Cape Peninsula
University of Technology

TEACHING AND LEARNING THRESHOLD CONCEPTS IN RADIATION PHYSICS FOR PROFESSIONAL PRACTICE

by

LIZEL SANDRA ANN HUDSON (nee SMIDT)

STUDENT NUMBER: 198093764

Thesis submitted in fulfilment of the requirements for the degree

Doctor of Radiography (DGRDGR)

in the Faculty of Health and Wellness Sciences

at the Cape Peninsula University of Technology

Supervisor:	Associate Professor Penelope Engel-Hills (DTech: Radiography) (CPUT)
Co-supervisor:	Professor Christine Winberg (PhD English Literature) (UCT)

Bellville
May 2020

DECLARATION

I, Lizel Sandra Ann Hudson (nee Smidt), declare that the contents of this thesis represent my own unaided work, and that the thesis has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

05 May 2020

Signed **Date**

ABSTRACT

Radiation therapy has undergone significant changes with regard to new medical imaging technologies, including computerised tomography (CT) and magnetic resonance imaging (MRI). Practitioners now have access to technologies that provide anatomical information in an infinite selection of views. Earlier advances in three-dimensional conformal radiation therapy (3D-CRT) allowed for the site of treatment to be accurately located. Intensity modulated radiotherapy (IMRT) enabled practitioners to accurately focus the ionising radiation beam, while modulating the intensity of the dose being administered. Currently, using image-guided radiotherapy (IGRT) methods, radiation therapists can track the effectiveness of treatment in real-time to provide better protection for the organs and tissue that are not targeted for treatment. The changes described above have fundamentally changed radiation therapy practice, and thus have implications for the training of radiation therapists.

This thesis argues that without a deep understanding of the science underpinning the advancements in radiation therapy techniques, practitioners will be unlikely to achieve the necessary level of accuracy and consistency in treatment. Radiation physics concepts, such as sources and types of ionising radiation, ionisation, the isocentre and the Inverse Square Law underpin competent and safe practice. Threshold concepts, such as those listed above, have been identified as concepts that pose difficulty to students due to its complexity and the increased levels of cognitive challenge required to master a threshold concept. In applied disciplines, such as radiation physics, threshold concepts are strongly associated with competent practice.

This study focused on the first year radiation physics curriculum and addressed the overarching research question: What is the relationship between threshold concepts in the radiation physics curriculum and radiation therapy practice?

The study was guided by a translation device that combined two conceptual frameworks namely the Threshold Concept Framework and Legitimation Code Theory’s (LCT) Semantics dimension. LCT is a knowledge base theory that explains the complexity of knowledge structures. The Semantics dimension provided an explanation of the difficulty of concepts and proposed five pedagogies for the cumulative learning of complex concepts.

A case study research design and methodology guided the research process. Data for the study comprised curriculum documents, and semi structured focus group and individual interviews with students, academic staff and clinical educators. The data were analysed using a translation device to show the semantic profile of curriculum documents, pedagogies and participants’ different understandings of the threshold concepts in radiation physics.

The study found that threshold concepts in radiation physics underpin competent and safe practice. An external language of description was developed to identify the characteristics of threshold concepts. A virtual clinical environment was proposed as one of the pedagogies to aid mastering of threshold concepts through visualisation of the unseen by facilitating students' understanding of threshold concepts for competent and safe radiation therapy practice. The study showed that students' mastery of threshold concepts in radiation physics is critical for practice.

Keywords: Threshold Concepts, Threshold Concept Framework, Legitimation Code Theory, Semantics, Health Professions Education, Radiation Therapy Education

DISSEMINATION AND OUTPUTS

This study responds to the broad focus area of 'human and social dynamics' and addresses the university's specific Research, Technology, Innovation and Partnerships (RTIP) focus areas of 'teaching methods' and 'work place learning' by aiming to achieve the objective of improving educational outcomes (CPUT RTIP: Blueprint, 2012:24). RTI implementation consideration 8.2 (d) was addressed by introspecting and intervening in the undergraduate system to produce competent post graduate students by identifying curricular needs to ensure RTI related learning outcomes (CPUT RTIP: Blueprint, 2012:35). The study forms part of the 'Putting knowledge to work' research stream of the National Research Foundation's (NRF) South African Research Chairs Initiative (SARChI): Work-Integrated Learning.

Herewith a list of publications, poster and oral presentations emanating from this research to date:

Hudson, L., Engel-Hills, P. and Winberg, C. 2020. Unpacking threshold concepts in the first year Radiation physics curriculum. *Paradigms, (In Press).*

Hudson, L., Engel-Hills, P. and Winberg, C. 2019. Radiation Physics in Theory and Practice: using Specialization to understand 'threshold concepts'. In Blackie, M., Adendorff, H. & Mouton, M. (eds). *Legitimation Code Theory: Knowledge building in research and practice*. Abingdon: Routledge (In Press).

Hudson, L., Engel-Hills, P. and Winberg, C. 2019. *Understanding threshold concepts in Radiation physics.* Oral presentation (winning third prize) at the CPUT Postgraduate Research Day, Saretec, 07 November 2019.

Hudson, L., Engel-Hills, P. and Winberg, C. 2019. *Specialization: An alternative language of description for threshold concepts*. Oral presentation at the 3rd International Legitimation Code Theory Conference, School of Education, University of the Witwatersrand, Johannesburg 01 – 05 July 2019.

Hudson, L., Engel-Hills, P. and Winberg, C. 2018. *Threshold concepts: making waves of change in a first year curriculum*. Oral presentation at the Higher Education Learning and Teaching Association of South Africa (HELTASA) Conference, Nelson Mandela University Port Elizabeth 20 – 23 November 2018.

Hudson, L., Engel-Hills, P. and Winberg, C. 2018. *VERT™: An innovative solution for Radiation therapy clinical training.* Oral presentation at the CPUT Postgraduate Research Day, Saretec, 07 November 2018.

Hudson, L., Engel-Hills, P. and Winberg, C. 2018. *Conceptual development in a computer-simulated learning environment*. Oral presentation at the International Conference on e-Learning (ICEL), CPUT Granger Bay Campus 05 and 06 July 2018.

Hudson, L., Engel-Hills, P. and Winberg, C. 2018. *Deconstructing knowledge transfer from the Physics 1 classroom to the clinical setting*. Oral presentation at the South African Association of Health Educationalists (SAAHE) Conference, Durban 27- 30 June 2018.

