ADDING PEDAGOGICAL PROCESS KNOWLEDGE TO PEDAGOGICAL CONTENT KNOWLEDGE: TEACHERS' PROFESSIONAL LEARNING AND THEORIES OF PRACTICE IN SCIENCE EDUCATION

Colin Smith[1]; Allan Blake[1]; Fearghal Kelly[2];

Peter Gray[3] and Michelle McKie[1]

[1]Strathclyde University and S-TEAM

[2]Norwegian University of Science and Technology S-TEAM

[3]East Lothian Council

Abstract:

A concept of pedagogical process knowledge (PPK) is introduced to partner pedagogical content knowledge (PCK). This concept arises from observing the learning of teachers engaged in a course supporting them in introducing more inquiry-based methods into their practice. This course aimed to empower teachers through professional learning. PCK alone did not seem adequately to explain the teachers' learning, which involved them developing new pedagogical processes to support the development of inquiry-based learning processes in their students – hence PPK. Together, PCK and PPK are important constituents of teachers' theories of practice, although PPK may be often less developed.

Keywords: Continuing Professional Development (CPD); PCK; PPK; empowerment; practitioner theory.

Corresponding author: Colin Smith
E-mail: colin.a.smith@btinternet.com
Submitted for publication 12/02/2013
Accepted for publication 15/05/2013
Educational Research eJournal -ISSN 2254-0385

DOI: 10.5838/erej.2013.22.05

1. Introduction

The concept of pedagogical process knowledge (PPK) introduced here is complementary to the well-established concept of pedagogical content knowledge (PCK) originating with Shulman (1986, 1987). Although PPK is a concept applied to particular teacher knowledge outcomes from a science education project, we believe that it is also useful in other curricular areas. From work in science education, we believe that PPK also arises in other areas. We use results from the Science-Teacher Education Advanced Methods (S-TEAM) project, which supported teachers in the use of inquiry-based methods in science and in recognising the skills developed by inquiry, such as problem solving, peer-discussion, communication, collaboration, critical thinking, creativity and innovation. S-TEAM collected data from fifteen European countries on teachers' attitudes to inquiry-based methods, their experience of continuing professional development in this area and their judgements about students' engagement in science and their interactions with them.

The work reported here draws on a continuing professional development module that supported teachers as they investigated how to guide their students to learn through increased use of inquiry-based methods. We wanted, therefore, to introduce teachers to new ways of thinking about the goals of their practice, so that they increased their use of inquiry-based methods. However, as will be discussed later, the PCK literature was consulted following this intervention with teachers, in an attempt to better conceptualise the outcomes they demonstrated when trying to use more inquiry-based methods. An issue emerged that the concept of PCK did not seem sufficient to describe or explain these outcomes – improved knowledge of how to support processes of inquiry, questioning, and scientific thinking.

Because our work did not begin with the issue of teacher knowledge, our argument has an unusual structure. It begins by presenting sufficient background to enable readers to understand why and how the work was conducted. Essentially, the project involved university researchers and teacher educators working with teachers in a professional development course that the teachers themselves shaped. The following sections focus on three of the teachers to illustrate the kind of knowledge they developed. We then turn to the concept of pedagogical content knowledge (PCK), which seems only partially to explain or describe these particular outcomes, leading us to introduce the concept of pedagogical process knowledge (PPK) to complement, but not to replace, PCK. The concept of practitioner theory is then used to discuss how these two features of teacher knowledge might interact.

It is first necessary to comment on our data. The aim of the course was not to contribute directly to understanding teacher knowledge, but to support teachers in making their practice more inquiry-based. In collecting data, therefore, we focused on how well the course supported this aim, both from our point of view and that of the teachers. The main data source was the teacher presentations and discussion at the course's end, in which participants described their experimental interventions, what they had learned from them and what impacts they had on themselves, their students, or their colleagues (Smith *et al.*, 2013). Recordings of the module sessions and the related discussions, teachers' textual or graphical responses to the various exercises, and electronic communications supplemented this data. The concept of PPK emerges largely from the teachers' presentations, as it was mainly here that they described their learning from the course as a whole.

The teachers' evaluation of the course was assessed through a focus group conducted by a member of the project team who had not previously participated in preparation or delivery of the course, Other team members did not attend this group, so as not to influence its outcomes. The teachers' discussion ranged over such issues as the methodology employed in leading the course, the utility of the conceptual tools provided, and the teachers' concepts of inquiry and how it might have changed or developed through it. Some of this material is presented in this paper, where it usefully illustrates how the teachers were thinking.

2. International Context and background

The response to international concerns that many young people show lack of interest in science, both during and after formal education, includes the suggestion that learning science should increasingly involve processes of inquiry and the development and refinement of ideas through processes of reasoning (for example, Millar and Osborne, 1998; National Academy of Sciences, 2012; Reiss *et al.*, 1999: Rocard, 2007; The Scottish Government, 2009a, 2009b). Funding has been provided by the European Union (EU) for a number of pan-European projects in Framework Programme 7, designed to support science teachers in using more inquiry-based practices.

The main intention of the EU was not to generate new research but to find ways of using existing knowledge to support inquiry-based practices. This is itself a complex issue. Even within one country (Scotland), deriving universally applicable, research-based prescriptions for action is difficult, as we found in a previous project looking at the early learning of teachers (McNally and Blake, 2010). The solution adopted at that time was to present a descriptive model of early professional learning that allowed schools and local education authorities to ask questions about their own practice in supporting new teachers and to identify desirable changes for themselves (Smith, 2010a).

This earlier experience was influential in our contribution to S-TEAM (S-TEAM, 2013). The project, as a 'Coordination and Support Action' (CSA), was intended to help teachers deal with issues of pupil engagement with science through applying existing research in inquiry-based methods, creating teacher professional development programmes based on this research and providing evidence to policymakers of the efficacy of these methods. This was not a simple task, given the fifteen national contexts involved and the wide range of educational research themes already in progress across the 26 partner institutions. S-TEAM differed from many other projects in this field in that we focused on teacher development rather than the provision of 'materials' or 'resources' for direct use in the classroom, an approach which we felt was flawed due to the highly contextualised nature of education and the consequent range of pedagogical, curricular and assessment methods applicable across the partner countries.

With international transferability in mind, our hypothesis was that teachers would be best helped to make their practice more inquiry-based if they were provided with 'tools' rather than 'materials'. These tools would take the form of models, concepts and ways of thinking to help teachers reflect on their practice and empower them to make changes themselves. These 'tools' could thus be used across different national contexts. That is, the idea was for teachers to develop their own knowledge through changes in representations

(Maclellan, 2008). These representations or conceptual tools were intended to help the teachers to re-conceptualise goals associated with inquiry and scientific thinking, and to solve for themselves the problems involved in achieving those goals in their own contexts.

Our work suggests that teachers using these tools can better engage their students in learning through inquiry, even in a crowded curriculum. They can support students in developing scientific thinking and learning more about how science works, with a marked improvement in understanding of content. There are a number of educational reasons for pursuing this goal. These include:

- •Facilitating an understanding of the nature of science,
- •Meeting a need to do science as well as to learn it,
- •Approaching 'authentic scientific activity' (McNally, 2006)
- •Promoting a sense of agency or self- as an active learner (Crick, 2009)
- •Fostering creativity (Haigh, 2007)
- •*"Support[ing] children to become curious, critical and enquiring about a complex and changing world that is not easy to assimilate"* (Williamson and Morgan, 2009, p. 288).

One could probably substitute the word 'science' with that of any other discipline to this argument, although within S-TEAM we emphasised the specificity of 'scientific thinking' and the consequent relationship to disciplinary norms and practices.

The authors did not originally plan to present the models as part of a formally delivered professional development module, but intended to negotiate with teachers to establish a knowledge building community (e.g. Bereiter, 2002) or professional learning community (e.g. Lewis and Andrews, 2004; Verscio *et al.*, 2008), and to introduce the conceptual tools in working towards problems that teachers had identified. Instead, teachers expected the delivery of accredited professional development. In Scotland, little professional development is provided for qualified teachers by universities, other than in the form of academic degrees (e.g. masters and doctorates in education) that few undertake. The common experience of most teachers, therefore, is for the Government or Local Authority to provide 'experts' in change processes, policy directions or initiatives, who prescribe how teachers should change their practice. These factors influenced the expectations of our teachers. As one put it…

> *'For the first couple of sessions, I was just like, 'Just give me the answer.' I just wanted a bit of paper to […] say 'do this'. But now at the end of it, I think it wouldn't have been ingrained in my practice.'* (Teacher 5 {T5} – commenting in the Focus Group)

There was, therefore, a mismatch between our concept of empowering teachers through their use of conceptual tools and the expectations of the teachers for some form of prescription coupled with university accreditation for being able to enact it. This mismatch is usefully encapsulated in Loughran's (2010) distinction between professional development and professional learning. Professional development arises during changes such as new curricular or policy initiatives, involving the assumption that teachers need to be 'up-skilled.' Therefore, teachers often experience traditional professional development as 'doing something to them' – professional development providers are in the business of developing teachers. Mandated changes are presented, teachers are trained in those changes in terms of technical requirements (sometimes as simple as re-labelling existing curriculum and practice) and are then expected to implement them, in a top-down approach.

