6 Radiation Physics in theory and practice

Using Specialization to understand 'threshold concepts'

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Introduction to radiation physics and radiation therapy

Radiation Physics is the study of ionizing electromagnetic radiation, including γ-rays obtained by the decay of an atomic nucleus and X-rays produced when electrons strike a target. Radiation Physics is the science that underpins the practice of Radiation Therapy. Radiation therapists treat patients with cancer, as part of a multidisciplinary oncology team. Advances in cancer management have been influenced by technological advances in medical imaging (Baumann *et al.* 2016) and Radiation Therapy equipment. Another major impact has been the expansion of radiation therapists' scope of practice to include decision-making in patient management (Harnett *et al.* 2014; Harnett *et al.* 2018). These developments in the profession have resulted in different approaches to the training of radiation therapists, in order to prepare them adequately for the changing clinical environment, as well as for their expanding roles. It is clear that students need scientific knowledge to enable new and evolving forms of practice. That is why consideration of key concepts of Radiation Physics is important in the education of radiation therapists, who face unknown future contexts.

Many lecturers and researchers have found the idea of 'threshold concepts' (Meyer and Land 2003, 2005) to be useful, but also confusing. For this reason, this study aimed to address the research question: How could threshold concepts in Radiation Physics be described in an empirically grounded and theoretically consistent way for the benefit of lecturers, students and clinical educators? This chapter presents a way of unpacking and tackling threshold concepts in Radiation Therapy education using concepts from the Specialization dimension of Legitimation Code Theory to demonstrate the development of what is termed an *élite code* orientation over time.

Brief overview of the literature on threshold concepts

The idea of threshold concepts emerged from an educational study into the disciplinary characteristics of the field of economics. Meyer and Land (2003) noted that 'certain concepts were held, by economists, to be central to the mastery of their subject.' They described these concepts as 'threshold'

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because they were analogous to a doorway into the discipline. In subsequent studies (e.g. Meyer and Land 2005; Meyer *et al.* 2006) researchers linked students' mastery of disciplinary knowledge to their understanding of its threshold concepts. The Threshold Concept Framework clusters together a range of ideas about why students might experience difficulty in mastering complex disciplinary knowledge and, in the context of this study, why applying them successfully in the clinical environment is so challenging. Cousin (2006) notes that all disciplines have threshold concepts that are fundamental to that discipline, for example, a limit in Mathematics (Scheja and Pettersson 2010) and atomic structure in Physics (Park and Light 2009). Understanding why students experience difficulties is the first step towards supporting them. In this regard, the Threshold Concept Framework provides a list of characteristics that lecturers can explore when modifying or redesigning curricula (Dunn 2019).

Threshold concepts are distinguished from other concepts by their complexity, their high level of abstraction, and their centrality to the discipline. Threshold concept descriptors, as explained by Cousin (2010: 1–2) and Meyer and Land (2005) have particular key features:

1. Transformative: New understandings are 'assimilated into our biography,' becoming a part of 'what we know' and 'who we are.'
2. Irreversible: Although difficult to grasp, once a threshold concept is understood, the student is unlikely to forget it.
3. Integrative: Threshold concepts tend to integrate prior disciplinary concepts, thus mastering a threshold concept can enable the student to make connections across the curriculum. 'Things start to click into place.'
4. Bounded: Threshold concepts occur in disciplinary knowledge; they are not part of everyday knowledge or common sense.
5. Troublesome: Threshold concepts are 'troublesome' because they are complex and challenging and, to a novice, seem 'counter-intuitive, alien or seemingly incoherent.'
6. Discursive: The idea that threshold concepts are associated with disciplinary discourses was a later addition to the framework.

Meyer and Land (2003) included the concepts of 'liminal spaces' and 'states of liminality' to explain the process of learning a threshold concept. Cousin argues that while most learning involves recursive processes, in the case of threshold concepts, learning 'involves a strong emotional dimension concerning the student's identification with both the subject and his [sic] perceived capabilities' (Cousin 2010: 3). Zaky (2018) points out that liminal spaces and states are not static but dynamic and argues that teaching threshold concepts requires locating students' progress along a liminal continuum. The pre-liminal space represents an initial encounter with 'troublesome knowledge.' In the liminal space, the student undergoes recursive processes of integration and discarding prior understandings, which include concomitant ontological and epistemic shifts. Finally, successful students emerge in a post-liminal state of transformation and irreversibility. This process is illustrated in Figure 6.1.

Zaky (2018) re-organized the Threshold Concept Framework for the purpose of understanding the processes of learning threshold concepts. Our purpose in this study was to understand the characteristics of the knowledge implied by the Threshold Concept Framework, with specific reference to Radiation Physics.