Hudson, L., Engel-Hills, P. and Winberg, C. 2018. *Threshold concepts in Radiation physics underpinning professional practice in Radiation therapy*. Oral presentation at the Society of Radiographers of South Africa (SORSA) Seminar, Cape Peninsula University of Technology (CPUT), Bellville Campus 23 June 2018.

Hudson, L., Engel-Hills, P. and Winberg, C. 2018. Threshold concepts in Radiation physics underpinning professional practice in Radiation therapy, *International Journal of Practice-based Learning in Health and Social Care, Special Issue*, 6(1), 53 – 63.

Hudson, L., Engel-Hills, P. and Winberg, C. 2017. *Threshold concepts in Radiation physics underpinning professional practice in Radiation therapy.* Poster presented at the 10th International Conference on Research in Work and Learning (RWL), Rhodes University, Grahamstown 06 – 10 December 2017.

Hudson, L., Engel-Hills, P. and Winberg, C. 2017. *The knowledge-blindness of research on technology supported Physics education*. Oral presentation at the 2nd International Legitimation Code Theory Conference (LCTC2), University of Sydney, Australia 04 – 07 July 2017.

Hudson, L. Engel-Hills, P., Winberg C. and Beavis, A. 2016. *Teaching Physics Using Virtual and Augmented Realities: A Systematic Review of the Literature.* Poster presented at the 54th National Congress of the South African Association of Physics in Medicine and Biology (SAAPMB), Cape Town 6 – 10 September 2016.

ACKNOWLEDGEMENTS

I wish to thank:

- My principal supervisor, Associate Professor Penelope Engel-Hills, for mentoring and coaching me since my undergraduate training. Thank you for always being there for me.
- My co-supervisor, Professor Christine Winberg, for tirelessly assisting me to develop into an ethical emerging researcher.
- Prof Andy Beavis for his input and assistance during the early stages of this project.
- Dr Jennifer Wright for ‘standing in’ for me during my sabbatical leave. Thank you, Jenny, for your spiritual support during this journey.
- Dr Elizabeth (Liz) van Aswegen for proofreading and editing the references cited in this thesis in such a professional manner.
- All the study participants: students, lecturers and clinical educators who contributed to this project in so many meaningful ways.
- All my colleagues in the Department of Medical Imaging and Therapeutic Sciences and throughout the Faculty of Health and Wellness Sciences, thank you for listening, comforting and just being there when I needed you.
- All the colleagues involved with the administrative and human resource matters at all research sites.
- My family and friends who supported me during this journey. Your prayers, presence and various other forms of support are much appreciated.
- My loving husband, Randall and precious son, Wesley, thank you for allowing me to ‘disappear’.
- The Lord Almighty, for His grace and mercy in all that I do. Without Your light, I will be in darkness forever, Amen.

The financial assistance of the National Research Foundation (Thuthuka Grant for Emerging Researchers - TTK180416321199) towards this research is acknowledged. Opinions expressed in this thesis and the conclusions arrived at, are those of the author, and are not necessarily to be attributed to the National Research Foundation.

The financial assistance of the following funding sources at various stages of this project is also acknowledged:
The university’s Research and Innovation Fund for Teaching and Learning (RIFTAL) in 2017 to conduct the pilot study; the University Research Fund (URF) in 2018 to cover running expenses; and the University Capacity Development Grant’s Improvement of Qualifications Programme in 2019 towards replacement staff while on study leave.

DEDICATION

Mom, thank you for passing on the love for life-long learning.

Dad, thank you for showing me how to persevere.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

APPENDICES 152

LIST OF ABBREVIATIONS ACRONYMS

BSc: RT	Bachelor of Science in Radiation Therapy
CPUT	Cape Peninsula University of Technology
HEQC	Higher Education Qualification Committee
HPCSA	Health Professions Council of South Africa
HPE	Health Professions Education
ISL	Inverse Square Law
LCT	Legitimation Code Theory
MITS	Medical Imaging and Therapeutic Sciences
REC	Research Ethics Committee
RT	Radiation Therapy
RTP	Radiation Therapy Practice
RTT	Radiation Therapist
SAQA	South African Qualifications Authority
SD	Semantic density
SG	Semantic gravity
SLEs	Simulated Learning Environments
TCF	Threshold Concept Framework
VERT	Virtual Environment for Radiotherapy Training
UoT	University of Technology
WIL	Work-integrated Learning
WMA	World Medical Association

CLARIFICATION OF TERMS AND CONCEPTS

These are standard definitions commonly used in literature.

TERM/CONCEPT	DEFINITION/MEANING
Career-orientated programmes	Under graduate courses preparing graduates for a specific occupation, for example the radiation therapy profession.
Computer simulation	An event, process, or scenario that is created on a computer.
Discipline	A branch of knowledge – also referred to as 'field'.
Key concept	Also termed 'building block' or 'bread-and-butter' concepts in this thesis when referring to important, core or fundamental ideas and facts.
Knowledge	Theoretical or practical understanding and awareness of something.
Knowledge building	Accumulation of facts/information/understanding in a discipline.
Legitimation Code Theory	A framework for the study of knowledge and education (Legitimation Code Theory Glossary, 2019).
Planning working area	A sub-division in a Radiation Oncology department where besides others, treatment plans are developed and verified before a patient starts radiation therapy.
Professional education	An educational process or programme that develops individuals to acquire special competencies for professional practice.
Radiation Physics	The branch of physics that deals with the effect of ionising radiation on matter. In this thesis, the term is used when referring to a sub-field of Medical Physics referred to as a module within a subject as communicated in curriculum documents used in professional education programmes offered at higher education institutions.
Radiation Therapy	Also known as Radiotherapy - the treatment of disease, especially cancer, using X-rays or similar forms of radiation.
Radiation Therapy Practice	Where radiation therapy is administered and managed at a health facility by a qualified, multi-disciplinary team of health care professionals.
Subject	A branch of knowledge studied or taught in a school, college, or university – thus an academic subject.
Teaching	To impart and share information with the intention to build knowledge.

Threshold concept	A portal opening up a new and previously inaccessible way of thinking about something (Meyer & Land, 2003).
Treatment working area	A sub-division in a Radiation Oncology department where Radiation therapy is administered either using an external or internal delivery format.
Virtual Environment for Radiotherapy Training	A virtual environment of a radiotherapy treatment room.
Virtual clinical environment	A computer-generated simulation of a three-dimensional radiation therapy environment that can be interacted with in a seemingly real or physical way by a person using special electronic equipment.