Professional learning, in Loughran's view (see also, Berry and Loughran, 2010), operates differently. The assumption is that teachers have some commitment to the changes through driving, developing or refining them. Professional learning is distinct from professional development because change results from work with, as distinct from on, teachers. There is also an assumption that teachers are able to bring expert judgement to bear in considering how best to implement change in their own contexts and practices. Therefore, professional learning is the learning that occurs through processes of reflection, discussion and experiments in practice. It begins with the current knowledge and beliefs of the teachers (Verloop *et al*., 2001). Involvement in professional learning is more likely to be voluntary, and the subsequent learning is personal and appropriately shaped and directed by each individual. As such, it is in line with conceptions of autonomy emphasising perceptions that what one does emanates from the self, is self-authored, relates to one's own interests and involves choice in actions (Su and Reeve, 2011). As Berry and Loughran, (2010, p.2) suggest:

> "The notion of teacher as pedagogical decision maker within a specific context has come to be recognised as a vital centrepiece to new understandings of professional development."

This concept of professional learning helps to articulate the idea of empowerment used here. Unless it incorporates concepts of professional learning, empowerment can still sound too much like 'doing things to teachers'. Although they may have expected 'prescriptions for action', the teachers came to use the models provided autonomously, and drove their own learning and knowledge development in a variety of directions according to their own perceived needs and the needs of their students. Berry and Loughran (2010, p.3) put it this way:

> "…professional learning involves the sharing of insights about teaching and learning between teachers in order to gain a sense of professional control and ownership over their learning, and concomitantly, a responsibility for the learning and teaching environment that they actively create in their classes.…an emphasis on professional learning is important for empowering teachers through valuing their voices and perspectives" (Gore & Gitlin, 2004); a process that is now recognized as developing throughout their whole career (Feimen-Nemser, 2001).

The teachers thus used the conceptual tools provided in order to be actively involved in exploring their individual experiences and contexts and in becoming articulate (in their presentations and subsequent discussions) about what they have learnt, both before and after their experiments in practice. The models helped them with the difficult task of defining the problems they faced (Verloop *et al*., 2001). Teachers used them to develop their 'own voices and perspectives.' They noted subsequently how the requirement to present to the group supported this. T5, one of the teachers discussed below, commented.

> T5: *It's embedded now into your practice.... I think the pressure, when we were told that we had to give evaluations, I was horrified, just the thought of having to present to people but it actually gives you the kick up the butt you need to actually go and put into practice and really seriously evaluate yourself and without having to feed back to the group - 'oh yes, it's been wonderful' - you wouldn't have gone about it.*

The compromise solution was therefore to develop a course that modelled as far as possible the sort of learning community we had initially envisaged, the difference being that the teachers were formally guided through the models and exercises and used them to identify the issues in their practice that they wished to experiment with. That is, the course did not aim primarily to transmit knowledge but to enhance the knowledge creation capacities of those taking part (Eraut, 1994, Thiessen, 2000). The next section briefly outlines the course.

3. The course in outline

The course was called PISCES. In Scotland PISCES stands for *Promoting Inquiry Skills for a Curriculum for Excellence in Science* to attract teachers concerned with meeting the requirements of the new 'Curriculum for Excellence'[1] for more pupil inquiry. However, as part of a European project, PISCES is intended for others to adapt and use across Europe and for this purpose is called *Promoting Inquiry in Science Classrooms in European Schools* (Smith *et al.*, 2011), though countries may use their own title, as has Gulbene in Latvia. On this basis, it is open to anyone in and beyond Europe.
As described above, the teachers expected university accredited professional development. This led to a module based on empowerment through helping the teachers to conceptualise their issues around inquiry (Table 1). Empowerment was achieved through bringing two analytical tools or models to the teachers. One of these was the Herron Model of Levels of Investigation (Forsman, and Kurtén-Finnäs, 2010; Herron, 1971, Smith *et al.*, 2011). The other was a five-dimensional model of investigations; including a dimension of scientific thinking based on Feist (2006) that we have developed in S-TEAM and reported elsewhere (Smith. 2010b, 2010c; Smith *et al.*, 2010a, 2010b, 2011, forthcoming). Space does not permit a full description of these models here.
The module lasted for six sessions of 90 min. with a minimum of two weeks between them to allow for reflection and reading. The first four sessions involved using the conceptual tools and discussing the results. This led to the teachers devising what they called 'intervention questions'. The last two sessions were for the teachers to present, and discuss as a group, what they had tried out in their classrooms.

Promoting Inquiry in Science Classrooms in European Schools (PISCES)
Empowerment, *not prescription*
Accredited module giving empowerment to teachers: · To conceptualise issues of inquiry · To devise and implement own intervention questions · To try out answers to the questions in their practice · To evaluate the outcomes of their interventions and present them to the whole group

Table 1. Basic outline of PISCES

Eight teachers participated in PISCES. They all reported that they had, in some way, changed the pedagogical process they were using. The outcomes can be divided into three categories:
1. New pedagogical processes to make their practice for the chosen topic more inquiry-based– three of the teachers (T5, T7 and T8)
2. Devising a new pedagogical process that was run in parallel with the existing pedagogical process for the topic (Teacher T2). This could be characterised

[1] A Curriculum for Excellence is a long-term initiative introduced by the Scottish Government to facilitate the individualised development of pupil capacities. See: http://www.educationscotland.gov.uk/thecurriculum/whatiscurriculumforexcellence/index.asp

as encouraging students, who were largely passive when it came to asking questions and thinking about what they were doing, to turn all lessons into a form of inquiry.

3. Devising enhancements or modifications of existing pedagogical processes that, in some way, made their lessons more inquiry-based. (Teachers T1, T3, T4 and T6)

In this paper we focus on T8, T5 and T2 since we see the forms of learning described by these teachers as sufficient to illustrate the concept of pedagogical process knowledge (PPK). These teachers cover a range of student ages – primary 1 (around age 5), secondary 2 (around age 13) and secondary 5/6 (around ages 16 to 18), so illustrating that both the methodology of PISCES and the concept of pedagogical process knowledge can be applied at all school levels of science teaching. As intimated earlier, the paper draws on the qualitative data from the teachers' presentations and discussion at the end of the course, as well as from the focus group evaluation that was undertaken one month later. These discussions were recorded and transcribed with the permission of the teachers, whose anonymity we protect by using codes (T1, T2, etc.). The methodological paradigm is naturalistic in that it relies on human interpretations of the everyday practice of teaching, in this case the empathetic and informed understanding between colleagues at different stages in their careers. This makes our findings subject to criteria appropriate to naturalistic investigation, as in for example transferability, dependability and confirmability (Lincoln & Guba, 1985). We are further guided in this by Flyvbjerg (2006, p. 222), for whom useful social science is characterised by practical, context-dependent data that are generated by insiders who 'operate on the basis of intimate knowledge of several thousand concrete cases in their areas of expertise', and which leads to the possibility of developing a 'nuanced view of reality'. That is to say, we have adopted the view of case researchers in seeking both what is commonplace and particular about our subject, with the possibility of portraying something of the uncommon (Stake, 2000).

4. How teachers developed new pedagogical processes

4.1. T8 and genetics with secondary 5/6 (ages 16-18)

T8 focused on ensuring that content in a high stakes examination course (Higher Biology) was understood. Highers are the flagship exams of the Scottish school system, being required for entry to university. Higher classes may contain students who are taking Higher for the first time or who are (in secondary 6) adding to the Highers they have already achieved. It is a common concern among teachers that inquiry-based methods may compromise the form of content understanding expected for high stakes assessments. However, T8 had concerns that students did not adequately understand the topic (linkage in genetics) using his usual, more lecture-based approach, and phrased the intervention question in more general terms:

> *How do I teach course outcomes through investigations- allowing students ownership of their own work?*

When planning his intervention, T8 writes:

> *Experience shows that students have difficulty with 'linkage'. Normally I would teach this straight after covering the dihybrid cross* (explained below) *and in a very traditional way* (as explained in his presentation, this was: teacher explanation using PowerPoint, working through an example of an exam problem/question, followed by students working through

practice problems). *My idea was to cover this in a completely different way to* promote student engagement and improved understanding (emphasis in the original).

T8 is a respected and experienced teacher, recognised as being innovative and dynamic, and is head of a Biology Department.T8 felt competent in guiding students through more 'set piece' inquiries, but saw PISCES as presenting a challenge to consider using inquiry in other areas of teaching. T8 commented in an email that:

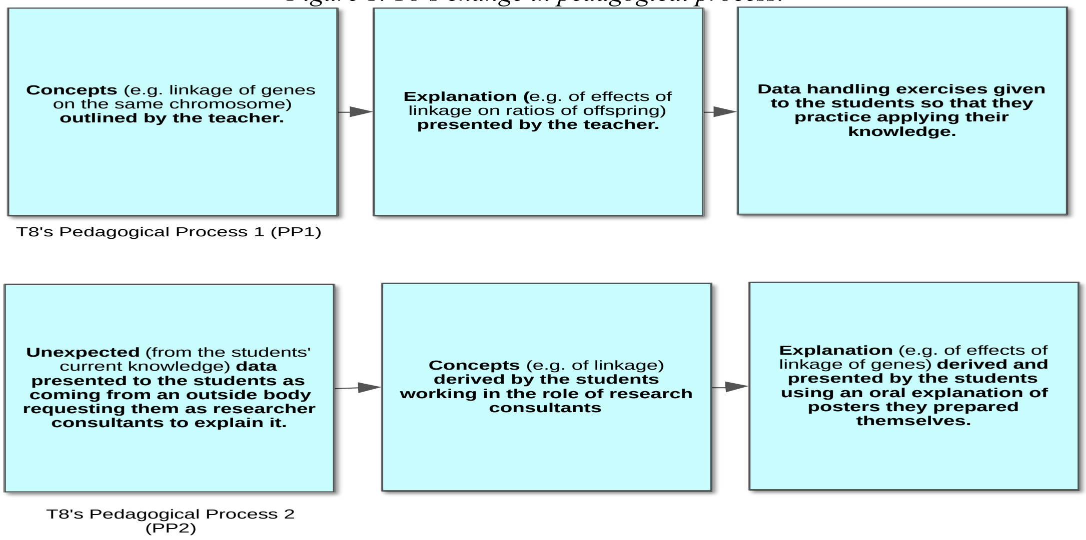
I made the naive assumption that I needed to engage my students in a practical investigation, but actually the investigative approach is something I am totally familiar with and hope I am good at. I need to bring inquiry skills to other areas of my students' learning.

