CHAPTER

Threshold Connections:

Engaging trainee teachers in collaborative curriculum research to explore Threshold Concepts within secondary school science disciplines

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Abstract

This chapter explores the pedagogical potential of investigating secondary school science curricula through the lens of the Threshold Concept Framework (TCF). A cohort of trainee secondary school science teachers in England worked collaboratively to co-construct their understanding of *threshold concepts* in A-level sciences based on their individual perceptions and experiences. Findings are presented thematically through the voices of the participants as they explored their subject disciplines and discussed and debated what they considered to be *threshold concepts*. Themes emerged which are argued here to be inter-disciplinary *Threshold Epistemes,* concepts that are not the difficult content areas identified as troublesome but constitute more abstract ideas which are fundamental to thinking as a scientist within and across sub-disciplines. These are ways of understanding, and/or systems of ideas. Threshold Epistemes identified and discussed here are: models, scale, randomness and language. This chapter further argues that the *process* of engaging with the TCF as a theoretical framework has potential to be pedagogically productive for teachers and pupils.

Keywords

Initial Teacher Education (ITE) - Secondary schools - Curriculum - Science

1 Introduction

The origins of this chapter lie in an earlier investigation conducted in secondary schools (Dunn, 2019) which highlighted the cognitive and affective discomfort brought about by pupils' encounters with threshold concepts (Meyer & Land, 2003). Inspired by that research, we embedded an exploratory investigation into our university-based Initial Teacher Education (ITE) curriculum, engaging trainee teachers in collaborative research to explore school curricula through the lens of the Threshold Concept Framework (TCF) (Land, 2013). The current chapter explores this project in detail, considering the benefits of the process to the trainee teachers, and the implications of the findings for Initial Teacher Education and schools.

We aim to demonstrate here that the *process* of engaging with the TCF as a theoretical framework offers significant benefits to ITE trainee teachers. Furthermore, we contend that foregrounding threshold concepts (TCs) within subject curricula as enabling components of disciplinary knowledge structures, has potential to be pedagogically productive for teachers and pupils. The findings of our research with ITE trainee teachers lead us to conclude that there are common *Threshold Epistemes* across all three science disciplines and that understanding these underpinning ideas and concepts will support learning, particularly of those topics often identified as TCs. We also argue that both teachers and pupils must identify TCs and Threshold Epistemes and address them head-on to be able to make *threshold connections* and instigate a conceptual or categorical shift within the discipline.

2 Threshold concepts in science disciplines – Threshold Epistemes

Several studies have explored threshold concepts within the science disciplines internationally. One particular body of work which has informed our study was an Australian Learning and Teaching Council (ALTC) project, designed to explore improvement of teaching and learning in undergraduate biology courses. Publications by members of the ALTC team between 2006 and 2014 reported on: the identification of TCs in the discipline (Taylor, 2006, 2008); the evaluation of intervention strategies to help address difficulties with the learning of TCs (Ross & Tronson, 2007) and how students respond to tasks involving specific TCs (Taylor & Cope, 2007; Taylor & Meyer, 2010; Taylor, Tzioumis, Meyer, & Ross, 2014;

Zimbardi et al., 2014). These projects also led to the generation of a matrix of TCs for biology (Ross et al., 2010).

Further work explored students' perceptions of TCs (Taylor, 2008). In this study, postgraduate students were asked to consider examples of TCs identified by teachers in earlier work (Taylor, 2006), or provide their own using Meyer and Land's (2003) original definition of a TC. Many of the respondents identified the sheer mass of theory covered in the first year as being troublesome, alongside difficulties with disciplinary language. They also highlighted specific concepts as counter-intuitive, such as osmosis. However, students were less able to identify abstract concepts, other than scale in relation to species and population.

It has been argued that it is helpful to view TCs within a discipline as a web of interrelated concepts (Davies & Mangan, 2007). Early observations by Taylor (2006, 2008) emphasised the complexity of biology as a discipline, proposing that many of the more difficult concepts to teach in biology stand alone as 'isolated islands of knowledge' (Taylor, 2006, p.89), and remain as such until students are encouraged to make links to a more complex 'web of composite knowledge and understanding'. A study in the UK (Kinchin, 2011) found concept mapping to be an effective tool for students to consider knowledge structures in biology. Empowering students to process and synthesise curriculum content through concept mapping enabled them to visualise the interrelated nature of concepts within the discipline, highlighting the value of the *process* of concept mapping the curriculum.

