Professional Knowledge Base of Science Teaching* (51 – 63). London: Springer.

Käplyä, M., Heikkinen J.-P., & Asunta, T. (2009). College students' conceptions of chemical stability: The widespread adoption of a heuristic rule out of context and beyond its range of application. *International Journal of Science Education*, 31, 1395–1415.

Kaya, O. (2009). The nature of relationships among the components of pedagogical content knowledge of pre-service science teachers: 'Ozone layer depletion' as an example. *International Journal of Science Education*, 31, 961–988.

Merriam, S. B. A. (2002). *Qualitative research in practice: Examples for discussion and analysis* (1st Ed.). San Francisco, CA: Jossey-Bass.

Nelson, M.M. & Davis, E.A. (2012). Pre-service Elementary Teachers' Evaluations of Elementary Students' Scientific Models: An aspect of pedagogical content knowledge for scientific modelling. *International Journal of Science Education*, 34, 1931-1959.

Nilsson, P. (2008). Teaching for Understanding: The complex nature of pedagogical content knowledge in pre-service education. *International Journal of Science Education*, 30, 1281-1299.

Rollnick, M., Bennett, J., Rhemtula, M., Dharsey, N. & Ndlovu, T. (2008). The place of subject matter knowledge in pedagogical content knowledge: A case study of South African teachers teaching the amount of substance and chemical equilibrium. *International Journal of Science Education*, 30, 1365 – 1388.

Russell, T. & Martin, A. K. (2014). Learning to Teach Science. In N.G. Lederman and S.K. Abell (Eds.), *Handbook of Research in Science Education, Volume II (*871 – 888). Abingdon, UK: Routledge.

Ryan, G. W. & Bernard, H.R. (2000). Data management and analysis methods. In N.K. Denzin & Y.S. Lincoln (Eds.) *Handbook of qualitative research* (2nd Ed.) (769-802).London, UK: Sage Publications Ltd.

Sanders, M. (1993). Erroneous ideas about respiration: The Teacher Factor. *Journal of Research in Science Teaching*, 30, 919 – 934.

Schwab, J.J. (1964). Structure of the disciplines: meanings and significances. In G. W. Ford, & L. Pugno (Eds.), *The structure of knowledge and the curriculum (*1-31). New York, NY: Rand McNally.

Spirandeo-Mineo, R.M., Fazio, C. & Tarantino, G. (2006). Pedagogical content knowledge development and pre-service physics teacher education: A case study. *Research in Science Education,* 36, 235 – 268.

Tobin, K. & Fraser, B. J. (1990). What does it mean to be an exemplary science teacher? *Journal of Research in Science Teaching*, 27, 3 – 25.

Universities and Colleges Admissions Service, UCAS (2014). Entry requirements for teacher training. Retrieved from http://www.ucas.com/how-it-all-works/teacher-training/entry-requirements accessed 8.5.14

Van Driel, J.H., Berry, A. & Meirink, J. (2014). Research on Science Teacher Knowledge. In N.G. Lederman and S.K. Abell (Eds.), *Handbook of Research in Science Education, Volume II* (848 – 870). London, UK: Routledge.

Veal, W. (2002). Content Specific Vignettes as Tools for Research and Teaching. *Electronic Journal of Science Education*, 6 (4), June 2002

Wandersee, J., Mintzes, J. & Novak, J. (1994). Research on alternative conceptions in science. In D. Gabel (Ed.), *Handbook of Research on Science Teaching and Learning* (177–210). New York, NY: MacMillan.

Windschitl, M., Thompson, J., Braaten, M. & Stroupe, D. (2012). Proposing a Core Set of Instructional Practices and Tools for Teachers of Science. *Science Education*, 96, 878 – 903.