The students had already acquired an understanding of inheritance patterns involving genes for two different characteristics when those genes are found on different chromosomes and each gene has two forms - the dihybrid cross. The students knew how to calculate the expected ratios of offspring for the dihybrid cross – i.e. the expected ratios of flies with normal colour and wings, to normal colour and vestigial wings, to ebony-bodied and normal wings to ebony-bodied and vestigial winged.

Once the students had the above knowledge, T8 would normally give PowerPoint explanations of what happens when genes are on the same chromosomes and at different distances apart. The distances apart are significant because, sometimes, genetic information crosses over between the pairs of chromosomes and the further apart they are, the more likely this is to occur. However, due to concerns about the students' not understanding this topic, T8 created a scenario in which the students worked in groups as consultants to an (fictitious) external agency who had approached them to find reasons for not getting the expected ratios of results from breeding fruit flies. They had to discover the explanation that the genes were on the same chromosomes, and the effect of them being different distances apart on these chromosomes. We can show T8's change in pedagogical process in Figure 1.

Not shown in the model of PP2 in figure 1 is the fact that T8 found it necessary to act as a prompter to thinking – like an experienced researcher saying, "I wonder if we thought about…" T8 was now organising the content in a form appropriate to this form of inquiry, that is, as prompts to help the students to reach the required content goals through thinking about data for themselves.

Figure 1. T8's change in pedagogical process.



The change (thought out by the teacher) from PP1 to PP2 is an example of professional learning: T8 has added a new pedagogical process to a repertoire (Schon, 1983). T8 was satisfied that this additional pedagogical process was effective, first because the students were engaged. At times it was possible to stand back, watch and listen, noting how the students were consistently discussing and working on the problems. Secondly, the students were asked to produce and talk through posters explaining their solutions to the data. This convinced T8 that they understood, while also supporting aspects of scientific thinking that were probably less well supported by PP1- in particular, recognising patterns, forming and testing hypotheses and collaboration in thinking. Subsequent discussion suggested that thinking about cause and effect and co-ordinating theory and evidence were also better supported.

In short, T8 has 'constructed' an alternative form of 'scaffolding' **(**Van de Pol *et al.*, 2010) the students' ways of engaging with and understanding content. Using the distinction originating from Bakhtin (1981), we can describe this new scaffolding as repositioning himself between authoritative discourse (in which knowledge must be taken in without negotiation) and internally persuasive discourse (discourse that becomes one's own through interaction with one's own words) (Tabak and Baumgartner, 2004). It also shows that inquiry-based teaching does not necessarily involve handing all control over to the students (Hohenstein and Manning, 2010) - something that in our experience many teachers fear. A more symmetrical form of teacher-student interaction can also encourage students to gain agency and enhances pedagogical efficacy (Hemlo-Silver and Barrows, 2008; Tabak and Baumgartner, 2004). What seems clear in this example is a shared authority between teacher and students in constructing the knowledge, with the teacher retaining some authority, as a 'more experienced researcher', over scaffolding the direction of inquiry and as arbitrator of the adequacy of the knowledge achieved.

> Teacher–student dialogues can reflect varying degrees of dialogicality depending, in part, on the ways in which teachers position themselves in relation to the students and their respective authority over the knowledge that is constructed (Tabak and Baumgartner, 2004, pp. 397-398)

T8 has taken a position so that objectives of teaching this course content through inquiry, supporting improvements in students' understanding of the topic and encouraging students to develop aspects of scientific thinking are all achieved. Both understanding of content and processes of scientific thinking and inquiry are supported. T8 sees it as a beginning to developing an understanding of the five-dimensional model, its challenges for thinking about practice and which will continue. We see this as exemplifying the conception of empowerment through professional learning outlined earlier.

T8 also noted that teaching this content by PP1 could be achieved in 1 to 1.5 teaching periods. To achieve it through PP2, albeit with improved understanding, took 3 periods. When asked if it was worth it, T8 responded, 'absolutely... but I think we need to reduce the content of the syllabus so that we can do more of this kind of teaching.' T8 may or may not find personal solutions to the time problem, but it is an issue that curriculum developers, policy makers and researchers should be addressing as an area of support for teachers. Answers might involve teachers experimenting with different forms of discourse, for example, saving time by using more authoritative pedagogical forms for topics with fewer problems of achieving understanding (Adey and Serret, 2010; Mortimer and Scott, 2003).

4.2. T5 and forces and friction with early primary school students

T5 is an experienced primary school teacher. This experiment in practice is interesting as it involves a Primary 1/2 class (age around 5 to 7), at the opposite end of the scale to T8, but also providing useful insights.

The students were studying the theme 'toys' with a science component of forces and friction. T5 outlined the previous pedagogical process by showing the widely used worksheet. This told students that they would need a toy car, some card, books and straws for measuring. It also stated the key idea - namely, 'If you change the steepness of the slope, the distance the car travels changes.' The worksheet set out the experiment through a combination of pictures and words- they were shown the card as a ramp on a pile of books, how to alter the ramp by changing the number of books, to measure the distance the car travelled with straws and finally to answer the question, 'What happens to the distance the car rolls as the ramp gets steeper?' The image presented was of the students following this worksheet routinely and without question. T5 commented that the students could do the worksheet without much thinking. We can represent this process as T5's PP1 (Figure 2, first part).

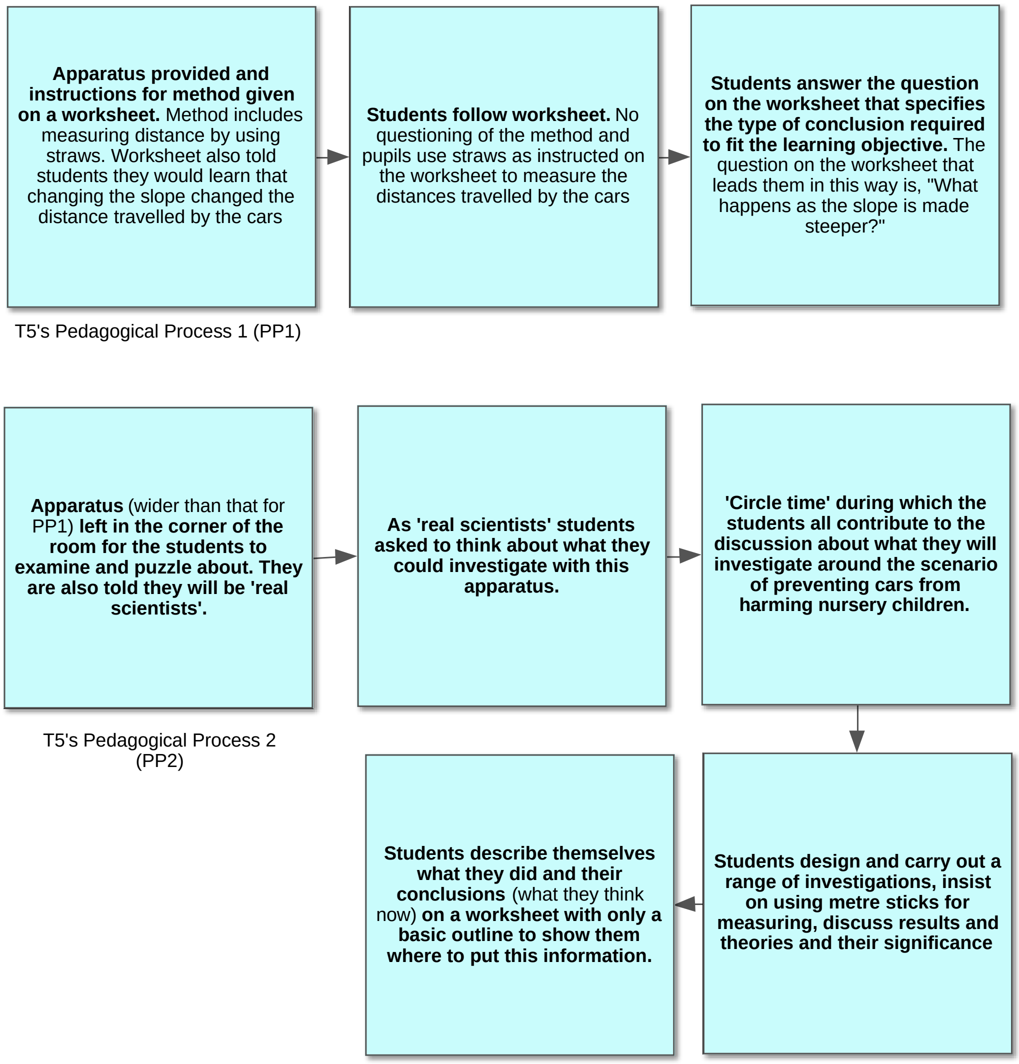
T5 aimed to help the children to think about cause and effect and also wanted to see them fully engaged and, in line with a previous piece of CPD, aimed to begin with the students' own thinking. T5 specified a number of success criteria at the beginning. Firstly, scientific thinking, or some aspects of it, should have occurred. This was assessed using the model of scientific thinking provided. Second, T5 wanted to see if the students were engaged in investigating and for how long and, third, wanted a sense through professional judgement that they understood friction.