While there is very limited literature on threshold concepts specific to Radiation Physics, a number of studies have identified threshold concepts in general Physics that have relevance to Radiation Physics. For example, 'probability' and 'energy quantization' were identified as threshold concepts for understanding atomic structure (Park and Light 2009), while 'electronic transition' and 'photon energy' were identified as threshold concepts for students' scientific understanding of atomic spectra (Körhasan and Wang 2016). These general Physics concepts were identified as threshold concepts because of their importance in enabling progression towards more advanced concepts. However, it is argued that transferring general Physics concepts to more specialized fields of study (e.g. Biophysics) is not helpful for identifying threshold concepts specific to these fields (Wolfson *et al.* 2014). In the case of Biophysics, Wolfson *et al.* (2014) point out that the interdisciplinary nature of threshold concepts in Biophysics means that they have characteristics that are distinct from pure Physics. Radiation Physics is an applied discipline in which pure Physics concepts are applied to the treatment of patients. Thus Radiation Physics contains threshold concepts that are not found in pure Physics, such as the isocentre (or centre of rotation) and the inverse

Model	**Pre-liminal**	→	**Liminal**	→	**Post-liminal**
	|		|		|
Features	○ Encounters with troublesome knowledge	→	○ Integration ○ Discarding ○ Ontological and epistemic shifts	→	○ Transformation ○ Irreversibility ○ Crossing conceptual boundaries ○ Changed discourse
	|		|		|
Type	Instigative	→	Reconstitutive	→	Consequential

Figure 6.1 A relational view of the features of threshold concepts (Zaky 2018: 110).

square law of exponential radiation absorption used in radiation protection (Hudson *et al.* 2018).

Threshold concepts in professional education

In professional education, threshold concepts encapsulate the essential subject knowledge of the course of study that underpins professional practice (Baillie *et al.* 2013). Thus competent practice has been associated with mastery of threshold concepts in the disciplines associated with particular fields of practice (Dunn 2019). Much of the literature on threshold concepts in the health sciences relates to concepts underpinning care (Neve *et al.* 2017; Clouder 2005), general professionalism (Kinchin *et al.* 2010), or concepts in the disciplines that are common across health professions, such as Anatomy and Physiology (Weurlander *et al.* 2016). Inter-professionalism has also emerged as a threshold concept for inter-professional education and practice (Royeen *et al.* 2010).

Land (2011) proposes that if students in professional programmes fail to master threshold concepts, they will only be able to perform in a 'ritualized manner.' Wheelahan argues that 'students need to be inducted into disciplinary systems of knowledge, so they have access to the criteria used to judge knowledge claims, and over time, [and to] change the terms of the debate' (2015: 760). Recently, Fredholm *et al.* (2019) pointed out that practical experiences in the clinical environment have a similar effect to threshold concepts; that is, they transform thinking and identity and serve 'as a trigger for transformational learning, therefore making the discussion about 'practical thresholds' or thresholds in practice possible' (Fredholm *et al.* 2019: 2).

Critique of the Threshold Concept Framework

The Threshold Concept Framework has been debated in the literature, and its theoretical inconsistencies have been pointed out (e.g. Barradell 2013). Researchers have shown that the terms used to describe the characteristics of threshold concepts are often subjective and difficult to measure (Nicola-Richmond *et al.* 2018). Rowbottom (2007) claims that thresholds are 'unidentifiable,' while Walker (2013) suggests that the framework is a cognitive framework, rather than a framework for describing concepts. These critiques of the Threshold Concept Framework do not imply that the framework is not useful, but that the framework might need to be strengthened, in particular to avoid a conflation of knowers, those who are doing the learning, and knowledge, that which is being learned.

Theoretical framework: LCT Specialization

Legitimation Code Theory (LCT) offers many tools for analysis of knowledge practices. In this study, the dimension of Specialization (Maton 2014, Maton and Chen 2020) was drawn on to analyze how threshold concepts in

Radiation Physics were enacted in the curriculum and in pedagogies towards competent and safe clinical practice. Maton explains Specialization in terms of *epistemic relations* to objects and *social relations* to subjects (2014: 29). It is important to note that Specialization codes are referred to in relational terms, on continua of strengths of the two relations, rather than as typologies. On the *Specialization plane*, the *x*-axis represents social relations, and the *y*-axis represents epistemic relations. A disciplinary field, or a curriculum, or pedagogies or any form of practice can be located on the Specialization plane to reveal their relative strengths and weaknesses of *epistemic relations* (to other knowledge and the object of study) and *social relations* (to ways of knowing or knowers). Figure 6.2 is a graphical representation of the Specialization plane.

The four principal modalities created by the intersection of the two continua in Figure 6.2 are described by Maton (2016: 13) as follows:

- *knowledge codes* (ER+, SR–), where possession of specialized knowledge, principles or procedures concerning specific objects of study is emphasized as the basis of achievement, and the attributes of actors are downplayed;
- *knower codes* (ER–, SR+), where specialized knowledge and objects are downplayed and the attributes of actors are emphasized as measures of achievement;
- *élite codes* (ER+, SR+), where legitimacy is based on both possessing specialist knowledge and being the right kind of knower; and
- *relativist codes* (ER–, SR–), where legitimacy is determined by neither specialist knowledge nor knower attributes – 'anything goes.'

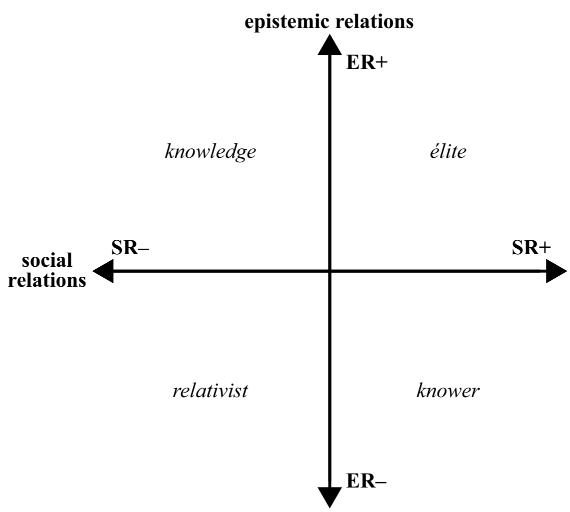

Figure 6.2 The specialization plane (Maton 2014: 30).