Applying the theoretical definitions of Davies and Mangan (2007), researchers from the ALTC project team (Ross et al., 2009) identified a range of concepts that fit within the definition of basic, discipline and procedural concepts. The ALTC model titled the Biology Thresholds Matrix (Ross et al. 2009, p.169) posits that TCs within biology occur where there is 'integration of discipline concepts and the emergence of a commonality or web of conceptual change' extrapolated from the procedural concepts. Embedded throughout the Biology Thresholds Matrix is the notion of language acquisition as a critical feature of development in the subject.

The model proposed in the Biology Thresholds Matrix contends that whilst there are specific TCs relating to areas of content knowledge, these also feed into a more generalised web of concepts that encompass the entire discipline of biology and occur throughout each area of knowledge. This proposed web of concepts may be considered transferable: particular concepts such as scale (Johnson et al., 2014) and hypothesis creation, are found in other sciences such as chemistry and physics (Ross et al., 2010) or even in other fields such as medicine and sociology (Johnson et al., 2014). They may not therefore be considered as bounded within the discipline as defined by Meyer and Land (2003). Thus, it was proposed by Ross et. al. (2010, p.173) that the process for identification of a TC in biology centres around it being considered transformative, irreversible and integrative coupled with consideration of the journey from novice to expert in the context of ways of thinking and practising.

Arguing that threshold concepts in biology are not the difficult content areas identified as troublesome but constitute more abstract ideas which are fundamental to thinking as biologists, Ross *et. al.* (2010) provided examples of energy and energy transformation, variation, probability and randomness, proportionality such as surface area to volume ratios, linkage of the subcellular (sub microscopic) with the macroscopic, temporal and spatial scales and equilibrium. These are defined as Threshold Epistemes by Ross, et al. (2009, p. 170) and are exemplified thus:

> For example; protein synthesis is frequently identified as a difficult troublesome content area in biology, but that does not automatically make it a threshold concept. To overcome the threshold needed to understand protein synthesis students need to operate and integrate simultaneously several hierarchical processes at sub cellular and sub microscopic scales while incorporating the dynamism and three dimensionality of cell processes.

Ross *et al*. (2010) go on to discuss the need for Threshold Epistemes to be made explicit to novices and that exploring them within the bounds of current curricula can be challenging since each threshold does not exist within a defined area of core content but underpins the way in which we think and practice as biologists. They also note that:

> The threshold or procedural concepts we have identified form 'epistemes' or ways of understanding, and systems of ideas, but often receive little direct attention in the teaching of biology.

In this chapter, we acknowledge this lack of attention, which resonated with our own experiences of teaching in schools and working with teachers. We argue that raising the profile of potential Threshold Epistemes in science may allow teachers to establish complex concepts more securely and more quickly with pupils. As researchers working with trainee teachers in all three science disciplines, we designed the Threshold Connections Project to provide opportunities for them to explore the theoretical framework of threshold concepts and apply this in the identification of potential Threshold Epistemes. Our findings are presented through the voices of the trainee teacher participants as they externalise their interpretations and experiences.

3 Threshold concepts in science disciplines – Conceptual Change

Many misconceptions in science, self-constructed ideas that do not align with generally accepted scientific understanding, are linked to threshold concepts (Driver et al., 1994 & EEF, 2018). Novak (2009 p.548-571) determined that such misconceptions were powerful and difficult to override. The conceptual change required to shift misconceptions needs time and the revisiting of ideas.

Chi (2008 p.61-82) describes how conceptual change can be assigned to three types depending upon the different conditions of prior knowledge and several complex, non-transparent and interleaved issues around how and why the knowledge is misconceived, and what constitutes change. These types are: Belief Revision, Mental Model Transformation, and Categorical Shift. When prior knowledge conflicts with new information at the grain size of a single idea, Chi refers to that idea as a False Belief that requires revision. She goes on to say that students' knowledge consists of an interrelated system of false beliefs and correct beliefs, forming a coherent but sometimes flawed mental model.