As did T8, T5 came up with a very different pedagogical process for PP2 compared to PP1. The intervention began with setting up a 'science corner' in which were placed wooden strips, different materials such as sandpaper and carpet to place on the strips, blocks of wood and cars, and then the children were allowed to play with them freely. However, T5 also told them that they were being 'real scientists' and to think about what they could investigate. One amusing outcome of this was that the children requested goggles and wore them throughout the science activities because, 'Real scientists wear scientific goggles.' However, as we shall see, 'being real scientists' also freed the students' thinking.

During this free play phase, T5 was able to gather comments that gave an insight into students' thinking. These included:

- The wooden bit is making it go faster *(the wooden edge of the ramp as opposed to the carpet or sandpaper).*
- How fast can the car go? I want to inspect the tester and see how fast they go on the fluff. *'Fluff' refers to carpet.*

Figure 2. T5's change in Pedagogical Process.



- …the boulders are making it go slow but it is very dangerous.
- I inspected *(expected)* them to fall off because they are crashing. I want them to slow down, they are hurting my toes.

To observers, some of these might appear to have more scientific potential than others, but to T5 they were all starting points for dialogue. To help structure this, a scenario was created in which the students had to work out how to stop cars crashing into a nursery full of children, but avoiding questions such as, 'How do we make the cars go slower?' T5 then sat in a circle with the students, and they talked about how they could stop the cars crashing. The children's comments were accepted non-judgementally and the students gradually moved from suggestions such as 'moving the nursery' or 'building a wall around it,' to putting sellotape or glitter on the 'road' (wooden strips) to slow down the cars. We can think of this as structured talk (Warwick and Stephenson, 2002) that acknowledges the students' pre-existing ideas - something that seems essential for the students to find meaning in science (Linn and Eylon, 2011; Warwick and Stephenson, 2002). Ideas are thus talked into existence (Asoko, 2002). The point came when the students could investigate their ideas - using carpet, sellotape, glitter, altering the slope, and so on. They worked in three groups, carrying out their own experiments but able to see the others. Another feature was that T5 used a very basic sheet for the students to plan (by drawing and labelling) what they were going to do and what they had found out. Here, being real scientists had the interesting effects alluded to above.

- They formed their own hypotheses and tested them. For example, heavy cars go faster down the slope than lighter ones.
- One of the children said that, 'We need to write this down.' So, their results were tabulated collectively
- When they asked to measure the distance travelled by the cars down different slopes, T5 produced straws, as that was the method generally used for this age group. However, the students said that using straws was 'not being a real scientist' and they needed metre sticks, which T5 then provided. These normally appeared in the third year of school. T5 commented that this took their thinking to a new level as they now could see numbers next to their names in their table.
- This led one boy to comment that he could see the results better in a bar chart.
- They sometimes used analogies for features they had noticed in the real environment. For example, strips of sandpaper were used to represent speed bumps. Also, analogies could be used to explain results. The cars went slower when the slope was covered with carpet because 'this was like driving over mud', for example. Or, 'rough things go slow, that's why sharks go fast'.
- Also, they collaborated in forming explanations, picking up on analogies that others had used and adding to them. For example, in response to the shark analogy, one referred to the difference in speed between hairy spiders and smooth ones.

T5 commented that none of this happened before, That is, PP1 did not lead to these outcomes. Another outcome was that this time, the students were engaged for an hour and forty minutes, including the circle time and their experiments. The previous norm was twenty to thirty minutes using the original worksheet. T5 is using similar methods now in other areas of the curriculum. For example, for the topic, 'Earth", different kinds of stones were placed in the corner and the students to place sticky notes on them with questions to explore. One example is that they are going to explore how to make crystals, as a result of one observation and the resulting pupil initiated question. We describe T5's PP2 in Figure 3 (second part). Again, the addition of PP2 to T5's repertoire is an example of professional learning.

In the discussion that followed T5's presentation, it was noted how this process had 'opened up' the students' thinking, resulting in the request for metre sticks. We wondered if the availability of more measuring equipment would have furthered this, for example, equipment for measuring the speed of the cars. T5 felt that this was something to take on board and try out in the future. What was clear generally is that these young students were thinking more deeply and in more sophisticated ways than expected. Indeed, it is concerning that underestimating students' abilities (for example, not allowing metre sticks and a rigidly structured worksheet) may actively restrict students' thinking, due to an artificial compliance with instructions. This is also an area where research is important. One group of researchers (Mantzicopoulos, *et al.*, 2009, Samarapungavan *et al.*, 2011) find that young children, with suitable structured support, are capable of engaging in, and understanding, the process of scientific inquiry. Mantzicopoulos, *et al.*, (2009, p.314) write:

> Conclusions … from current research programs include that it is both

realistic and feasible to implement early education programs that encourage participation in contextually rich inquiry experiences, as opposed to engagement with discrete sets of process tasks (e.g., sorting objects). Information collected as children enact science in the classroom (e.g., analysis of the moment-to-moment classroom discourse, artifacts developed in the course of the inquiry activities), as well as from assessments designed to document science learning, confirms that participation in inquiry science promotes children's science learning.

These scholars argue for educational processes that support the development of an understanding of the nature of science and of scientific knowledge from an early age - a process that makes it clear to the students that they are being scientists and studying science. Their evidence shows increased motivation and interest in doing science. T5 has begun and continues with, such a process. If these pedagogical methods are used more widely, we may go some way to alleviating the later loss of interest in science and in pursuing science careers that societies can experience (for example, Millar and Osborne, 1998; Schreiner and Sjøberg, 2004; Warwick and Stephenson, 2002). Certainly, in their focus group, the PISCES teachers recognised this possibility of long-term developmental benefits of more inquiry-based methods.

T6: *I think that science teachers in particular complain quite a lot that students can't draw graphs. They can't carry out experiments. They just sit there and they want to be told what to do. But that is conditioning. The way we teach them makes them behave like that. They're not born like that. So, if we make changes like this, the students in your class are going to be more independent, more able to do things by themselves, more interested and engaged in things like that. If that's your complaint, that students…just want you to spoon-feed them. 'Do this'. They're not going to expect that. They're going to change their way of thinking about it as well.*

T1: *Especially if they've got T5 doing it with them from Primary 1.*

There are also some possible lessons regarding the emergence of teaching norms. One of the group asked how this dependence on worksheets had arisen. The conclusions were that, firstly, because they are on file. When the teacher has so many subjects to think about, using already developed materials is easier. Secondly, the worksheet was thought to have its particular structure because, when it was constructed, the focus was on guiding the learning of content. Although T5 still had an eye on prescribed content, the focus was more on the process of inquiry. As a result, the students mastered the required content and gained much more as well. Again, issues for the wider educational community are raised by T5's work, such as science as a distinct subject in early primary; time for teachers to think about and develop their practice and having access to resources to help with this, and how to focus on the processes of scientific inquiry while not undermining, over the longer term at least, the students' development of science's normative concepts, explanations and theories.

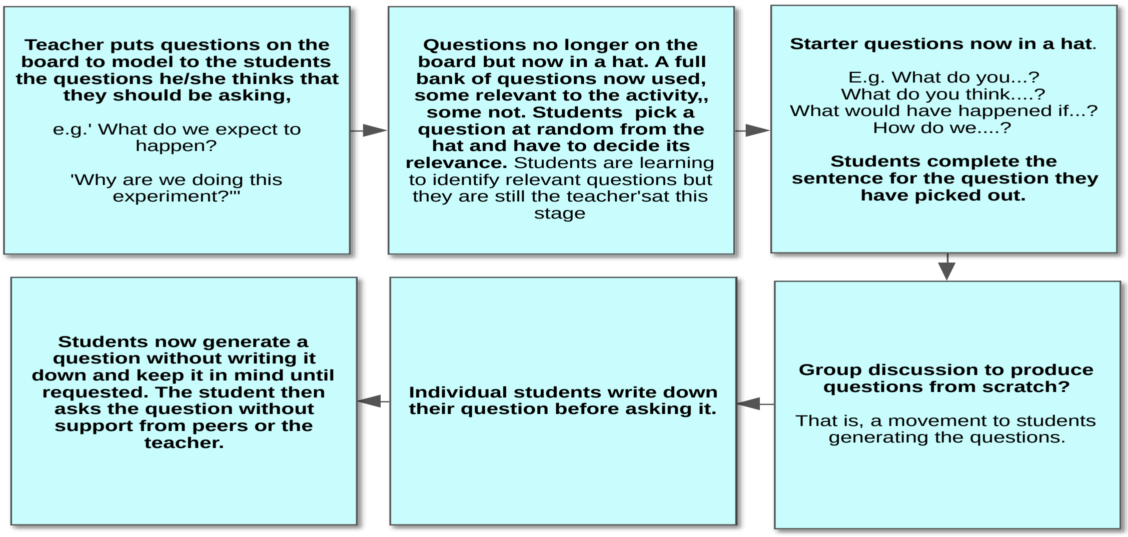
4.3. T2 and a process for encouraging students to ask and answer questions

T2, a teacher in the first year of teaching, took a very different approach to the others. The Herron model analyses investigations on a dimension from closed (the students are led more directly to the correct answer or the answer is given at the beginning) to open (there is more and more choice for the students both in determining which questions to ask and what methods to use to find the answers). T2's ultimate aim was for the students themselves to drive the movement from the more closed levels on the Herron model to the more open. This teacher wanted them to be more questioning during the current classroom procedures, so that these in turn gradually became more open in response to their questions. Although T2 felt obliged to cover the prescribed curriculum, there was also a concern about the students' passivity. That is, the fact that they did not ask many questions, either about what they were doing or why, and their tendency to wait for answers to be provided.