Maton (2016: 13) describes these codes as emphasizing 'what you know' (knowledge code), 'the kind of knower or practitioner you are' (knower code), both specialist knowledge and being a particular kind of knower (élite code) and emphasizing neither (relativist code).

Specialization codes were considered to be appropriate for analyzing how threshold concepts in Radiation Physics were enacted in theory-based learning and in clinical practice. Specialization affords a focus on epistemic relations to knowledge as well as social relations of 'practitioners' of the discipline. The use of Specialization in this study provided insights into threshold concepts in Radiation Physics, as well as their role in underpinning Radiation Therapy practice.

For the purpose of this study, the four codes on the Specialization plane (Figure 6.2) were adapted as in Figure 6.3.

Radiation Physics is the physical science that underpins Radiation Therapy practice. Radiation Physics can be characterized as a knowledge code, emphasizing epistemic relations (ER+) to knowledge and downplaying social relations (SR–) to knowers. In other words, it is an abstract scientific discipline. We thus expect to find threshold concepts that are abstract and complex in Radiation Physics. Radiation Physics underpins Radiation Therapy. Radiation Therapy is a clinical practice and has stronger social relations (SR+), but because it is underpinned by Radiation Physics, it also has stronger epistemic relations (ER+). For these reasons, it is described here as an élite code (ER+, SR+). Patient care is an ethical position, a mandated code of conduct for radiation therapists and a core competence for students. Although patient care requires underpinning by scientific knowledge, much patient care, such as attending to the comfort and well-being of the patient, has weaker epistemic relations and stronger social relations because it is dependent on

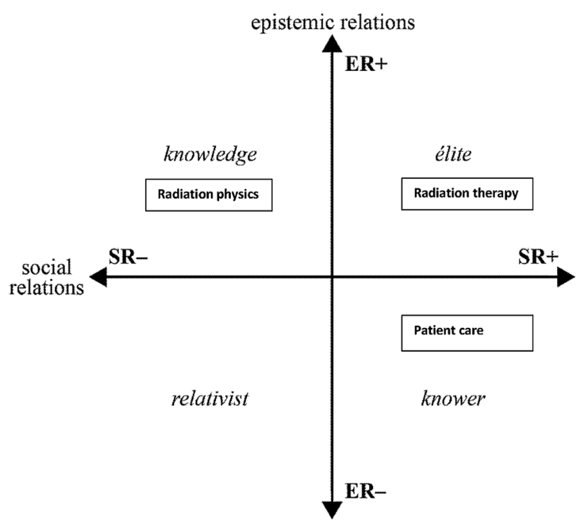

Figure 6.3 The specialization plane for Radiation physics.

appropriate dispositions. Thus patient care is a knower code (ER–, SR+). Relativist codes (weaker epistemic relations to knowledge and weaker social relations to practice) have no official space in the training or practice of radiation therapists.

Research design and methods

This study focused on the first-year Radiation Physics subject and addressed the research question: how could threshold concepts in Radiation Physics be described in an empirically grounded and theoretically consistent way for the benefit of lecturers, students and clinical educators? The research question called for an understanding of how threshold concepts in Radiation Physics were understood by lecturers, students and clinical educators. Lecturers are subject experts and experienced in teaching key concepts in a discipline; they, therefore, played an important role in the identification of threshold concepts. In this study, clinical educators were also included as experts because they understood the value of Radiation Physics in practice. Meyer and Land (2005) point out that because the experts have moved beyond threshold concepts, they find it difficult to identify concepts that they have long internalized. Thus, to ensure the accurate identification of threshold concepts, there is a need for a partnership between experts, educational researchers and students. Cousin calls this partnership a 'transactional curriculum inquiry' (2009: 202).

Participants' descriptions of first-year Radiation Physics were expected to be dependent on their contexts. Understanding was therefore anticipated as being determined by whether they were lecturers of first-year Radiation Physics, first-year students learning the subject, senior students reflecting on their learning in their first year or practising radiation therapists (referred to as clinical educators in the study).

The site selected to conduct this inquiry was the only university where a Bachelor of Science in Radiation Therapy was offered in South Africa. This study was approved by the Faculty Research Ethics Committee and permission was given by the relevant department to interview lecturers and students. Permission was also granted by clinical sites, where the clinical educators were interviewed.

Participants' perspectives on radiation physics knowledge

This section outlines the key issues raised by the participants in the 'transactional curriculum inquiry' (Cousin 2009). Data provided by participants provided different perspectives on what makes Radiation Physics challenging to learn, and challenging to teach.

Students' perspectives on first-year radiation physics

The students consistently described Radiation Physics as complex and difficult to understand. Reflecting on her first-year experience, a senior student comments: 'I honestly didn't understand a single thing' (Third-year student 3). A large part of the difficulties associated with Radiation Physics had to do with its abstract nature; first-year students used words like 'up there' (First-year student 1) or 'in the air' (First-year student 6) to describe their difficulty with the subject: '[The Physics lecturer is] like very up there … clever with Physics and I'm like … don't understand' (First-year student 3); 'But in Physics, I always feel it's – out of the air just here' (First-year student 6). For one interviewee, Radiation Physics was simply 'way too Physics-full' (First-year student 4).