A flawed Mental Model can be said to conflict with a scientific model if it is incorrect but coherent. It is argued that conceptual change requires a Categorical Shift. Chi (2008, p.61-82) also states that 'such a shift necessitates that the learner is aware that the shift is needed and that the correct category is available'. It is this awareness, both on the part of the teacher and the pupil, that we argue is essential to allow the opportunity for conceptual change to take place. The Threshold Connections Project enabled trainee teachers to establish when and how they had achieved a conceptual, or categorical, shift in their own thinking then acknowledge that their pupils too would reach these moments and how best they could support them through such shifts.

4 The Threshold Connections Project

A qualitative approach to the research design for this project was adopted, with the intention that participants might co-construct their understanding of threshold concepts in A-level sciences based on their individual perceptions and experiences. The study was conducted with PGCE (Postgraduate Certificate in Education) Secondary ITE trainee teachers following science routes in chemistry, biology and physics. The study was situated in a UK university and full ethical clearance was obtained from the university ethics committee prior to commencing the research. In an initial workshop, the trainee teachers were introduced to the theoretical framework of the TCF by the authors, both of whom are experienced teacher educators. The workshop was designed with a particular focus on the characteristics of a threshold concept, as defined by Meyer & Land (2003; 2005).

Following this seminar, trainee teachers were asked to conduct a specification analysis, where they were provided with a range of A-level examination specifications and investigated them through the lens of the TCF, annotating the content with TCF-related coding linked to the characteristics identified by Meyer & Land (2003; 2005). Subsequently, trainee teachers were asked to work collaboratively to co-construct concept maps in their sub-disciplines, identifying potentially transformative and integrative concepts and highlighting links between them. This approach has previously been found to be effective in enabling the visualisation of disciplinary knowledge structures and their interrelatedness (Kinchin, 2011).

Once the concept maps had been created, a facilitated focus group discussion was undertaken and trainee teachers from each sub-discipline were asked to discuss and explain how they had constructed their concept map, whilst also identifying potential threshold concepts. During this session, the research team asked questions to draw out and challenge identification against the TCF. Further thematic analysis of the findings was then undertaken by the research team, to identify cross-discipline themes and to further consider the trainee teachers' responses against the TCF.

5 Perceptions of trainee teachers

This section considers the findings of our research. We use direct quotes from the students, allowing their voices to lead the discussion. These are presented thematically in four sections, each of which featured prominently in the focus group discussions and subsequent cross-discipline analysis. We later argue that these themes could be considered as inter-disciplinary Threshold Epistemes. These are:

– Models
– Scale
– Randomness
– Language

5.1 ***Models***

Many concepts in science are abstract and either too large or too small to visualise so models can help pupils to visualise such concepts and make a complex reality more understandable. There are many different kinds of models. These can include (EEF, 2018, p. 18):

– Three-dimensional models e.g. models made from plasticine or other materials
– Analogies
– Mathematical models e.g. formulae
– Visual models e.g. animations
– Computer models e.g. simulations

For pupils to get the most out of a model they need to be able to critique it, comparing it to the reality it is attempting to portray. The trainee teachers in our study considered that the ability to do this well is an important step to 'becoming a scientist'. They identified that revisiting and reviewing models is essential as pupils gain the skills and tools to build on them. Grosslight *et al*. (1991, p. 799-822) define three levels for understanding the nature of models:

– Beginner – 'I think that models are a direct copy of reality and don't see how they differ from reality';
– Intermediate – 'I understand that models are not direct copies of reality and I understand that models are used to help me develop my scientific understanding'; and
– Expert – 'I know that several different models can be used to explain different aspects of an idea; I understand that models have strengths and weaknesses and that existing models can be changed and improved; I know that models can be used to test ideas and are created for specific purposes'.

We suggest that an awareness of 'models' as a Threshold Episteme, whilst building explicit learning opportunities into lessons to move pupils from a beginner to an expert understanding of models, will potentially develop learning of a concept more quickly and more securely.