To meet these concerns and achieve this ultimate aim, T2 developed a new pedagogical process (PP2) (figure 3) to run in parallel with the existing one (PP1). The latter seemed to be the traditional mix of set experiments, demonstrations and teacher-led activities. Another part of T2's PP2 was that the students were to consider how to answer the questions, not just have them. To support this, T2 devised a success scale.

1. I can answer my own question.
2. I can answer another's question/ someone can answer my question.
3. I can look up the answer to a question.
4. I can ask the teacher where to find an answer.

Figure 3. T2's new pedagogical process (PP2) to run in parallel with his current pedagogical process (PP)1 in order to support the students in developing a more questioning approach to what they are learning.



At the time T2 reported, it was still work in progress as students progressed at different rates. The quickest required 6 lessons, whereas others still needed forms of prompting. However, one finding was that students spontaneously grouped questions – for example,

- Why are we doing this? Similar to:
- What are we trying to find out? And
- Why did that not work? Similar to:
- What will we do differently next time?

Also, the students were beginning to realise that the aim was to give them confidence to volunteer both questions and answers and, if they cannot answer, consider how they might find an answer. T2 explained that before PISCES, verbally prompting questions, and also directly asking questions would have been the techniques used, but this process of stimulating students to ask questions was not taking extra time, just using time differently with beneficial results.

As with the other two examples, we see a teacher working towards solving a pedagogical problem for her/himself and developing a new pedagogical process. What is particularly interesting about this example is that, unlike the other two, it does not focus on content, which is delivered in the usual way. T2 appears to have been influenced by an early discussion during the course in which it was decided that a useful 'rule of thumb' definition of inquiry could be adopted.

> *Any lesson is an investigation from the students' point of view if, during it, they are exploring their own questions or having their own questions answered.*

Inquiry, in this view, is not a particular form of lesson but a learning orientation of the students that is applied to all forms of lessons. So T2 aimed to support students in developing that orientation.

5. Towards understanding the outcomes in teacher learning

What seems notable is that these teachers all developed, for themselves, new pedagogical processes to use instead of, or along with, existing processes. They have widened their repertoires of possible actions in the classroom. Also, all of them (including those not discussed here) could demonstrate beneficial changes in students' understanding, and/or engagement in scientific thinking and/or their confidence in asking and answering questions for themselves. The teachers' learning is, therefore, not inert (Whitehead, 1929) but is applicable to particular problems they have identified (with the help, perhaps, of the tools and discussions in PISCES). This could be related to learning as a situated process model (Lave and Wenger, 1991), since it is embedded in and contributes to the production of a dynamic pedagogical environment, in which these new pedagogical processes are fit for particular purposes. T8, it could be argued, already had the goal that his students should understand the topic of linkage in genetics. He approached, and better achieved, this aim in a new way through his PP2. T5 and T2 either had new goals or, at least, goals that were now better articulated through the process they went through in PISCES. They also could see ways to try to reach these goals.

Teachers in PISCES are thus professionals in situ, solving pedagogical problems and developing new (to themselves, at least) pedagogical processes, so increasing their repertoires of action. They have added to their teacher knowledge, leading to the question of 'How do we conceptualise this learning?' It seems to us to be a particular form of teacher knowledge that only they, as professionals in situ, were likely to develop, and so the concept of pedagogical content knowledge (PCK), - "…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) -seemed the place to start in trying to conceptualise and understand this form of learning.

5.1. Pedagogical content knowledge (PCK) and pedagogical process knowledge (PPK)

Teacher knowledge is a complex construct of sub-constructs. Shulman (1987) identifies seven including PCK. Others have been added, for example, societal issues (Gorski, 2009, Holden and Hicks, 2007) and teachers' practical theories or knowledge (Buitink, 2009, Yee Fan Tang, 2003). However, PCK has made a lot of impact as a concept and is generally seen to be a form of knowledge that develops through the experience of teaching itself (Lee and Luft, 2008; Van Dijk and Kattmann, 2007), so making it a likely candidate for conceptualising what we saw happening.

There is not space to review PCK fully, so see Berry *et al*. (2008), Kind (2009) and Park and Oliver (2008) as useful entry points. There is, however, a problem in applying the concept post-activity, rather than as a prior theoretical framework. PCK is argued to be:

-Useful (for example, Abell, 2008; Bausmith and Barry, 2011; Bullough Jr., 2001);

-Generative in the sense that it has opened up thinking about the distinctive forms of professional knowledge of teachers, in different subjects (Berry *et al*, 2008);

-An almost unquestioned academic construct (Loughran *et al*., 2004) with a long pre-history (Bullough Jr, 2001).

Nevertheless, there is neither a clear definition of PCK nor of its relationships with other forms of knowledge, such as disciplinary or subject matter knowledge [SMK], and teachers' knowledge of their own contexts (Kind, 2009; Lee and Luft, 2008; Park and Oliver, 2008). It has not, perhaps, yet reached the full stability of an 'objective concept' in which the relevant community has come to a universal and characteristic way of describing it (Bereiter, 2000) which may be due in part to context dependent aspects (Loughran *et al*., 2004) and its multifaceted and non-linear nature (Veal and MacKinster, 1999).

What concepts of PCK generally share, however, is the idea that teachers have a role in making disciplinary or subject matter knowledge (SMK) accessible to students in such a way that they come to understand it (for example, Lee and Luft, 2008; Loughran *et al*, 2004; Padilla *et al*., 2008)

> *A common view of PCK is that it is bound up—and recognizable—in a teacher's approach to teaching particular content. The foundation of (science) PCK is thought to be the amalgam of a teacher's pedagogy and understanding of (science) content such that it influences their teaching in ways that will best engender students' (science) learning for understanding.* (Loughran *et al*, 2004, p.371)

Expert teachers, therefore, have

> *…the capacity … 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''* (Shulman, 1987, p.15).

Following Shulman, (1986, 1987) another common feature is that many authors use the term 'instruction' as focussing on such actions of the teacher as organising, sequencing and presenting the target knowledge; explaining (perhaps through developing analogies and metaphors); and setting problems, while taking into account the interests and other characteristics of one's students. Some authors do study attempts by teachers to support students in gaining particular forms of knowledge through processes such as inquiry (Kanter, 2010) and inquiry combined with use of scientific literature (Hanuscin *et al*., 2011). The latter authors' focus was on teaching the nature of science (NOS) and is, perhaps, a closer study to ours in that our teachers were also aiming to support their students in developing scientific thinking, questioning and inquiry. Although not an articulated aim, one would assume that this would also lead to a better understanding of NOS.

However, even in these studies, based as they are upon PCK, what seems to us to be lacking in understanding the learning of our teachers is explicit consideration of the knowledge the teachers are developing and using in supporting the processes of inquiry, questioning and scientific thinking. Starting with the concept of PCK can lead one to seeing these processes as supportive of learning content but not as educational ends in themselves. We are not suggesting that the authors' aims are unimportant or that they were wrong to use the theoretical frameworks that they did. Indeed, as we shall again point out, students learning and understanding content was important for our teachers also. Nor are we suggesting that teachers in the above studies do not consider how they might scaffold inquiry or use of literature. We are simply suggesting that, when using PCK in order to understand how our teachers learn when aiming to make their practice more inquiry-based, we do not find an explicit academic concept of the knowledge we saw developing. The problem to which we now turn is how to conceptualise that learning in order to give it explicit academic recognition. PCK remains a part of that conceptualisation, along with the concept of pedagogical process knowledge (PPK)

Definitions are always matters of choice (Schiappa, 1993) and one strategy within areas lacking agreement is to devise a stipulative definition of the type, 'Let X mean…' (Shibles, 2011). This strategy was adopted by Park and Oliver (2008) who, through analysing concepts of PCK, reached a comprehensive working definition for their own study:

> *PCK* is teachers' understanding and enactment *of how to help a group of students understand specific subject matter using multiple instructional strategies, representations, and assessments while working within the contextual, cultural and social limitations in the learning environment* (ibid, p.264, emphasis in original).

This definition is taken here as a useful starting point because:

1) As described above, our teachers were concerned that their students understood the content as required by the curriculum. Although we perceive the need for a concept of PPK, it does not replace PCK or eliminate a concern with content.