Lecturers' perspectives on first-year radiation physics

The lecturers, who were either physicists or radiation therapists, did not perceive Radiation Physics as difficult. The physicists understood Radiation Physics as an abstract discipline, and they wanted students to achieve a level of abstract comprehension. The radiation therapists, on the other hand, did not experience Radiation Physics as particularly abstract. Although they described Radiation Physics as a discipline, they also recognized it as an integral part of Radiation Therapy practice. The physicists described Radiation Physics in the specialized language of the discipline, while the radiation therapists understood it in the language of Radiation Therapy practice. Both sets of lecturers interviewed described Radiation Physics as a blend of Physics and Therapy concepts: the 'concept of the x, y and z axis,' 'bending magnets,' 'waveguides,' 'anodes,' 'isocentre,' 'collimation,' 'virtual wedges,' and 'head of the machine' (Lecturer 4). They also understood the importance of the Radiation Physics concepts in underpinning skilled and safe practice: 'It's a high stakes environment. You know, if we conceptually get it wrong here, you know, you can imagine what the implication could be in clinical' (Lecturer 3).

For the physicists, Radiation Physics was separate from Radiation Therapy and worthy of study as a discipline in its own right that taught 'the process of thinking' (Lecturer 2) as much as the content of Physics. However, the physicists also understood Radiation Physics and Radiation Therapy as almost interchangeable:

> Radiation, how do we protect ourselves from it…? How do we utilize it to our maximum … capabilities … high dose to the tumour and then less dose to the surrounding tissue? That's the aim of Radiation Therapy and with Radiation Physics, we can understand that concept.
>
> (Lecturer 2)

In some cases, Radiation Physics was understood as a discipline with its own characteristics and properties – 'It is what it is' (Lecturer 1), but in most cases it was understood in relation to Radiation Therapy. As Lecturer 1 explains: 'I teach in a way that I learned how to set up in the department.' She explained that this was 'not necessarily an academic way of teaching,' but her teaching followed the sequence of practice:

> What do you need? You need A to get to B and then from B, we can move to C and so that's how … we need to straighten our patient. We need to look at the x, y and z. It's a three-point set up and that's where our … set up starts. So it starts at straightening your patient and then choosing your reference and then from the reference moving to your isocentre and once your isocentre is there, we move onto the next step which is then the verification step. So that's how I sort of plan my lessons.
>
> (Lecturer 1)

Lecturer 1 teaches Radiation Physics by starting in the knower quadrant ('straightening the patient'), in contrast to Lecturer 2, who talks about radiation safety (in the élite quadrant) in relation to a depersonalized tumour.

Clinical educators' perspectives on first-year radiation physics

The clinical educators were not involved in the academic teaching of Radiation Physics but valued the role of the discipline in underpinning competent and safe practice:

> You need to understand exactly why there is no room for error … which is why radiation physics is so important. You can't just blindly push buttons you need to know … why you're doing what you're doing.
>
> (Clinical educator 1)

The clinical educators were aware that students had acquired a considerable knowledge of Radiation Physics. They described this as having 'head knowledge of radiation and what it entails' (Clinical educator 1). They were, however, sceptical of students' ability to apply the knowledge learned in the clinical context, as '…that comes with experience' (Clinical educator 1).

Revising the Threshold Concept Framework

Having studied participants' different understandings of first-year Radiation Physics from their various positions and experiences, elements of the Threshold Concept Framework were modified in the light of empirical data and insights provided by Specialization.

Explaining the (not entirely) boundedness of threshold concepts in Radiation Physics

Meyer and Land (2003, 2005) argue that it is the discipline-specific quality that makes threshold concepts difficult to learn and difficult to teach. The Radiation Physics lecturers were not in agreement about how 'bounded' the concepts of Radiation Physics were. Radiation Physics was recognized as a specialized sub-discipline of Physics, but it was also understood as an applied discipline developed for the treatment of patients. One of the lecturers described this bounded-yet-permeable nature of Radiation Physics as follows: 'I think it starts off in Physics … that's where the concept starts. It starts with concepts that are taught in Physics and so it does start there' (Lecturer 1).

In another version, its concepts are derived from practice, as another lecturer explained:

> And then we applied it … we went into the application straight away. In fact, what we did was we first went into that … there's two ways to look at radioactive decay. The description of it and then … the physics of it. The description actually we realized is independent of them having learned all this other Physics.
>
> (Lecturer 3)

This not-entirely-bounded nature of Radiation Physics characterizes many of its concepts. The students identified with the version of Radiation Physics that was closely tied to Radiation Therapy practice. A lecturer who taught a 'pure' version of Radiation Physics was said to be teaching 'Harvard University Physics' (Third-year student 4).

The notion of the bounded-yet-permeable is enhanced with the more precise descriptors of epistemic relations and social relations. Radiation Physics was not consistently described in terms of its epistemic relations to the discipline of Physics, and was, in fact, more often explained in terms of its application to Radiation Therapy practice. Radiation Therapy practice has stronger epistemic relations to Radiation Physics and stronger social relations to subjects. Patients are always at the centre of practice. Thus it makes sense for radiation therapists, who teach Radiation Physics, to understand Radiation Physics in terms of practice, rather than as a sub-discipline of Physics. This was evident in interviews with the clinical educators, most lecturers (especially lecturers who were radiation therapists), and among the students themselves, as is evident in the exchange between the interviewer and a senior student below:

INTERVIEWER: But if there's this one thing … what are [Radiation Physics concepts] … the must have?