CHAPTER ONE

INTRODUCTION AND ORIENTATION TO THE STUDY

1.1 Introduction

Over the last few years, there have been major changes in the radiation therapy profession globally. Practice is increasingly taking place in a fast paced technological environment. Advances in medical imaging and cancer management by use of sophisticated technology such as Computed Tomography, Magnetic Resonance Imaging and Oncology Management Systems have had a significant impact on radiation therapy practice (Baumann et al., 2016). Image-Guided Radiotherapy uses imaging techniques to track the location of the tumour and ensure that it is accurately targeted during each treatment (Verellen et al., 2007). The improved accuracy enables targeting of the tumour with higher doses, while sparing the nearby sensitive organs and tissue. These and other developments, such as the precision needed to accurately deliver Volumetric Arc Therapy and Stereotactic Radiosurgery have fundamentally changed radiation therapy practice, and thus have important implications for the training of radiation therapists.

Another major development is the expansion of the radiation therapists' scope of practice, especially in the United Kingdom, Australia and Canada, where they have become important decision makers in patient management (Matthews, Wright & Osborne, 2014; Harnett et al., 2014; Harnett et al., 2018). Such changes in the profession have resulted in the need for a different approach to the training of student radiation therapists, in order to prepare them adequately for the constantly transforming clinical environment, as well as for the expanding roles that they need to fulfil. The reality of the swiftly changing times that we live in, means students need to be prepared for the unknown, as some of what they have learned in their first year of study, might no longer be relevant to what they will be exposed to once they graduate. To equip practitioners for the rapidly changing workplace, students need powerful knowledge that will underpin new and evolving forms of practice (Wheelahan, 2012). Students need to understand the nature of the changing world of practice as they prepare to face the unknown future, and they also need to acquire forms of knowledge that will support their practice, regardless of technological advancement in the field (Muller, 2015). That is why the timeless concepts of radiation physics are important in the education of radiation therapists. The radiation physics component of the curriculum addresses the constant and known aspects of radiation therapy. Radiation physics therefore enables the student to conceptualise knowledge and build an understanding of important concepts for application, even in the unknown future context.

In the South African radiation therapy education context, a three-year National Diploma in Radiation Therapy that was a hospital-based, hands-on qualification, foregrounded the practical skills needed to work competently in clinical practice. In the light of the changes in technology and the scope of practice, a new qualification for radiation therapists was developed; a four-year Bachelor of Science degree in Radiation Therapy. Curriculum developers provided a strong rationale for why radiography training should move towards professional degrees. At the Cape Peninsula University of Technology, a Bachelor of Science was understood to be necessary for practice in the changing and challenging clinical environment. A Bachelor of Science degree must have a 50% generic science base; and it is this science base which is intended to support students in the ever-changing world of clinical practice. In contrast to the practice-based diploma, the new integrated curriculum of the Bachelor of Science programme focuses on the scientific knowledge that is needed to prepare graduates for treating cancer patients and providing quality, holistic patient care within a highly technologised environment. The new qualification foregrounds a solid understanding of the basic sciences that are the backbone of good patient care; if students do not understand the fundamental concepts on which technology-based clinical practice has been built, they will not be able to deliver quality patient care to each individual patient.

Students enrol for radiation therapy training because they are interested in caring for patients, and are often surprised when they find that the study of physics, and radiation physics in particular, is necessary to equip them with the knowledge base that will underpin their practice and ensure quality patient care. The requirements for entry into radiation therapy varies across universities and programmes. At the Cape Peninsula University of Technology, a prospective student is required to have passed Physics <u>or</u> Life Sciences [Biology] and Mathematics at school level. Physics is therefore not a prerequisite for the course. It is widely known that the South African schooling system poorly prepares the majority of students (Scott, 2018) for higher education. That same majority of students often struggle with the basic sciences at university (Muller, 2014) which are reflected in the assessment results and pass rates of the first assessment tasks. Knowledge of key concepts in mathematics and physics are assumed to be in place, an assumption which is problematic in a poor and unequal schooling system. Hudson, Engel-Hills and Winberg (2018) noted that solid knowledge of key and threshold concepts in radiation physics is challenging to students, but nevertheless forms an essential component of competence for efficient patient care.

The focus of this research is the challenging concepts in radiation physics, which comprise the scientific basis of the Bachelor of Science in Radiation Therapy. A solid scientific base in radiation physics is an essential component of not only quality patient care, and of preparing students for highly technological clinical environments, but also of preparing students for an unknown future.

This thesis argues that without a deep understanding and internalisation of what the literature refers to as challenging concepts in radiation physics, radiation therapists are unlikely to achieve the necessary level of accuracy and consistency in treatment. There are many concepts to be learned in radiation physics, such as sources and types of ionising radiation, ionisation and excitation, the Inverse Square Law, Electromagnetic Radiation, the electromagnetic spectrum, wave theory, properties of Electromagnetic Radiation, quantum theory, lasers and radiological quantities and SI units (Podgorsak, 2005). Within the list of concepts above, there are likely to be 'threshold concepts' (Meyer & Land, 2003; 2005; and Meyer, Land & Davies, 2006). Threshold concepts have been identified as concepts that pose challenges to students due to its complexity and the increased levels of cognitive challenge required to master a threshold concept. In the applied disciplines what sets threshold concepts apart from non-threshold concepts is their importance to professional knowledge, identity and competence, as well as their potential for opening the way for future learning possibilities (Meyer & Timmermans, 2016). This study thus aimed to address the overarching research question:

> What is the relationship between threshold concepts in the radiation physics curriculum and radiation therapy practice?

The overarching research question points to the need for a knowledge based conceptual framework for the study.

1.2 Focus on theory-based practice

The Bachelor of Science in Radiation Therapy qualification is registered with the South African Qualifications Authority and regulated by the Health Professions Council of South Africa. The qualification is required for employment in both the public and private health care sectors. Graduates from the programme are an integral part of a multi-disciplinary team providing a holistic health care service in general and a radiation therapy service to cancer patients in particular. In radiation therapy, practitioners have to be able to extract crucial information from their understanding of complex knowledge systems derived from subjects like General Physics, Radiation Physics, Human Biology and Computer Science (SAQA, 2018). It is therefore essential that undergraduate students understand and are able to apply concepts from these subjects to a variety of contexts in the multi-disciplinary clinical environment. To facilitate the transfer of knowledge, the programme is structured so that students are placed in clinical practice on a rotational basis throughout the academic year. The radiation physics module is currently taught using complementary pedagogical approaches such as web-based learning, small group tutorials, practicals, a virtual clinical environment, as well as traditional lectures. The science-based focus of the Bachelor of Science in Radiation Therapy qualification is intended to provide a solid scientific foundation for radiation therapy practice, not for the sake of science, but because of the need for competent and safe practice.