2) They used multiple strategies to support the students' learning. However, as their focus was on inquiry-based methods, and in line with our philosophy, we would prefer to change 'multiple *instructional strategies'* to *'multiple strategies for supporting learning.'*

3) The teachers were aware of the contextual limitations of their own learning environments and probably also consider the cultural and social limitations of these learning environments.

However, the above definition, and, as noted earlier, much of the PCK literature, uses the word or metaphor of instruction. This is perhaps a result of the concept's focus on delivering content by the teacher so that students understand it. Also, as hinted earlier, we do not believe that this role of teachers can be eliminated. In discussing T8, we saw that different goals may require a different degree of symmetry in dialogue and that also there may be times when it may be appropriate for teachers to impart information, describe events and provide explanations, if only to cover sufficient curriculum content to make time for other more pupil-led activities. Maclellan (2008) makes the important point that the teacher has to:

> *…enable learners to refine the powers of reasoning and judgement through making use of publicly developed bodies of knowledge* (Pring, 2000)

Maclellan goes on to argue for the need for teachers to construct a corpus of abstract knowledge that is not inert (Whitehead, 1929), but the above point concerning reasoning and judgement is left behind as she focuses on content. The implicit assumption seems to be that understanding precedes reasoning. The concept of PCK can over-emphasise the role of the teacher in organising and explaining content and can thus overlook the potential role of the learner in using reasoning and questioning to develop understanding. Maclellan forcibly argues that teachers cannot do the learning for their students and that learning, from a constructivist perspective, depends upon some effort by the students. Teachers teach and learners learn.

Nevertheless, it is not, in our view, made sufficiently explicit that this does not always involve presenting content directly, but creating or scaffolding conditions in which the students find or construct knowledge and understanding for themselves. This is increasingly emphasised in the academic literature as well as the policy responses noted in section 2 (for example, Aitkenhead *et al.*, 2011; Hargreaves, 2003; Linn and Eylon, 2011; Osborne and Dillon, 2010) though there is still emphasis on the importance of scientific understanding. The 'conceptual toolkit' offered here is designed to make teachers' knowledge of how to support students' learning processes more explicit.

Looking at the outcomes shown by T8, T2 and T2, the knowledge they developed was not solely PCK, as defined above. It also incorporated better support for processes of scientific thinking, inquiry and questioning, processes that enabled students to better understand the content, to find and develop it for themselves, or to be more critical in considering why they were studying it and what questions it raised in their own minds. Table 2 shows the processes, identified in the three examples above, that probably would not have occurred without the new pedagogical processes these teachers devised. The PP2s developed by these teachers are supporting processes, not just understanding of content. The teachers now know more about how to support these processes and this is the form of knowledge that should to be added as a sub-construct to the wider construct of teacher knowledge. Therefore, we believe that we need a concept similar to PCK that allows us as teacher educators, science teachers and educational researchers to think more specifically about supporting processes. That is the concept of pedagogical process knowledge or PPK.

However, we introduce our concept of PPK with some caution. Seemingly similar terms are found in the literature- 'pedagogical patterns' (Eckstein *et al.*, 2001) and 'repertoires of practice' (Berrill and Addisson, 2010), for example. Also, we are aware how ideas can 'transmute quickly into new ideas – and back again: the same, yet different' (Hamilton and Clandinin, 2011, p.681). We are also aware that some writers (for example, Gess-Newsome, 1999; Veal and Makinster, 1998) have tried to distinguish between different forms of PCK. However, we find our solution simpler to conceptualise, saving PCK (in line with its name) for the ways in which teachers 'handle' knowledge and understanding, and PPK for the way in which they focus on supporting processes. Nevertheless, as for other aspects of teacher knowledge (Kind, 2009; Loughran *et al.*, 2004), the boundary between them is not necessarily absolute. We treat them as separate but interacting constructs, as this seemed natural in thinking about our teachers' learning. Time will tell if this is the case more widely.

Our definition of PPK therefore reworks Park and Oliver's definition of PCK in line with the comments above and in terms of the 'empowerment' that underpinned our own work in PISCES:

> *Pedagogical Process Knowledge (PPK) is teachers' understanding and enactment of how to empower students to develop the processes involved in a discipline, using multiple strategies for supporting learning, representations and methods of evaluation while working within the contextual, cultural and social limitations in the learning environment.*

T8	T5	T2
Able to stand back and watch *students consistently discussing and working on problems*	Students *come up with ideas to investigate and plan their investigations*	Students, albeit at different rates, *progress towards asking more questions about what they are doing and why and more questions about the outcomes of their experiments, what the teacher tells them, and so on*
Students *talking to posters to explain their solutions to the problems arising from the data.*	Students demonstrate *unexpected process abilities – the use of meter sticks, the use of tabulation and graphing of results*	Students *consider how to answer questions that they have in mind.*
Students identified as *using aspects of scientific thinking- particularly, recognising patterns, forming and testing hypotheses, collaboration in thinking, thinking about cause and effect, co-ordinating theory and evidence.*	Students identified *as using aspects of scientific thinking – particularly, forming and testing hypotheses, thinking about cause and effect, forming explanations, using analogies, collaboration in thinking*	
	Students *thinking more deeply and in more sophisticated ways than previously.*	

Table 2. Processes that can be identified as being better supported by teachers' changes to their pedagogy.

All the teachers showed development of PPK, as defined above, in presenting evidence of supporting inquiry and scientific thinking. However, PCK still played a part. For example, as described earlier, T8 found it necessary to prompt students' thinking, like an experienced researcher saying, "I wonder if we thought about…" This new PPK required a re-organisation of PCK as well – a PCK that now organises content knowledge as prompts, rather than as ways of explaining, that help the students to reach the required content goals through thinking about data for themselves. T5 stated that, as a primary teacher, her scientific knowledge was poor compared to the rest of the PISCES group. If so, this teacher's PCK is logically less developed in this area also.

However, Harris (2011) notes the academic distinction between concepts of behavioural and psychological engagement that are constructed through such features as participation, positive pupil behaviour, and student enjoyment, and concepts of cognitive and academic engagement. The latter are constructed, for example, through students more often using deep learning strategies and a commitment to mastery learning, and, from the research perspective, is more often associated with improvements in student learning. T5's development of a powerful PP2 enabled a better engagement of the students behaviourally, psychologically, cognitively and academically in the process of developing scientific thinking and understanding. The PPK T5 developed through participation in PISCES compensated for a less developed PCK, and may have helped its development and enrichment. T2 does not present any data that suggests a challenge to existing PCK for the topic, but one could hypothesise that it would be, as the students ask more and more questions.

So, PCK and PPK interact with each other. In fact, the more consciously they are combined into sequences of pedagogical processes - one following on the other or the two running in parallel, as appropriate - the more they would become instructional patterns as described by Linn and Eylon (2010) that guide students through whole topics. Also, the more we focus on developing PPK through better support processes for scientific thinking and inquiry, the more we see new opportunities for changing practice and for developing or re-organising PCK. However, this knowledge is context-based: it is developed in the practice of teachers. On this broader scale, PCK and PPK are part of teachers' theories of practice – *practitioner theories*. Practitioner theories, as they become more complex, enable teachers to form hypotheses about what will work with other classes and courses, to experiment with their practice, and to learn from it. Practitioner theory develops from their repertoire of pedagogical processes in a way similar to that outlined by Schon (1983). Practitioner theory involves judgement and understanding by the teachers in their working contexts (Usher and Bryant, 1987). We cannot simply provide the answers, as our teachers originally wished, but we can empower them to develop their practitioner theory to incorporate a wider range of ideas about combining PCK and PPK for themselves. The challenge is to use that insight more widely in working with teachers to research and develop educational practice.

In adding PPK to our 'tool box' of concepts, along with practitioner theory, we feel that we have progressed towards integrating the metaphors of teacher knowledge identified by Mulholland and Wallace (2008) – of 'computer database,' of 'craft,' of 'complexity' and of 'change.' They place PCK in the 'database' category, although they admit to some overlap between metaphors. However, through developing PPK and extending their practitioner theories, our teachers displayed 'craft' in devising different ways of supporting the learning of their students; 'complexity' in solving problems particular to their own contexts; and 'change' through innovative practices that impacted positively on their students' learning.

Our hypothesis is that PPK is often less developed than PCK and we also hypothesise that this may be due to teachers having fewer tools for reflection upon it. In developing their PCK, teachers have access to the content as outlined in the syllabus, textbooks aimed at their age groups, materials prepared by colleagues, and any internal and external assessment questions their students will face. The models from PISCES played a similar role for PPK, but in a relatively non-prescriptive way that allowed the teachers to solve process issues for themselves with their own students and contexts-empowerment through professional learning, as we have characterised it. The following interchange in the focus group illustrates this - the teachers were inquiring into supporting inquiry.

> *Interviewer: I get the impression that if it had been something rigid and inflexible and prescriptive, then it would have been a bit of a contradiction in terms of when you're trying to…*
>
> *T6: It would have been really tokenistic just saying to the kids 'You're enquiring today but you're not because I'm giving you how you're going to do it and telling you what mistakes there are.' It doesn't mean anything.*
>
> *Interviewer: And in a similar way, if this CPD had been delivered in that*

fashion…

T6: It's good that way because what's the point of teaching us differently from the way we've to teach the students? It's related to each other because it gave you a way of doing it.

PISCES is a way of supporting teachers in inquiring how to support inquiry by their students and one that supports them in developing PPK.