In the group discussions, trainee teachers in our study talked frequently about science being taught through models; this was particularly prevalent in the chemistry and physics focus groups. Trainee teachers identified that models allowed an understanding of the real world, but that these models needed to change over time, both in complexity but also in the way they relate to other components of knowledge in the subject, as this Chemistry trainee teacher articulated:

> All the way through school you get taught these modules and you get taught one and then another and it's the idea that you understand that the models you get taught are not concrete and they are not perfect and that they will change.

There was an acceptance that pupils might find use of models frustrating and that they often felt 'lied to' because previously taught models had to be discarded, but that if models are identified as a useful learning tool and it is made clear to pupils why this model is being used then pupils might be more accepting. One Physics trainee teacher explained their thoughts on this:

> When we were saying that kids think they have been lied to or what they have been taught is wrong, when really it is just building on a model. Because they think that there is a truth that they are heading towards. A lot of people say that they want to do the sciences because there is a right idea or because they are discovering the truth.

They go on to discuss that pupils need to accept that 'truth' is often an illusion and that much of science 'fact' is still being challenged and as such models still need to be adapted. If pupils can accept this notion of constant query and evolution of ideas, then they can perhaps be less frustrated when a new model for the same concept is introduced. One approach to address this is to ask pupils to critique and evaluate any model that is presented to them. The trainee teacher participants identified this as important, potentially allowing for a greater understanding both at the time and in the future. This is exemplified by this quotation from a Physics trainee teacher:

> Science isn't an absolute description, it is all a model and you are supposed to teach students models at Year 7 and then they should be able to critique the model and then improve the model. And that is all your doing. So, if it comes to A-level and they say you have changed what you taught us last time and they haven't got the

> concept of – I am continually improving this model, or I am changing it for these circumstances, and in actual fact, it's all just a model by then – then you have failed totally.

Teachers need to identify the most appropriate model to use for a particular explanation. A trainee teacher will be making decisions about this based on their own experiences and knowledge as well as what they deem most appropriate for their pupils. This may occasionally produce conflict between teacher and pupil. One Physics trainee teacher described when they were teaching a particular simplistic model for atomic orbitals that the pupils asked if this model was going to be changed for them in future. By briefly revealing the more complex model, pupils were willing to accept that their current knowledge would not allow them to access this way of thinking at this moment in time.

Through the process of discussing the use of models the trainee teachers themselves identified that revisiting and reviewing models is essential to enable pupils to gain the skills and tools to build on them.

> Some of the earlier points when we were looking at threshold concepts, we picked out some of the models that we thought were difficult, probably for those sorts of reasons, that you have to explain them in different ways at different times for students because they don't have the tools required to work with the most detailed explanation of the current model that we have. (Physics trainee teacher)

In summary, it seems that many of the trainee teachers considered it important that the pupils were clear that they were being taught using a model. Over time and with increased knowledge pupils can move towards a model closer to 'truth' but in the meantime, an acceptance that models are a 'work in progress' is required. In this quote the Physics trainee teacher identifies that understanding that a model is being used is a threshold concept in itself:

> So it's more about understanding that it's about what's appropriate for what you need at the moment. So the threshold concept is using models and understanding that physics <u>is</u> a model. The model itself is not the threshold, it's the understanding that it is a model.

Models are used in teaching across all three science disciplines and their use is integral to building understanding of many scientific concepts over time. A pupils' awareness that a model is being used and what that might mean to them as a learner seems crucial. This is why we see an understanding of the use of models as a Threshold Episteme.

5.2 ***Scale***

Scale has previously been identified as a threshold concept in science, both in terms of temporal and spatial scale (Ross *et al.* 2009; Taylor, 2006). Although size and spatial scale were mentioned by participants in our study, temporal scale was not highlighted by any of them. It was acknowledged that science explores the extremes of spatial scale and pupils need to have an awareness of how this relates to themselves:

> The way I described is that the concept I came across that led to me thinking about maths in this way is scale. Physics covers really, really big things like the size of the actual known universe, right down to the smallest possible things. And humans weirdly enough come right in the middle. (Physics trainee teacher)

This relates back to why we use models to help pupils to visualise phenomena or entities that are too big or too small. However, it also helps us to identify why models can be problematic since models are often made up of objects or images that we can visualise, and this often drastically distorts the size. It is important when using models to ensure that differences in size and scale are made clear.