1.3 Focus on clinical practice

This study speaks to the professional education of radiation therapists, but the particular focus of the study is on first year radiation physics. The knowledge base of radiation therapy draws heavily from the professions of Oncology, Radiology, Medical Physics, and Nursing (Delwiche, 2013). Radiation therapy practice demands high levels of technical knowledge, drawing particularly from the disciplines of radiation physics and mathematics, together with a human component of the desire to work with patients and to be part of a multi-disciplinary health care team (Schneider-Kolsky, Wright & Baird, 2006). Selecting suitable candidates into a specialist health care programme such as the Bachelor of Science in Radiation Therapy can, therefore be difficult, as having an ability in physics and mathematics is but one of the essential requirements. Students must be able to understand abstract concepts and tend to the physical and psychological needs of the patient while setting technical parameters for safe and accurate treatment. Managing abstract thinking, emotional well-being and practising technical skills can be difficult for first year students who are not yet familiar with the concepts, environment or techniques. To overcome these difficulties and provide students an opportunity to be immersed in real-life situations, it is appropriate that the Bachelor of Science in Radiation Therapy is offered at a University of Technology. As learning institutions, Universities of Technology promote learning and create and produce knowledge in technical fields (Winberg, 2005); such knowledge should be ‘based on an understanding of technology, drawing on key concepts and principles of science…’ (2005: 46)

In the radiation therapy clinical environment, a quality treatment process requires highly competent health care professionals and high-technology equipment (Engel-Hills, 2009). Recently, Walsh and Craig (2016) confirmed that professionals need to keep up-to-date with new techniques and technologies in a rapidly changing clinical environment. The training of students studying to become qualified radiation therapists, therefore, needs to be up-to-date, reflecting the rapidly changing clinical environment. Alternative pedagogies are therefore continually sought to assist with the teaching and learning of difficult concepts, but also to familiarise students with technologies used in clinical practice. Such pedagogies need to complement and build the knowledge base and enhance the students' learning experience, but also develop their skills to transfer and apply knowledge in different contexts. In this technology-driven environment computer assisted teaching and learning has become an important component of professional education.

1.4 Structure of the thesis: Chapter outline

This chapter has outlined the real world problem addressed in this thesis, that is, the need to support new and increasingly technology-based practices with appropriate and powerful underpinning knowledge. It clarified the focus of the study, which is the first year radiation physics curriculum, with the over-arching guiding research question: What is the relationship between threshold concepts in the radiation physics curriculum and radiation therapy practice?

Chapter 2, *Literature Review and Conceptual Framework,* extends the focus by detailing the relevant literature reviewed in the fields of Threshold Concepts, Simulation-based teaching in Health Professions Education, and introduces the Virtual Environment for Radiotherapy Training (VERT) as a complementary educational tool. The chapter concludes by drawing on Maton's (2014) Semantics dimension of Legitimation Code Theory (LCT) to provide a conceptual framework for this inquiry.

Chapter 3, *Research Methodology: A Case Study of Radiation Physics,* presents a description of the features and influences of the case investigated. It provides a detailed account of the data generation and analysis methods. More detail is provided on the ethical considerations that underpinned this inquiry as well as the methods used to ensure continuous quality in the research process and data produced.

Chapter 4, *Languages of Description for Threshold Concepts,* introduces a revised external language of description as a bridge between LCT as the internal language of description and the empirical data.

Chapter 5, *Identifying Threshold Concepts in the First Year Radiation Physics Curriculum,* focuses on findings related to the radiation physics curriculum using data from the curriculum documents and the student participants. The revised external language of description offers a theorised description of the relative complexity of identifying threshold concepts in radiation physics, as well as the different stages of their acquisition.

Chapter 6, *Towards a Pedagogy for Threshold Concepts,* presents the findings of how first year students learned to understand, transfer and apply the threshold concepts that underpin radiation therapy practice. The voices of lecturers, clinical educators and student participants provided valuable insights to understand how these concepts are taught and learned. This chapter concludes with a summary of key pedagogies, one of which a virtual clinical environment, for threshold concepts in radiation physics.

Chapter 7, *Conclusion* provides a summary of the main research findings in relation to addressing the four sub-research questions and ultimately the main research question which informed this inquiry. Implications for theory, practice and the radiation physics curriculum are discussed and recommendations for future studies are offered.

CHAPTER TWO

LITERATURE REVIEW AND CONCEPTUAL FRAMEWORK

2.1 Introduction

Chapter Two reviews the literature on threshold concepts and provides a rationale for the conceptual framework that was drawn on to explain threshold concepts in radiation physics. There is limited literature on threshold concepts in radiation physics, thus the focus of the literature review is on threshold concepts in physics more generally. Because of the growing importance of the virtual environment in the teaching of physics, and radiation physics for radiation therapy in particular, the literature review also covers the literature on teaching physics in a virtual clinical environment. The chapter also addresses the threshold concept literature with regard to its implications for curriculum development and pedagogical approaches. These sections include an explanation of how the terms ‘curriculum’ and ‘pedagogy’ are used in this study. The chapter ends with an explanation of the Semantics dimension of Legitimation Code Theory (LCT), and a rationale for Semantics as a conceptual framework for the thesis. Semantics has the explanatory power needed to understand threshold concepts in radiation physics, as well as to explain the relationship between the underpinning knowledge of radiation physics and radiation therapy practice.

2.2 The Threshold Concept Framework

The Threshold Concept Framework is a classification of attributes that characterises highly complex concepts. The framework is intended for the study of complex concepts in disciplinary contexts. The idea of threshold concepts emerged from an education 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 mastery of their subject’ (Cousin, 2006a: 4). Meyer and Land (2003), described these concepts as ‘threshold’ because they were analogous to a doorway into the discipline. Meyer and Land (2003; 2005) and Meyer, Land and Davies (2006) extended the idea of the threshold concept into the Threshold Concept Framework to explain why certain concepts across disciplines pose particular challenges to students. Threshold concepts have implications for the facilitation of students’ mastery of the critical concepts found in most disciplines. The Threshold Concept Framework offers insights into why students might be experiencing difficulties in their learning. This is particularly important in the South African context where many students have the potential to excel in their studies, but are underprepared for higher education (Bradbury & Miller, 2011). For example, many school leavers find physics challenging, even though they might have achieved good marks in mathematics. This may partly be ascribed to the fact that many disadvantaged schools do not have adequate laboratories and the many other resources needed for the effective teaching of science (Cassidy, 2015). Such students would thus demonstrate the potential to succeed in a programme such as radiation therapy, but would need to be supported in the challenging context of radiation physics.