6. Conclusion

We have introduced the concept of PPK for the educational community to consider as a partner to PCK. This enabled us to describe the teachers' learning we observed, which led to changes or additions to the pedagogical processes they were using. This increase in their repertoire of pedagogical processes was aimed at supporting their students in developing processes, such as inquiry, to support their understanding of content knowledge, scientific thinking and questioning. We suggested that along with PCK, PPK forms an important part of their practitioner theories. Teachers' PPK may often be less developed than PCK, but can be developed by teachers themselves when provided with suitable tools for reflection. More powerful practitioner theories lead to teachers becoming more expert at hypothesising about pedagogical problems in their classrooms and to experiment confidently with their practice. Supporting teachers in becoming expert practitioners is a challenge not only for educational researchers and teacher educators, but also for curriculum developers and educational policy makers. We were reminded recently of the distinction between the metaphors of 'education as an end point' and 'education as a journey.' It is a journey that we need to learn to travel together.

We raised a number of issues that we believe the educational community needs to pursue more vigorously, including supporting teachers in dealing with pressures of time to teach the syllabus; avoiding methodological restrictions on students' thinking; taking a long term view on bringing students' understanding into line with the norms accepted in science, while still encouraging critical thinking; and providing resources for teachers themselves to analyse and develop their practice. These are not particularly new conclusions, but the approach here is one of inquiring into how to support teachers to inquire into how to support their students in learning through inquiry. This may be the general approach we should follow for these issues, and PPK adds to our conceptual toolkit in pursuing them.

References

Abell, S. K. (2008). Twenty years later: Does pedagogical content knowledge remain a useful idea? *International Journal of Science Education, 30*(10), 1405-1416.
[Back to text] [Full text]

Adey, P. & Serret, N. (2010). Science teaching and cognitive acceleration. In J. Osborne & J. Dillon (Eds.), *Good Practice in Science Education: What research has to say* (2nd edition). Maidenhead: Open University Press.
[Back to text] [Abstract]

Aitkenhead, G., Orpwood, G. & Fensham, P. (2011). Scientific literacy for a knowledge society. In C. Linder, L. Östman, D.A. Roberts, P-O. Wickman, G. Erickson & A. MacKinnon (Eds.), *Exploring the Landscape of Scientific Literacy*. New York: Routledge.
[Back to text] [Abstract]

Asoko, H. (2002). Developing conceptual understanding in primary science. *Cambridge Journal of Education, 32*(2), 153–164.
[Back to text] [Full text]

Bakhtin, M. M. (1981). *The Dialogic Imagination: Four essays by M. M. Bakhtin.* Austin: University of Texas Press.
[Back to text] [Abstract]

Bausmith, J. M. & Barry, C. (2011). Revisiting professional learning communities to increase college readiness: The importance of pedagogical content knowledge. *Educational Researcher, 40*(4), 175-178.
[Back to text] [Full text]

Bereiter, C. (2002). *Education and mind in the knowledge age.* Mahwah, NJ: Erlbaum.
[Back to text] [Abstract]

Berrill, D. P. & Addison, E. (2010). Repertoires of practice: Re-framing teaching portfolios. *Teaching and Teacher Education, 26*(5), 1178-1185.
[Back to text] [Full text]

Berry, A., Loughran, J. & Van Driel, J. H. (2008). Revisiting the roots of pedagogical content knowledge. *International Journal of Science Education, 30*(10), 1271-1279.
[Back to text] [Full text]

Berry, A. & Loughran, J. (2010). *What do we know about effective CPD for developing science teachers' pedagogical content knowledge?* Paper presented at the International Seminar, Professional Reflections, National Science Learning Centre, York.
[Back to text] [Full text]

Buitink, J. (2009). What and how do Student Teachers Learn During School-Based Teacher Education. *Teaching and Teacher Education, 25*(1), 118-127.
[Back to text] [Full text]

Bullough, Jr. R. (2001). Pedagogical content knowledge circa 1907 and 1987: A study in the history of an idea. *Teaching and Teacher Education, 17*(6), 655-666.
[Back to text] [Full text]

Crick, R. D. (2009). Inquiry-based learning: reconciling the personal with the public in a democratic and archaeological pedagogy. *The Curriculum Journal, 20*(1), 73-92.
[Back to text] [Abstract]

Eckstein, J., Manns, M. L. & Voelter, M. (2001). Pedagogical Patterns: Capturing best practices in teaching object technology. *Software Focus, 2*(1), 9-12.
[Back to text] [Full text]

Eraut, M. (1994). *Developing Professional Knowledge and Competence.* London: Falmer Press.
[Back to text] [Abstract]

Feimen-Nemser, S. (2001). From Preparation to Practice: Designing a Continuum to Strengthen and Sustain Teaching. *Teachers College Record, 103*(6), 1013-1055.
[Back to text] [Abstract]

Feist, G. J. (2006). *The Psychology of Science and the Origins of the Scientific Mind*. New Haven:

Yale University Press.
[Back to text] [Abstract]

Flyvbjerg, B. (2006). Five Misunderstandings about Case-Study Research. *Qualitative Inquiry, 12*(2), 219-245.
[Back to text] [Full text]

Forsman, L. & Kurtén-Finnäs, B. (2010). Training package on use of open investigations and Vee-heuristics within science education. In *S-TEAM, WP6 Training Materials Part 1: Developing Scientific Thinking in the Classroom Through Inquiry*. Trondheim, Norway: NTNU.
[Back to text] [Full text]

Gess-Newsome, J. (1999). Pedagogical content knowledge: An introduction and orientation. In J. Gess-Newsome & N. G. Lederman (Eds.), *Examining pedagogical content knowledge: PCK and science education* (pp.3-17). Netherlands: Kluwere Academic Publishers.
[Back to text] [Abstract]

Gore, J. M. & Gitlin, A. D. (2004). [RE] Visioning the academic-teacher divide: power and knowledge in the educational community. *Teachers and Teaching: Theory and Practice, 10*(1), 35 – 58.
[Back to text] [Full text]

Gorski, P. C. (2009). What We're Teaching Teachers: An Analysis of Multicultural Teacher Education Coursework Syllabi. *Teaching and Teacher Education, 25*(2), 309-318.
[Back to text] [Full text]

Haigh, M. (2007). Can investigative practical work in high school biology foster creativity? *Research in Science Education, 37*(2), 123-140.
[Back to text] [Full text]

Hamilton, M. L. & Clandinin, J. (2011). Becoming researchers in the field of teaching and teacher education. *Teaching and Teacher Education,* 27, 681–682. [Back to text]

Hanuscin, D. L., Lee, M. H. & Ackerson, V. L. (2011). Elementary teachers' pedagogical content knowledge for teaching the nature of science. *Science Education, 95*(1), 145-167.
[Back to text] [Full text]

Hargreaves, A. (2003). *Teaching in the Knowledge Society: Education in the age of Insecurity*. Maidenhead: Open University Press.
[Back to text] [Abstract]

Harris, P. (2011). Secondary teachers' conceptions of engagement: Engagement in learning or in schooling. *Teaching and Teacher Education, 27*(2), 376-386.
[Back to text] [Full text]

Hemlo-Silver, C. E. & Barrows, H. S. (2008). Facilitating collaborative knowledge building. *Cognition and Instruction, 26*(1), 48-94.
[Back to text] [Full text]

Herron, M. D. (1971). The nature of scientific enquiry. *School Science Review, 79*(2), 171- 212.
[Back to text] [Abstract]

Hohenstein, J. & Manning, A. (2010). Thinking about learning. In J. Osborne & J. Dillon (Eds.),

Good Practice in Science Education: What research has to say (2nd edition). Maidenhead: Open University Press.
[Back to text]

Holden, C. & Hicks D. (2007). Making global connections: The knowledge, understanding and motivation of trainee teachers. *Teaching and Teacher Education, 23*(1), 13-23.
[Back to text] [Full text]

Kanter, D. E. (2010). Doing the project and learning the content: Designing project-based Science curricula for meaningful understanding. *Science Education, 94*(3), 525-551.
[Back to text] [Full text]

Kind, V. (2009). Pedagogical content knowledge in science education: perspectives and potential for progress. *Studies in Science Education, 45*(2), 169-204.
[Back to text] [Full text]

Lave, J. & E. Wenger. (1991). *Situated learning.* Cambridge: Cambridge University Press.
[Back to text]

Lee, E. & Luft, J. A. (2008). Experienced secondary science teachers' representation of Pedagogical content knowledge. *International Journal of Science Education, 30*(10), 1343-1363.
[Back to text] [Full text]

Lewis, M. & Andrews, D. (2004). Building sustainable futures: Emerging understandings of the significant contribution of the professional learning community. *Improving Schools* *7*(2), 129–150.
[Back to text] [Full text]

Lincoln, Y. S. & Guba, E. G. (1985). *Naturalistic Inquiry*. California: Sage.
[Back to text] [Abstract]

Linn, M. C. & Eylon, B-S. (2011). *Science Learning and Instruction: Taking Advantage of Technology to Promote Knowledge Integration*. New York: Routledge.
[Back to text] [Abstract]

Loughran, J., Mulhall. P. & Berry, A. (2004). In search of pedagogical content knowledge in science: Developing ways of articulating and documenting professional practice. *Journal of Research in Science Teaching, 41*(4), 370-391.
[Back to text] [Full text]

Loughran, J. (2010). *What expert teachers do: Enhancing professional knowledge for classroom practice.* London: Allen and Unwin.
[Back to text] [Abstract]

Maclellan, E. (2008). Pedagogical literacy: What it means and what it allows. *Teaching and Teacher Education, 24*(8), 1986-1992.
[Back to text] [Full text]

Mantzicopoulos, P., Samarapungavan, A. & Patrick, H. (2009). "We Learn How to Predict and be a Scientist": Early Science Experiences and Kindergarten Children's Social Meanings About Science. *Cognition and Instruction, 27*(4), 312-369.
[Back to text] [Full text]

McNally, J. (2006). Confidence and loose opportunism in the classroom: Towards a pedagogy of investigative science for beginning teachers.