SENIOR STUDENT: It has nothing to do with Physics, but I would say patient care is always number one (Third-year student 3).

Integrative (conceptual and practical)

Threshold concepts are said to reveal 'the previously hidden interrelatedness of things' (Meyer and Land 2005: 377). Threshold concepts build on prior concepts and once grasped enable the student to make connections between other concepts. This realization is often referred to as a 'light-bulb' or 'a-ha' moment (Cousin 2009). Lecturers in the study spoke about '…making connections to build knowledge' (Lecturer 3) and 'sequencing activities to build concepts' (Lecturer 3). These descriptions suggest that the threshold concepts in Radiation Physics integrate prior concepts learned in the discipline:

> It's impossible too for someone to understand [radiation physics], really understand it … without first understanding it conceptually. … If they don't have the conceptual understanding you never quite understand the Inverse Square Law, you never quite understand radioactive decay.
>
> (Lecturer 3)

But participants also proposed another version in which the concepts of Radiation Physics were integrated with practice. A first-year student explained her developing understanding in terms of integrating theory and practice:

> I think for me … it was the clinical part, like … going to the hospital and actually seeing it and experiencing what they are doing and I think that really brought it together.
>
> (First-year student 6)

The integrative nature of both non-threshold and threshold concepts in Radiation Physics refers to its 'hierarchical knowledge structure' (Bernstein 1999); that is, the concepts are cumulative; one concept is built on the other. It is difficult for students to acquire more advanced concepts if there are conceptual gaps in their understanding. As a Radiation Physics lecturer explained: 'I think it's got to do with conceptualization of basic principles that they are taught. Some people can't understand actually what we are doing' (Lecturer 3). Because Radiation Physics is so closely tied to Radiation Therapy, its integrative nature enables it to describe practice in particular ways. Radiation Physics is an applied discipline that describes the Physics of radiation treatment machines.

Temporarily troublesome

For first-year students, the concepts in Radiation Physics seemed, as Perkins put it, 'counter-intuitive, alien or seemingly incoherent' (Perkins 2006: 7). The students' troublesome experience was, however, temporary. Senior students, lecturers and clinical educators had mastered the once-troublesome concepts. Many could remember some of the difficulties that they had initially experienced. A senior student explained what encountering Radiation Physics for the first time felt like:

> I think if I look now at previous Physics lectures we've had … well, quite difficult, more difficult concepts that we haven't done in high school … so it's very difficult … [the lecturer is] talking about something there but you have nothing to reference it with. You have basically no idea what it's about really.
>
> (Third-year student 6)

Drawing on Specialization, the 'troublesome' nature of threshold concepts in Radiation Physics can be explained by a strengthening of the epistemic relations, described as a 'code drift' – that is, an occurrence in which a feature of a code is strengthened but not changed (ER↑) (Maton 2016: 237). Therefore, while Radiation Physics is characterized by a knowledge code (ER+, SR–), in threshold concepts epistemic relations are strengthened (ER↑). Understanding threshold concepts as rises in the epistemic relations enables us to separate the difficulty experienced by students as they enter the liminal zone, from the 'troublesome' nature of a discipline that has many threshold concepts, each of which represents an increase in the strength of epistemic relations. As an example of an increase in the strength of epistemic relations, Radiation Physics is used to develop algorithms for the three-dimensional geometrical plotting of the location of tumours and to plan the radiation dose to administer. The three-dimensional concepts that are embedded in Radiation Physics can cause students to experience difficulties:

> But [for] most students, it's just a difficult concept for them thinking, three dimensionally, where must a field come in? Just talking about maybe [organs at risk] a lung.... You know it's important to spare the other lung those kind of little stuff and that comes with experience ... you know ... where must a field go? How must it be labelled? Those simple type of things they struggle with.
>
> (Lecturer 1)

Radiation Physics is densely packed with non-threshold and threshold concepts which accounts for its being troublesome. It has ever-strengthening epistemic relations (ER+↑) comprising multiple non-threshold and threshold concepts, each of which needs to be mastered by the students before they can move on to the next one.

Liminality as encounters with radiation physics in theory and practice

Meyer *et al.* (2006) use the term 'liminality' in the sense of a 'rite of passage' that the student has to undergo before being accepted into a disciplinary community. Cousin (2006) describes how students often become 'stuck' and oscillate between understanding and misunderstanding. Most participants remembered their struggles with disciplinary concepts. In the excerpt below, a clinical educator recalls her struggles with Radiation Physics:

> Me personally, I panicked. I used to panic, you have to go read this, read that because the first question [the Supervisor is] going to ask you is how are you going to bring in your first beam? How are you going to place your first beam?
>
> (Clinical educator 7)

Land (2011) proposes that if the liminal space is not traversed, the student will only be able to perform in a 'ritualized manner.' This description is echoed in a clinical educator's account of the robot-like behaviour of some students, who seem to be stuck in this confusing space:

> … there is something that I have picked up. The knowledge is there but the application of knowledge. … For them, theory and practical, [are] two separate things. They know these things but to apply the knowledge in the clinical situation. It's like; it's a little bit far-fetched. As a result, what they do. … I don't know which other words … this might sound dramatic … but it's like a robot issue. … Because sometimes I ask a question, you do this, but why? Because … you need to understand why am I doing it.
>
> (Clinical educator 2)

Land describes the liminal state as 'approximate to a kind of mimicry or lack of authenticity' (Land 2011: 176). This state is identified by Lecturer 2 who describes a student as going through the motions without comprehension:

> There is a missing link between the classroom and … their technical environment, for sure. Because when you go to work then they stop thinking about the Physics. So, you just go and do your work, go and press the buttons, go and it's their day to day.
>
> (Lecturer 2)

Being in a state of 'liminality' is a characteristic of students learning threshold concepts. It should also be accepted that students will inevitably spend time in the liminal space in which they will experience difficulties in understanding, discussing and writing. The liminal space should be a safe space for students to learn from their mistakes (Land 2011). In LCT terms the liminality could be understood as recursive movements between weaker and stronger epistemic relations (ER↓↑).

Eventually irreversible

The idea of irreversibility was explained by the senior students as a gradual process of cumulative learning and gaining of insight: 'Radiation Physics … then it just gets … more clarity … with every single time I got introduced to it again' (Second-year student 4). For many lecturers, for whom the concepts of Radiation Physics had long been internalized and irreversible, the idea of 'irreversibility' was evident in their frustration in trying to teach students something that was self-evident to them:

> I think the hardest thing to teach the students … top of the list was x, y and z coordinates and understanding that x, y and z is not just one thing. So when I put the patient on the bed it's not just looking at midline and reference level and reference height. It's them translating that x, y and z to the x, y and z of the isocentre, which is a different x, y and z.

> … It's a matter of explaining it and practising it and explaining and practising it and explaining it and practising it and then eventually a year down the line they'll understand it.
>
> (Lecturer 1)

Threshold concepts are often described as 'irreversible,' but it is the student's attainment of the concept that is irreversible rather than the concept. Clouder (2005) for example, proposes that 'patient care' is a threshold concept in the health sciences and that 'the negotiation of a threshold is irreversible because experiences of caring are profound and are therefore not likely to be forgotten or unlearned' (Clouder 2005: 513).

Reconstitutive: The disciplinary underpinnings of practice

Meyer and Land's (2005) later inclusion of 'reconstitutive' as a threshold concept characteristic was an attempt to explain that when a student understood a threshold concept, there would be a shift in the student's 'mental models,' which is initially more likely to be noted by people other than the student, as Lecturer 1 explains: 'I think that is when the light-bulb moment comes, when you can amalgamate why you're doing that in planning and how you got the end result' (Lecturer 1).

Initially, Meyer and Land (2005) understood that it is students' thinking that is 'reconstituted' following the crossing of the threshold: 'What is being emphasized [in reconstitutiveness] is the inter-relatedness of the student's identity with thinking and language' (Meyer and Land 2005: 375). In a later work, however, Land *et al.* (2010) describe the threshold concept itself as 'reconstitutive.'

> This reconfiguration occasions an ontological and an epistemic shift. The integration/reconfiguration and accompanying ontological/epistemic shift can be seen as reconstitutive features of the threshold concept.
>
> (Land *et al.* 2010: iii)

Drawing on Specialization, a 'reconstitution' of the threshold concept would entail an understanding of its relationship to Radiation Therapy practice. Radiation Therapy has strong epistemic relations to Radiation Physics, as well as strong social relations to subjects. This suggests that disciplines can shift towards, or underpin practices. This is characteristic of applied disciplines in particular and was evident in much of the Radiation Physics lecturers' descriptions of their teaching, where they framed Radiation Physics concepts through the practice of Radiation Therapy:

> What does it mean if I'm moving SUP? What does it mean if I'm moving INF? What is my x, y and z? How does the x, y and z apply to what my patient is doing or what I'm expecting the bed to do or…? and how

> that x, y and z, then relates to the treatment plan of the patient. … So those bases help them understand not only the planning principles but also the set up principles which is the bread and butter of Radiation Therapy.
>
> (Lecturer 1)

In LCT terms, applying abstract Radiation Physics concepts in practice involves a 'code shift' (Maton, 2016: 237) from weaker to stronger social relations (ER+,SR– → ER+,SR+).

Discursive: The specialist language of Radiation Physics

The 'discursive' dimension was also a later addition to the Threshold Concept Framework (Meyer and Land 2005). As threshold concepts would be likely to incorporate an enhanced and extended use of the language of the discipline and initially, lecturers found that:

> Textbook terminology just goes straight over their heads I think sometimes. So I teach a concept the way I hope that they will understand and so in sort of layman's terms, I'll put up a presentation, showing them what I need for them to know with definitions in simple terms and we'll talk through it.
>
> (Lecturer 1)

In time – and particularly with clinical experience – students started to use the disciplinary and professional discourse, as shown in the exchange between the interviewer and first-year student, who had returned from their first clinical rotation:

INTERVIEWER: Just -- what did you see and how did you do it?

FIRST-YEAR STUDENT 8: Oh, firstly you put the patient on the bed. Then you align the midline…

INTERVIEWER: What else after the midline?

FIRST-YEAR STUDENT 8: From the midline then you check the lateral tattoos. Then again, the midline.

INTERVIEWER: Can you see how you're starting to talk like them? Them … the staff in the department and that's good. The more you do it the more confident you're going to become.