Cousin (2006a) notes that all disciplines have threshold concepts that are fundamental to that discipline, for example, a limit in mathematics (Meyer & Land, 2003; Scheja & Petterson, 2010) and atomic structure in physics (Park & Light, 2009). Understanding why students experience difficulties is the first step towards supporting them towards successful completion of their studies. The Threshold Concept Framework provides a structure through which lecturers can explore appropriate ways of modifying or redesigning existing pedagogical approaches so that students will be able to understand such concepts fully (Dunn, 2019) and, in the context of this study, apply them successfully in the workplace.

The Threshold Concept Framework continues to develop, with additional characteristics of threshold concepts recently added to the framework. For example, the 'discursive' dimension was a later addition to the Threshold Concept Framework to indicate that the crossing of a threshold concept would be likely to incorporate the academic discourse of the discipline (Meyer & Land, 2005). The framework has also changed since its inception in 2003, following on-going educational and professional practice research. It is important to note that not all concepts are threshold concepts. To fit into the Threshold Concept Framework, concepts need to have certain features in common. The list below is adapted from Cousin (2010):

- Troublesome – Perkins (2006) refers to threshold concepts as 'troublesome knowledge' which is 'counter-intuitive, alien or seemingly incoherent' (2006);
- Bounded – the more discipline-specific the concept, the more complex it is to understand and explain to new students, particularly if they are entering a discipline for the first time;
- Integrative – threshold concepts make connections between other concepts; for students this realisation is often referred to as a 'light-bulb' or 'a-ha' moment; threshold concepts in the applied disciplines that are essential building blocks for

practice can be seen as integrated with practice concepts (Hudson, Engel-Hills & Winberg, 2018);

- Irreversible – once understood, one is unlikely to forget a threshold concept. It is very difficult for lecturers, who are often experts, to teach these concepts to novice (especially first-year) students. In first year subjects the threshold concepts are often the building blocks needed for further conceptual development;
- Transformative – 'we are what we know' – Cousin (2010) argues that acquiring the new knowledge and understanding presented by threshold concepts can transform one's sense of being;
- Discursive – the crossing of a threshold concept will incorporate the appropriate academic discourse for the discipline;
- Reconstitutive – when a student understands a threshold concept, there is a shift in identity – which is initially more likely to be noted by people other than the student;
- Liminality – also referred to as 'rite of passage', where the student negotiates a transitional space to master the threshold concept. Cousin (2006a) notes this often "involves messy journeys" back and forth and across conceptual fields.

As suggested by the descriptors above, the term 'threshold concepts' refers to those crucial points in learning that form the building blocks of each academic subject, but which are challenging moments in the process of learning – particularly when learning ever more complex concepts, or applying concepts to different contexts. However, once the threshold concepts are understood, it is difficult to un-learn them. Threshold concepts are multi-layered, that is, they are often underpinned by more than one concept and each must be accurately understood in order to enable progress in the discipline or be applied in practice. In the case of professional disciplines, without an understanding of threshold concepts students might have significant gaps in their understanding and be unable to apply or transfer the important concepts that underpin effective practice (Tanner, 2011). Threshold concepts are often termed interchangeably as 'fundamental', 'core' or 'must-know' concepts; but threshold concepts are distinguished from other concepts by their complexity, their high level of abstraction, and their centrality in the discipline.

2.3 Threshold Concepts in Physics

The focus of this study is on threshold concepts in radiation physics, however there is very limited literature on threshold concepts in radiation physics (Hudson, Engel-Hills & Winberg, 2018). In fact, there is not a large body of educational literature on radiation physics. Much of the literature on radiation physics focuses on quality assurance (see e.g. Rosca et al., 2006).

For this reason, the focus of the literature review is on threshold concepts in physics more generally.

A key difficulty for learning threshold concepts in physics is that on first encounter many concepts seem ‘counter-intuitive, alien or seemingly incoherent’ (Perkins 2006). Studies have shown that students find physics a difficult subject to learn as the entities involved (i.e., atoms, molecules, ions), and the interactions of these entities, are ‘aperceptual’ (Tan et al., 2008).

A number of studies have identified threshold concepts in general physics that have relevance for radiation physics. ‘Probability’ and ‘energy quantisation’ were identified as threshold concepts for understanding atomic structure as scientific models (Park & Light, 2009) while ‘electronic transition’ and ‘photon energy’ were identified as threshold concepts for students’ scientific understanding of atomic spectra (Körhasan & Wang, 2016). These general physics concepts were identified as threshold concepts because of their importance for enabling progression towards more advanced concepts. However, Wolfson and colleagues argue that transferring general physics concepts to more specialised fields of study (e.g., BioPhysics) is not helpful for identifying threshold concepts specific to these fields (Wolfson, Rowland, Lawrie & Wright, 2014). This is the case in radiation physics which has its own set of threshold concepts. While most health care professionals need to understand the importance of radiation protection, for example in Dentistry (Crane & Abbott, 2016), General Clinical Practice (Hamid et al., 2016), or in Emergency Medical Care (Ditkofsky et al., 2016), few of the clinical health sciences focus as much attention on radiation physics as radiation therapy.

2.4 Threshold Concepts and Curriculum

Threshold concepts are an attempt to understand the challenges that disciplinary content poses to lecturers and students (Cousin, 2006). The literature on threshold concepts thus signals an important development in higher education studies and a shift away from ‘constructive alignment’ (Biggs, 1996), that is the focus on the relationships between curricular outcomes and student learning. Threshold concepts focus on the roles of lecturers and students in the mastery of disciplinary content. Thus threshold concepts signal a shift from outcomes (or the end points of a course of study) to disciplinary knowledge and the need for both lecturers and students to engage with knowledge. The Threshold Concept Framework addresses the key issue of what makes a discipline difficult to learn and challenging to teach (see e.g. Male & Bennett, 2015).

Before threshold concepts as curricular elements are addressed, it is necessary to explain different understandings of curriculum and different approaches to curriculum design and development.