Size and scale were identified as a TC on all constructed concept maps, leading us to label this as a Threshold Episteme. Indeed, in one discussion the trainee teacher recognised spatial scale to be what they describe as a 'pillar' of knowledge:

> If you understand structure and function and the difference, you can understand cells and then that goes off into photosynthesis, organisation, and it's that pillar of size and scale, how big everything is, structure for function, this is why everything behaves like it does… (Biology trainee teacher)

The use of the word 'pillar' here suggests that scale is seen as an under-pinning concept, or as we have defined such concepts so far in this chapter, a Threshold Episteme. Further potential under-pinning concepts of randomness and language are discussed below.

*5.3 **Randomness***

The random nature of particle movement was noted on all of the concept maps produced in our project. It was also part of the discussions across all three science disciplines. Here it is discussed in relation to how the random nature of particles can result in different experimental outcomes, how this influences experimental design and the need to repeat experiments to validate results:

> …and then talking about threshold concepts, there is the uncertainty in biology, that you have got to be okay with a grey area. Things are always chopping and changing and you can do an experiment fifty times over and in biology you can get fifty different results. So it's that random unpredictability that you have to be okay with, if you are not then biology is not for you as a science. (Biology trainee teacher)

Many phenomena in science are described as a net movement, an overall pattern. For example, diffusion can be simply defined as the net movement of particles from a high to a low concentration. Each particle is moving randomly but observed from 'afar' an overall pattern of movement in one direction can be seen. This concept was identified too for radioactivity during the discussion between the physics trainee teachers:

> And even randomness comes into scale, because if you look at radioactive decay, if you look at it from the outside, it's quite linear, so you have a half-life, it's predictable, but if you look at the atomic level, it's very, very random. (Physics trainee teacher)

Our findings support the notion that randomness along with probability and uncertainty are Threshold Epistemes.

*5.4 **Language***

The language of science is often identified as being troublesome and creating a threshold concept (Taylor, 2006 p.87-99), or indeed it could be argued a Threshold Episteme, as we suggest here. In this context language often refers to literacy and terminology. Taylor (2006 p. 87-99) describes how the language of science by its nature is very specific, in part to maintain continuity in use of concepts and in part to simplify the discussion of complexity.

As previously mentioned, embedded throughout the Biology Thresholds Matrix is the notion of language acquisition as a critical feature of development in the subject (Ross et al., 2009). The biology trainee teachers recognised the importance of literacy and particularly the origins of key terminology in the understanding of biology concepts:

> …so the most important thing is that scientific language and literacy skills so you know your terminology, your prefix and suffix, 'cause that breaks down a whole understanding of everything and the words that follow by understanding that. (Biology trainee teacher)

Language also featured in the discussions of the chemistry trainee teachers as being enabling if used accurately and understood sufficiently well by the pupils:

> I think language versatility is really important…and scientific literacy. So, in some lessons I have done for A-level I would ask them if anyone knows what dative covalent bonding was. She had remembered what it was from a previous module in AS and she was like…oh yes so, I can see how the mechanism works based on that. And if I had to beat around the bush and not use the correct terms it would have taken a lot longer to get to the point. So, knowing the correct words really does make a difference. But it comes back to the authenticity again versus mimicking…there is a difference between being able to know and say the words and being able to use them, in your own discourse and conversation being able to use it properly. (Chemistry trainee teacher)

Mathematics and numeracy are also important, indeed essential to understand many concepts in science. The biology concept map produced by participants identified both 'scientific language skills' and 'scientific numeracy skills' as being essential to move a pupil towards scientific understanding and independence. The chemistry trainee teachers listed both 'maths literacy' and 'terminology' under a heading entitled 'language versatility'. It is perhaps telling that the physics trainee teachers stated on their concept map that 'maths describes the world', placing much more emphasis on numeracy than literacy. The physics trainee teachers discussed how a good understanding of mathematics can be part of the shift in identity often associated with TCs, as a pupil becomes more able to 'talk like a scientist':