International Journal of Science Teaching, 28(4), 423-438.
[Back to text] [Full text]

McNally, J. & Blake, A. (Eds). (2010). *Improving Learning in a Professional Context: A Research Perspective on the New Teacher in School.* London: Routledge.
[Back to text] [Abstract]

Millar, R. & Osborne, J. (1998). *Beyond 2000: Science Education for the Future.* The Report of a Seminar Series Funded by the Nuffield Foundation. London: King'd College School of Education.
[Back to text] [Full text]

Mortimer, E. F. & Scott, P. H. (2003). *Meaning Making in Secondary Science Classrooms.* Maidenhead: Open University Press. [Back to text] [Abstract]

Mulholland, J. & Wallace, J. (2008). Computer, craft, complexity, change: explorations into science teacher knowledge. *Studies in Science Education, 44*(1), 41-62.
[Back to text] [Full text]

National Academy of Sciences. (2012). *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas.* Washington: The National Academies Press.
[Back to text] [Full text]

Osborne, J. & Dillon, J. (2010). How science works: What is the nature of scientific reasoning and what do we know about student's understanding. In J. Osborne & J. Dillon (Eds.), *Good Practice in Science Teaching: What Research has to Say* (pp. 20-46). Maidenhead: Open University Press.
[Back to text] [Abstract]

Padilla, K, Ponce-de-lion, A. M., Rembado, F. M. & Garritz, A. (2008). Undergraduate professors' knowledge of pedagogical content knowledge: The case of 'amount of substance'. *International Journal of Science Education, 30*(10), 1389 – 1404.
[Back to text] [Full text]

Park, S. & Oliver, J. S. (2008). Revisiting the conceptualisation of pedagogical content knowledge (PCK): PCK as a conceptual tool to understand teachers as professionals. *Research in Science Education, 38*(3), 261-284.
[Back to text] [Full text]

Pring, R. (2000). *Philosophy of Education: Aims, Theory, Common Sense and Research.* London: Continuum Studies in Education.
[Back to text] [Abstract]

Reiss, M. J., Millar, R. & Osborne, J. (1999). Beyond 2000, Science/biology Education for the Future. *Journal of Biological Education, 33*(2), 68-70.
[Back to text] [Abstract]

Rocard, M. (2007). Science Education Now: A Renewed Pedagogy for the Future of Europe. Brussels: European Commission.
[Back to text] [Full text]

Samarapungavan, A., Patrick, H. & Mantzicopoulos, P. (2011). What Kindergarten Students Learn in Inquiry-Based Science Classrooms. *Cognition and Instruction, 29*(4), 416-470.

[Back to text] [Full text]

Schiapp, E. (1993). Arguing about definitions. *Argumentation, 7*(4), 403-417.
[Back to text] [Abstract]

Schon, D. A. (1983). *The Reflective Practitioner: How professionals think in action.* London: Temple Smith.
[Back to text] [Abstract]

Schreiner, C. & Sjøberg, S. (2004). *ROSE: The Relevance of Science Education*. Oslo: Department of Teacher Education and School Development, University of Oslo.
[Back to text] [Full text]

Shibles, B. M. W. A. (2011). Definition. *The Philosophy and Practice of Medicine and Bioethics, International Library of Ethics, Law, and the New Medicine, 47*, 15-22. [Back to text]

Shulman, L. S. (1986). Those who understand: Knowledge growth in teaching. *Educational Research, 15*(2), 4-14.
[Back to text] [Full text]

Shulman, L. S. (1987). Knowledge and teaching: Foundations of the new reform. *Harvard Educational Review, 57*(1), 1-22.
[Back to text] [Full text]

Smith, C. (2010a). The implication of early professional learning for schools and local authorities. In J. McNally & A. Blake (Eds.), *Improving Learning in a Professional Context: A Research Perspective on the New Teacher in School.* London: Routledge.
[Back to text] [Abstract]

Smith C. (2010b). *Thinking pedagogically about scientific thinking: Towards a taxonomy of investigations.* Nottingham: S-TEAM Conference.
[Back to text] [Full text]

Smith C. (2010c). *Teaching Scientific Thinking. The ICASE Newsletter.* Newsletter of the International Council of Associations for Science Education.
[Back to text] [Full text]

Smith C., Kelly, F. & Mackenzie, S. (2010a). Support for Scientific Thinking in School Science Investigations: A Teaching Tool. In *S-TEAM, WP6 Training Materials Part 1: Developing Scientific Thinking in the Classroom Through Inquiry*. Trondheim, Norway: NTNU.
[Back to text] [Full text]

Smith, C., Kelly, F., Blake, A., Gray, P., Mackenzie, S. McNally, J. & Stanfield, D. (2010b). *Empowering Teacher Collaboration To Promote Scientific Thinking Through Inquiry: Towards Lessons For Initial Teacher Education (ITE).* The European Conference on Educational Research. ECER, Helsinki.
[Back to text] [Full text]

Smith C., Blake, A., Kelly, F., Gray. P. & McNally, J. (2011). *Promoting Inquiry in Science Classrooms in European Schools (PISCES): A Handbook for Tutors.* S-TEAM.
[Back to text] [Full text]

Smith, C., Blake, A. Gray, P. & Kelly, F. (2013). Teachers can overcome challenges to inquiry

by developing Pedagogical Process Knowledge (PPK): The PISCES experience. In M. H. Hoveid (Ed.), *Inquiry in Science Education and Science Teacher Education.* Tapir (Academic Publishers): Trondheim, Norway.
[Back to text] [Full text]

Stake, R. E. (2000). Case Studies. In N. K. Denzin & Y. S. Lincoln (Eds.), *Handbook of Qualitative Research* (pp. 435-454). London: Sage. [Back to text]

S-TEAM. (2013). *S-TEAM: Firing up Science Education*. Available from: http://www.s-teamproject.eu [Accessed May, 2013]. [Back to text]

Su Y. L. & Reeve, J. (2011). A meta-analysis of the effectiveness of intervention programs designed to support autonomy. *Educational Psychology Review, 23*(1), 159-188.
[Back to text] [Full text]

Tabak, I. & Baumgartner, E. (2004). The teacher as partner: Exploring participant structures, symmetry, and identity work in scaffolding. *Cognition and Instruction, 22*(4), 393-429.
[Back to text] [Full text]

The Scottish Government (2009a). *Curriculum for Excellence: Sciences, Experiences and Outcomes.* Edinburgh: The Scottish Government.
[Back to text] [Full text]

The Scottish Government (2009b) *Curriculum for Excellence: Sciences, Principles and Practice.* Edinburgh: The Scottish Government.
[Back to text] [Full text]

Thiessen, D. (2000). Developing Knowledge for preparing teachers: Redefining the role of schools of education. *Educational Policy, 14*(1), 129-144.
[Back to text] [Full text]

Usher, R. S. & Bryant, I. (1987). Re-examining the theory-practice relationship in continuing professional education. *Studies in Higher Education, 12*(2), 201-212.
[Back to text] [Abstract]

Van Dijk, E. M. & Kattmann, U. (2007). A research model for the study of science teachers' PCK and improving teacher education. *Teaching and Teacher Education, 23*(6), 885-897.
[Back to text] [Full text]

Van de Pol, J., Volman, M. and Beishuizen, J. (2010). Scaffolding in teacher-student interaction: A decade of research. *Educational Psychology Review, 22*(3), 271-296.
[Back to text] [Full text]

Veal, W. R. & Makinster, J. G. (1999). Pedagogical content knowledge taxonomies. *Electronic Journal of Science Education, 3*(4).
[Back to text] [Full text]

Verloop, N., Van Driel, J. & Meijer, P. (2001). Teacher knowledge and the knowledge base of teaching. *International Journal of Educational Research, 35*(5), 441-461.
[Back to text] [Full text]

Verscio, V., Ross, D. & Adams, A.

(2008). A review of research on the impact of professional learning communities on teaching practice and student learning. *Teaching and Teacher Education 24*(1), 80-91.
[Back to text] [Full text]

Warwick, P. & Stephenson, P. (2002). Reconstructing Science in Education: Insights for making it more meaningful. *Cambridge Journal of Education, 32*(2), 143-151.
[Back to text] [Full text]

Whitehead, A. (1929). *The Aims of Education and Other Essays*. New York: The Free Press.
[Back to text]

Williamson, B. & Morgan, J. (2009). Educational reform, enquiry-based learning and the re-professionalisation of teachers. *The Curriculum Journal, 20*(3), 287-304.
[Back to text] [Abstract]

Yee Fan Tang, S. (2003). Challenge and support: the dynamics of student teachers' professional learning in the field experience. *Teaching and Teacher Education, 19*(5), 483-498.
[Back to text] [Full text]