2.4.1 Definitions and Conceptions of 'Curriculum'

Many definitions of curriculum exist in the educational literature; these different definitions often reveal different understandings about what a curriculum is. Some educational scholars understand the term 'curriculum' in relation to a qualification, while other understand curriculum at the level of subject or discipline (Van den Akker, 2004). Differentiation of the terms according to level implies different understandings with regard to curricular activities such as curriculum policy development, curriculum design, curriculum review, implementation and evaluation (Van den Akker, 2004). The etymological origin of the term compares a curriculum to a path or journey to be undertaken:

> The term curriculum is of Latin origin, and it comes to us through the Old French verb *currere* meaning 'to run'. Related terms include current, currency, and courier. Translated into English, curriculum means, roughly, a course, as in a running course. Over time … it has come to signify a course of study (Ellis, 2006: 3).

A common understanding of curriculum in the literature is to view it as a course or 'plan for learning' (Taba, 2013). The problem with a 'common sense' definition, such as Taba's (2013), is that the components of the curriculum are not specified and therefore unclear. The lack of specificity about curriculum has resulted in extremely broad interpretations of what a curriculum is, such as the following definition:

> All the learning which is planned or guided by the school, whether it is carried on in groups or individually inside or outside the school (Kerr, 1968).

The broadness of the above definition is unhelpful when trying to understand curricular elements, such as threshold concepts. This is also a difficulty in definitions of curriculum that only take into account the end point of a curriculum, as in outcomes-based education. In conflating outcomes and curriculum, the idea of a curriculum as a 'plan of learning' which includes inputs and as well as outcomes is lost:

> Outcomes make explicit what learners should attend to. Outcomes assess towards specified goals. Outcomes signal what is worth learning in a content-heavy curriculum. Outcomes can be a measure of accountability, i.e. a means of evaluating the quality and impact of teaching in a specific school (Jansen, 1998: 2).

While outcomes, as the passage above suggests, can be helpful, leaving out the course of the educational journey, the 'plan of learning', is potentially restrictive of students' development, particular with regard to enabling students to grasp complex concepts.

Ellis (2006) suggests that there are two fundamental approaches to curriculum, namely curriculum as 'prescription' (or content) and curriculum as 'experience'. A process approach to curriculum exemplifies curriculum as 'experience', or:

> … a concern for coherence manifested through attention to processes, messages, and the quality of communities and environments (Knight, 2001: 379).

A process approach has been offered as an alternative to outcomes-based curriculum planning, emphasising

> …those transactions and interactions that take place between students and teachers and among students with the intent that learning take place (Bevis, 1989: 72).

The 'prescription' or content-based approach and 'experiential' or process-based approach to curriculum have been described in different ways:

> Curriculum can be differentiated into the intended and the enacted. The former refers to the curriculum structure and design, the latter to how that design is implemented and its effects on learning and learners (Shay, Wolff and Clarence-Fincham, 2016).

Shay and colleagues (2016) argue that the focus of much curricular research has been on a process-oriented view of curriculum, that is, 'on the learning and teaching that is enacted through a particular curriculum experience' (Shay et al., 2016) while less attention has been given to curriculum content and structure. This thesis has a particular focus on curriculum content, in the form of threshold concepts in first year radiation physics, and draws on Bernstein's (1977) distinction between curriculum, pedagogy and assessment:

> Curriculum defines what counts as valid knowledge, pedagogy defines what counts as a valid transmission of knowledge, and evaluation[1] defines what counts as a valid realization of this knowledge on the part of the taught (Bernstein, 1977: 76).

By the term 'curriculum' Bernstein refers to 'the principles governing the selection of, and relation between, subjects' (Bernstein, 1977: 61). In addition to the principle of 'selection' and 'relations between subjects', Bernstein also points to the 'organization, pacing and timing of the knowledge transmitted and received in the pedagogical relationship' (Bernstein, 1977: 80). The 'selection, organization, pacing and timing of knowledge realized in the pedagogical frame' (Bernstein, 1977: 89) are key elements of a curriculum. There is a difference between radiation physics as a body of knowledge and the kind of radiation physics found in a first year physics curriculum. It is the human interventions of selection, sequencing and pacing that create key differences between the body of knowledge known as radiation physics and the ways in which radiation physics is represented in a curriculum, in this case, a curriculum for radiation therapists:

> This process of selection, abstraction and re-focusing leads to re-contextualizing. At this level, the activities, meanings and social relationships, their inter-relationships, their sequencing, their evaluation and above all their relation to the procedures and performances acquired through primary contextualizing are a function of the code underlying the process of re-contextualizing (Bernstein, 1977: 29).

Radiation physics is recontextualised into radiation physics for radiation therapists in a process that involves a 'selective organization, transmission and evaluation of knowledge' (Bernstein, 1977:73). Bernstein's (1977) inclusion of assessment as a curricular element emphasises the idea that what is selected for curricular inclusion is valued by curriculum developers, what is assessed as evidence of learning is what is valued by the educators.

[1] In South Africa, 'evaluation' is more often termed 'assessment'.

2.4.2 Threshold Concepts as an Element of the Curriculum

There are many threshold concepts in the curricula of programmes offered at higher education institutions. In the sections below understandings of threshold concepts as curricular elements are explained.

'Jewels in the curriculum'

Land, Cousin, Meyer and Davies, (2005) refer to the difficult concepts in the curriculum as the 'jewels' of the curriculum because, once mastered, they open up new ways of understanding and thinking in the discipline. Cousin (2006b:198) argues that threshold concepts define 'potentially powerful transformative points in the student's learning experience'. When lecturers focus on the 'jewels of the curriculum': this enables students to develop

> richer and more complex insights into aspects of the subjects students are studying; it plays a diagnostic role in alerting tutors to areas of the curriculum where students are likely to encounter troublesome knowledge and experience conceptual difficulty (Cousin, 2006b:198).

Cousin (2006a) points out that it is important to address the curricular jewels in curriculum design. The complex nature of threshold concepts needs to be considered with regard to the sequencing of the curriculum and the allocation of sufficient time to allow in depth engagement with threshold concepts.

Avoiding a content-heavy curriculum

Many curricula are over-loaded with topics. Cousin (2006a) proposes that a focus on threshold concepts will help lecturers and other curriculum developers to make informed decisions about curricular selection:

> a focus on threshold concepts enables teachers to make refined decisions about what is fundamental to a grasp of the subject they are teaching. It is a 'less is more' approach to curriculum design (Cousin, 2006a:4).