> I see it as you can learn about scale, you can learn about randomness and deriving equations, the language of physics, dimensional analysis on their own. But, if you understand that they are all mathematical and you understand a bit of the mathematical knowledge, then that is the transformational thing. And that is also integrative because you can integrate it across things, and it allows you to see things across the subject. And of course, it is troublesome, but also, it's discursive in the way we were talking about mathematics being the language that we would use to describe things. And it does give you a shift in identity because when you can do that you can talk like a scientist, like a physicist, just because you have integrated it and you can apply it in an abstract way across different topics. (Physics trainee teacher)

The ubiquity of the use of the term 'language' by the trainee teachers prompts us to suggest this is another Threshold Episteme but we posit that 'language' in this instance should refer to both literacy and numeracy.

6 **Discussion**

Much of the early TCF literature sought to identify, and in some cases, isolate threshold concepts within disciplines, leading to critique (Rowbottom, 2007, O'Donnell, 2010). In these relatively early stages of the evolution of the TCF, the perception from some was that 'until the challenges of identifying true threshold concepts are overcome, we will struggle to create scenarios which can explore student's understanding of concepts' (Taylor, 2006, p. 95).

Rather than adopting the normative stance of these early critiques, we would suggest that whilst there are common Threshold Epistemes across all three science disciplines, different pupils and different teachers arrive at new knowledge with very different conceptual change types. It is the *process* of analysing and debating possible threshold concepts and/or epistemes that encourages individual teachers to explore their own misconceptions, identify what worked for them to make any conceptual changes and thus suggest approaches that might be useful in the classroom. Constant reflection on practice and pedagogy will allow such approaches to be adapted in response to pupils learning to maximise progress. This was captured for us by one trainee teacher comment in particular:

> The fact that there are threshold concepts is in itself a threshold concept. (Biology trainee teacher)

Ross & Tronson (2007) determined from their study of Biology undergraduates in an Australian University that teachers reflecting on their own experiences helped to imagine their student's conceptual difficulties, as advocated by Brookfield (1995). Brookfield's four lenses for viewing teaching practice can be used to identify liminal or 'stuck' places and help identify possible teaching and learning strategies that may open conceptual doors for students. There were numerous examples from the trainee teacher discussions that revealed possible teaching strategies from their reflections. One group talked about making the curriculum relatable to every day:

> If you don't have the relatability and the things that makes kids go 'ahhh, okay', then they are not going to ask more questions and want to go further. (Chemistry trainee teacher)

They went on to discuss what in their opinion was necessary to be taught and why. This particular example links back to the Threshold Episteme of randomness and the ability to spot patterns as discussed previously:

> It's the ability to be able to spot patterns, so you need to be able to analyse data which…if you can't do that or you haven't been taught how to do it or understand how to do it, you are facing a massive barrier in your understanding and how much you will ever understand in chemistry. (Chemistry trainee teacher)

This reflective process encourages movement towards being an independent scientist and/or an independent science teacher, so may well benefit both pupil and trainee teacher.

7 Conclusions and implications

Through the voices of the trainee teachers who participated in the Threshold Connections Project we have argued that it is the *process* of engaging with the TCF as a theoretical framework that offers the greatest potential to be pedagogically productive. The thematic analysis of our research with ITE trainee teachers also lead us to conclude that there are common Threshold Epistemes (Ross *et al*. 2010) across all three science disciplines.

We suggest that by reflecting upon and defending decisions about what constitutes a TC, trainee teachers begin to make *threshold connections:* links between 'isolated islands of knowledge' to create a more complex 'web of composite knowledge and understanding' (Taylor, 2006, p.89). This empowers them to then identify pedagogical approaches that will allow their pupils to do the same over time. By identifying, acknowledging and addressing TCs, trainee teachers and pupils can begin to make the conceptual or categorical shifts (Chi, 2008) within the discipline required to maximise learning. Trainee teachers thus need to be given the theoretical underpinning and time within an ITE training course to be able to gain the most from this process.

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