Meyer and Land (2005, 374) claim that the crossing of a threshold will incorporate an enhanced and extended use of language.

> It is hard to imagine any shift in perspective that is not simultaneously accompanied by (or occasioned through) an extension of the student's use of language. Through this elaboration of discourse new thinking is brought into being, expressed, reflected upon and communicated.

Scientific discourses have developed within disciplines to represent complex disciplinary concepts, and these can be challenging for the newcomer, especially if the terms used also have everyday, non-specialist meanings. Cousin points out that mastery of a threshold concept can be inhibited by the prevalence of a 'common sense or intuitive understanding of it' (Cousin 2006: 5). Tan *et al.* (2019) warn that lecturers need to be careful with their use of 'anthropomorphic language' when discussing ionization energy and should consistently demonstrate the correct and technical language in their presentations and conversations with students (Tan *et al.* 2019).

The language of Radiation Physics requires stronger epistemic relations to the discipline and weaker social relations. First-year students find it difficult to remember the specialized terms and ways of communicating disciplinary knowledge, and would initially have weaker epistemic relations to Radiation Physics, but acquire the disciplinary discourse over time.

Transformative (knowledge and identity)

A threshold concept, once understood, causes a significant shift in the student's understanding, simultaneously with an identity shift. As Cousin puts it: 'New understandings are assimilated into our biography, becoming part of who we are, how we see, and how we feel' (Cousin 2010: 2). For the students in this study, these transformative shifts tended to happen in the clinical environment, rather than in the Physics classroom. A first-year student, recently back from her first clinical experience describes how the practice enhanced her conceptual understanding:

> And then by Linac 3, the referencing I understood better and even seeing it on the monitor and the calculations, you take the calculator and try to do it before. And then yes, that was what I have learned from there.
>
> (First-year student 10)

The clinical educators confirmed that transformative shifts were only likely to occur through practice:

> So … say they're measuring a sep … on the understanding that you … measure from ant to post and … they just don't get that – that's what they're doing. But the concept of what a sep is … they know what it is.
>
> (Clinical educator 1)

In other words, students might know the concept of a sep (separation), but it is unlikely to become an internalized, irreversible or transformative concept until they have extended clinical experience. The clinical educators further cautioned that mastery of theoretical knowledge does not predict competent practice:

> I think the type of student … because [they] are more confident … but they're not necessarily right. So, they are confident in the knowledge that they have with the studying. But then they think because they know that they automatically … can apply it … and they are very taken aback when they realize but they can't do it or they don't do it correctly.
>
> (Clinical educator 2)

Reaching the point of transformative understanding through the integration of theory and practice is a long process:

> And their time in the [clinical] department is different and their clinical exposure is different and I think what we want to see in a fourth year, we're possibly only going to see when they do community service.
>
> (Clinical educator 6)

In the process of learning, the student changes, as Land *et al.* (2010) explain: 'the outcome of transformative learning … is that the content of the field of consciousness change' (Land *et al.* 2010: viii). Descriptions of the threshold concept as 'transformative' thus describe its effects, rather than its nature. However, in the same way that concepts can be 'reconstituted,' they can also be 'transformed,' such as in the 'code shift' (Maton 2016: 237) from Radiation Physics to Radiation Therapy, which was understood by a first-year student as the 'disappearance' of Radiation Physics in practice: 'Like when you work on the machines, you're not going to do any Physics there. It's just like in the background basically' (First-year student 11).

From the discussion above, we can locate elements of the Threshold Concept Framework on the Specialization plane (Figure 6.4). Radiation Physics is located in the 'knowledge' quadrant (ER+, SR–); threshold concepts in Radiation Physics are represented as a strengthening of the epistemic relations, or in LCT terms as a 'code drift' (Maton 2016: 237) (ER↑). Radiation Therapy is located in the élite quadrant (ER+, SR+) as it has epistemic relations to Radiation Physics and the necessary dispositions for clinical practice. Threshold concepts in Radiation Physics underpin practice, for example, the concepts of ionizing radiation underpin the practice of radiation protection in Radiation Therapy, the shift from the knowledge quadrant to the élite quadrant in LCT terms is a 'code shift' (Maton 2016: 237) from weaker social relations to stronger social relations to practice (ER+, SR– → ER+, SR+). Students' progress through the liminal zone is represented by the dotted line which moves from recursive learning to irreversible understanding of the threshold concept (ER↓↑, SR–); threshold concepts in Radiation Physics are represented as a strengthening of the epistemic relations, or in LCT terms as a 'code drift' (Maton 2016: 237) (ER↑). Radiation Therapy is located in the élite quadrant (ER+, SR+) as it has epistemic relations to Radiation Physics and the necessary dispositions for clinical practice. Threshold concepts in Radiation Physics underpin practice, for example, the concepts of ionizing radiation underpin the practice of radiation protection