Ontological as well as epistemological shifts

While threshold concepts are more closely associated with epistemological shifts, that is, a dramatic increase in the understanding of disciplinary content; threshold concepts also impact on identity formation and students' sense of belonging to a particular disciplinary community. These shifts are not easily attained. Dunn (2019:37) points out that students' encounters with threshold concepts pose 'a degree of cognitive and affective challenge which serves to exacerbate the difficulty of transition already caused by increased workload and pressure'. The findings offer insights into students' struggles to adjust to shifting identity and membership of communities which is further intensified by the integrative, discursive and transformative nature of threshold concept acquisition. Cousin (2010) explains that 'New understandings are assimilated into our biography, becoming part of who we are, how we see, and how we feel' (Cousin, 2010:2).

Threshold concepts in professional education

In professional education, threshold concepts encapsulate the essential subject knowledge of the course of study that underpin professional practice (Baillie, Bowden, & Meyer, 2013). Thus competent practice has been associated with mastery of threshold concepts in the disciplines associated with particular fields of practice, including the ability to apply these in practice (Dunn, 2019). Much of the literature on threshold concepts in the health sciences relates to concepts underpinning care (Neve, Lloyd & Collett, 2017; Clouder, 2005), general professionalism (Kinchin, Cabot & Hay, 2010), or concepts in the disciplines that are common across health professions, such as anatomy, and physiology (Weurlander et al., 2016). Interprofessionality 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, in the language of the Threshold Concept Framework, if students fail to traverse the liminal space, they will only be able to perform in a 'ritualised manner'. Fredholm and colleagues point out that practical experiences in the clinical environment have a similar effect as 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).

Central to the Threshold Concept Framework is the idea that students overcome obstacles by learning how to integrate and apply knowledge and, by doing so, they transform their level of understanding and ability to engage with the increasing complexity of concepts (Yorke, 2013). In the next section, the focus is on how pedagogies might facilitate students' attainment of threshold concepts.

2.5 Threshold Concepts and Pedagogy

Wilson et al., (2010:99) observe that it is vital to 'clarify the troublesome and path-blocking nature of threshold concepts'. Once a threshold concept has been identified, the next step is how to teach it – understanding that supporting students across the 'threshold' will be challenging (Ballie, Bowden & Meyer, 2013). To explain the concept of ionisation, for example, lecturers have developed tools and pedagogical approaches that 'afford certain ways of thinking and talking about underlying entities and processes' (Schank & Kozma, 2002:256). Without a specific and focussed pedagogy for teaching threshold concepts in physics, for example, students are likely to experience difficulties when they are required 'to shift between the macroscopic, microscopic, and symbolic/algebraic representational systems to understand concepts … and to engage in … reasoning' (Tan et al., 2008).

Meyer and Land (2003) suggest that variation theory provides a basis for developing a pedagogy for threshold concepts. The variation theory of learning proposes ways 'to increase the amount of critical aspects and features a learner can discern and be focused on simultaneously' (Marton, 2014:60). Marton argues that the learning process is fundamentally about moving from one way of understanding to another more powerful way (Marton, 2014). With regard to threshold concepts in physics, Moore (2012) suggests that students need to be taken from a 'concrete operational' stage of understanding to an 'abstract reasoning' level. The terms 'concrete reasoning' and 'abstract reasoning' derive from Piaget's cognitive levels, which include a transitional stage between the two (Inhelder & Piaget, 1958). Students described as mostly 'concrete operational' tend to experience difficulties when solving problems outside of a concrete context (Moore, 2012), while formal operational reasoners are able to think abstractly and reason logically. Formal operational reasoners 'can begin to think like a scientist, and specifically develop strong hypothetico-deductive reasoning' (Moore, 2012:3). Transitional reasoners fall between the other two types and can successful engage with some hypothetical tasks in some contexts. With regard to a pedagogy for transitional learners, Moore (2012) reports that:

> Through the incorporation of context-rich activities, authentic research experiences, and explicit interventions on reasoning patterns, we have been able to increase gains in student scientific reasoning abilities as well as transition students from transitional reasoners to more formal operational reasoners (Moore, 2012: 3).

Additional pedagogies for threshold concepts include peer learning:

> … the key result of Physics Education Research is that students learn best by interacting with their peers while working with conceptually-based activities using a guided-discovery model of instruction … We believe that these same strategies can be easily modified for fields other than Physics that confront their students with troublesome knowledge and threshold concepts (Harrison & Serbanescu, 2017:357-358).

Peer-learning has a long tradition in science education and was popularised by Mazur and colleagues in physics as 'peer instruction' (Crouch, Watkins, Fagen & Mazur, 2007). Peer instruction, and the associated 'flipped classroom' has become a signature pedagogy for physics education.

Because threshold concepts are challenging, studies point out that repetition and practice are needed before the concepts can be fully understood:

> Our study pointed out that transformative thinking needed to pass a threshold in Physics is acquired in many cases by repetition (recursiveness). We identified a horizontal direction in recursiveness (courses taken in the same year of study) as well as a vertical direction (courses from different years) (Serbanescu, 2017).

The pedagogies described above are intended to support students in coping with the high level of difficulty that threshold concepts in physics represent. Most of the pedagogies have the intention to simplify the concepts (at least initially) in order to scaffold students' transition across the thresholds. The work on troublesome knowledge by Perkins (1999) suggests that when lecturers over-simplify a threshold concept in order to make it easier for students, they can cause additional difficulties for students later on as students will have to re-learn more basic principles when they have to deal with the full complexity of the threshold concept. Simplification on its own is not a good pedagogy as the critical features of the threshold concept have to be dealt with (Baillie, Bowden & Meyer, 2013).

Threshold concepts are associated with 'troublesome language' (Cousin, 2010). Scientific discourses have developed within disciplines to represent complex disciplinary concepts, and these can be troublesome for the newcomer, especially if the terms used also have every day, 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 2006a: 5). Tan and colleagues (2019) warn that lecturers need to be careful with their use of ‘anthropomorphic language’ when discussing ionisation energy. Lecturers should require students to use the correct academic or technical language. Lecturers should consistently demonstrate the correct and technical language in their presentations and conversations with students (Tan et al., 2019).

In preparing to teach threshold concepts, lecturers need to focus on the problematic aspects and find ways to link the unfamiliar with the more familiar (Baillie et al., 2013). 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).