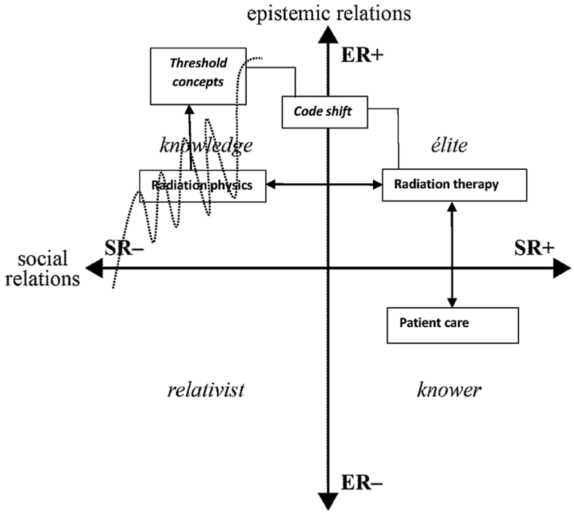

Figure 6.4 Plotting the Threshold Concept Framework on the specialization plane.

in Radiation Therapy, the shift from the knowledge quadrant to the élite quadrant in LCT terms is a 'code shift' (Maton 2016: 237) from weaker social relations to stronger social relations to practice (ER+, SR– → ER+, SR+). Students' progress through the liminal zone is represented by the dotted line which moves from recursive learning to irreversible understanding of the threshold concept (ER↓↑, SR–).

Detailed examples of the characteristics of threshold concepts with regard to their location on the Specialization plane are provided in Table 6.1.

Conclusion: An empirically grounded and theoretically consistent Threshold Concept Framework for Radiation Physics

This chapter set out to describe Radiation Physics in a theoretically consistent way for the purpose of benefitting lecturers, students and clinical educators. To address the research question, students, lecturers' and clinical educators' perceptions of Radiation Physics were elicited. These data were analyzed both with reference to the Threshold Concept Framework and Specialization. The engagement with empirical data and with theory enabled both a theoretically consistent and empirically grounded framework for the description of threshold concepts in Radiation Physics.

Through the analytical lens of Specialization, Radiation Physics was seen as having stronger epistemic relations and weaker social relations. The threshold concepts embedded in Radiation Physics were understood as increases in the strength of the epistemic relations, known in LCT terminology as an upward 'code drift' (Maton 2016: 237), thereby creating 'epistemological obstacles' (Meyer and Land 2005: 377) to student learning. In other words, those areas in which the epistemic relations become

Table 6.1 Using specialization codes to understand threshold concepts

Threshold Concept Descriptors	*Using Specialization as Threshold Concept Descriptors*	*Codes*	*Example from the Data*
Bounded	Radiation Physics is a Specialization of physics, the discipline is located in the knowledge quadrant.	ER+, SR–	*Physics is theory. It is what it is, what it is … you're teaching a concept (Lecturer 4).*
Integrative	Threshold concepts integrate prior concepts in Radiation Physics, represented as the strengthening of epistemic relations. Threshold concepts also underpin practice and need to be understood in terms of practice. This is represented as a code shift towards Radiation Therapy.	ER↑, SR– ER↑, SR+	*'if you don't actually understand the concept, you can't put a picture together of what is' (Third-year student 3).* *'…the linking of their book-based knowledge into clinical practice (Clinical educator 1).*
Troublesome	The epistemic relation strengthens in threshold concepts; this makes threshold concepts challenging or 'troublesome.'	ER↑	*When [clinical staff] mention SUP and moving from the reference to the isocentre…calculating that could be confusing at times (First-year student 6).*
Liminality	Liminality is explained as students' recursive attempts to understand the threshold concept.	ER↓↑, SR–	*I didn't understand a word he was saying because he's like very up there, clever with Physics and I'm like … don't understand (Third-year student 3).*
Irreversible	Students emerge from the liminal state when they grasp the threshold concept.	ER↑, SR–	*Radiation Physics … then it just gets … how can I put it … gets more clarity … with every single time I got introduced to it again (Second-year student 4).*

(*Continued*)

Table 6.1 (Continued)

Threshold Concept Descriptors	*Using Specialization as Threshold Concept Descriptors*	*Codes*	*Example from the Data*
Reconstitutive	Threshold concepts in Radiation Physics underpin Radiation Therapy practice, this is represented as a code shift on the Specialization plane.	ER↑, SR↓ ER↑, SR+	*when the light-bulb moment comes, when you can amalgamate why you're doing that in planning and how you got the end result (Clinical educator 2).*
Discursive	Discursive practices in an academic setting express strong epistemic relations, while in the clinical setting will have stronger social relations as well.	ER↑, SR±	*I think the difference between SSD and the different setups of the fixed Iso and the Iso on the patient itself (First-year student 5).*
Transformative	Transformation is understood as both understanding a threshold concept and being able to apply it in competent and safe practice. This could be understood as a code shift.	ER↑, SR↓ ER↑, SR+	*And then by Linac 3 … the referencing I understood better and even seeing it on the monitor and the calculations, you take the calculator and try to do it before … and then yes … that was what I have learned (First-year student 10).*

stronger, cause students who are learning the discipline to experience them as 'troublesome.' Students then (usually temporarily) enter the liminal zone, where they experience confusion, but which is a process of recursive learning. As the students become more able to access and understand the strengthened epistemic relations of the threshold concept, they cross the threshold into clarity. When they venture into the clinical environment, they undertake a code shift (Maton 2016: 237) into the field of Radiation Therapy. In this shift, they have to move from an area of weaker social relations to one of stronger social relations, as they apply Radiation Physics in skilled and specialized practice. The students will also have to acquire the stronger social relations associated with patient care. All these aspects need to be taken into account by the Radiation Physics lecturers and clinical educators who will have to teach the difficult concepts in Radiation Physics.

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