Prior research has built a knowledge base of effective undergraduate physics pedagogies such as thinking through problems with peers (Watkins & Mazur, 2013), the use of practical or workplace examples (Nerland & Jensen, 2014), making assessment practices more transparent (Wolff & Hoffman 2014), socially inclusive pedagogies (Killpack & Melón, 2016) and the ‘mainstreaming’ of student support mechanisms, such as academic and technical literacies (Airey & Linder, 2009; Shay, Wolff & Clarence-Fincham, 2016). The effectiveness of these pedagogies for undergraduate student success in physics has been verified through systematic reviews of the research literature (e.g., Savelsbergh et al., 2016). An important pedagogy in the health sciences is learning in a simulated clinical environment. It is this pedagogy that is examined in the next sub-section.

2.5.1 Simulation in learning physics concepts

The Society for Simulation in Healthcare has an active working group attempting to streamline definitions and differentiating the terminology used in highly technical computer related programmes from those used in the healthcare settings (Lopreiato et al., 2016). The focus of this sub-section of the review will be on computer-based simulation where real life processes are modelled using a computer and/or a modified learning environment. Motola et al. (2013) note the exponential and enthusiastic adoption of simulation-based education in healthcare education over the last two decades, drawing on lessons learnt from established non-medical fields such as commercial aviation, the military and space exploration. Clinical lecturers are now faced with a plethora of equipment and software packages designed to teach an ever-increasing number of basic and advanced technical and clinical skills (Burch, 2014).

According to Alessi and Trollip (2003), simulation is an increasingly popular method for learning anything. The authors classify procedural and situational simulations as ‘how-to-do-something’ simulations (2003:214) which are used in health professions education to teach cognitive, psychomotor, procedural and affective skills to students before they enter clinical practice. The rationale for the educational use of simulation to train students in most undergraduate healthcare programmes have been documented (Motola et al., 2013; Bradley, 2006; Gaba, 2004; Good, 2003) and range from increased demands on training hours, limited patient encounters, increased patient numbers in understaffed settings, a focus on patient and trainee safety, to medico-legal consequences of procedural errors and the need for a safe learning environment where errors could be made.

In a report to the Australian government regarding the use of simulated-learning environments in Radiation Science (referred to as Radiography), Thoirs, Giles and Barber (2011) argued for the use of these environments to substitute clinical days as activities where simulation could be used to focus on clinical or technical competencies. Radiation physics concepts were not explicitly identified, however, the building blocks for activities such as quality control, image interpretation and image manipulation were reported (Thoirs, Giles, & Barber, 2011). Students find most concepts in radiation physics challenging, but it is a key underpinning learning module for both theory and practice in the radiation therapy discipline. Radiation physics education includes teaching abstract concepts to students that are traditionally taught through text, numerical symbols, diagrams, examples, and laboratory or clinical-practice based practicals. Alternative methods of teaching and learning the subject are often explored, and immersing students in virtual worlds is increasingly being used by lecturers as an alternative pedagogy to bring such abstract concepts to life.

In order to reach abstract thinking and critical reflection, simulations are potentially useful in the teaching and learning processes at the basic university level. However, adequate didactic strategies are required to use these resources (Concari et al., 2006). This serves as a motivation to further explore and match the appropriate simulations with concepts that students find difficult to understand and transfer to the clinical setting.

2.5.2 Simulation in teaching and learning radiation physics concepts

With the demands of both the radiation therapy profession and higher education constantly changing, there is a continuous need to re-evaluate teaching and assessment practices. In order to provide the students with rich learning experiences, their competencies should be assessed against set professional criteria (Flinton, 2013). Student radiation therapists need to acquire a wide range of patient care and technical skills for the benefit of their patients. The underpinning threshold concepts of radiation physics are difficult because they are not in students' practical experiences in the clinical environment. The literature supports a wide-ranging blended learning approach, combining real-world technology with hybrid virtual radiotherapy systems, such as the Virtual Environment for Radiotherapy Training (VERT) (Beavis & Ward, 2014). Such systems have been used to enhance student learning and provide an engaging, safe and effective environment for learning (Kirby, 2015).

Flinton (2013) contested the use of VERT as a measure of radiation therapy competence, but agreed that it was effective as a training tool, provided that final assessments were conducted on the actual treatment unit. However, the simulated learning environment is a realistic environment to enhance understanding of radiation physics concepts (Beavis & Ward, 2012). Flinton (2013) notes that "visualisation of the isocentre concept is a relatively trivial demonstration to provide, but is extremely effective in discussions with early career professionals, especially for the subset of trainees who find it particularly challenging to understand" (Flinton, 2013:2). The author notes that the software package was designed to give lecturers a tool for explaining concepts and process issues which were vastly superior to using slides or white-boards. He also warns that computer simulation training is not expected nor intended to replace practical experiential training, however it most certainly provides the opportunity to understand a wide spectrum of error conditions and their implications in a compressed time frame, which is confirmed by Beavis and Ward (2014) that simulation training can be used to demonstrate the basic concepts, processes, and work-flow of radiation therapy effectively.

The VERT training package includes Medical Physics 'equipment and accessories' software which is needed to do quality control tests in radiation therapy practice. This extension is called 'VERT Physics' and can also be used to demonstrate 'basic level' concepts such as the isocentre and beam divergence. It is important to note that these concepts are referred to as 'basic level' concepts for qualified staff, but threshold concepts for undergraduate students. With the VERT Physics software package, threshold concepts such as the isocentre, beam divergence, and the Inverse Square Law could be demonstrated efficiently and effectively (Beavis & Ward, 2012).

Other features of the VERT software package include a three-dimensional (3D) effect to get a better visual understanding of the dose distribution, consideration for organs at risk and therefore an improved understanding of the patient's side effect profile. Osterhölm, Framholt and Nordentoft (2010), reported that students experienced their training as less pressured when they learned in a 'patient free' environment. Osterhölm et al. (2010) also note that the students' understanding of the clinical techniques improved as they could see the inside of the patient and relate it to critical structures and 3D anatomy of the patient.

2.6 Critiques of the Threshold Concept Framework

The literature on threshold concepts includes several critiques of the framework from a number of perspectives. The Threshold Concept Framework has been debated in the literature and its theoretical inconsistencies have been pointed out (e.g., Barradell, 2013). Researchers have pointed out that the terms used to describe the characteristics of threshold concepts are subjective and difficult to measure as they are neither precise nor measurable (Nicola-Richmond, Pėpin, Larkin & Taylor, 2018). Rowbottom (2007) contests the Threshold Concept Framework by claiming that thresholds are 'unidentifiable'. Walker (2013), in her critique of the Threshold Concept Framework, suggests that the framework is a cognitive framework, rather than a framework for describing concepts; she notes 'a great deal of conceptual overlap between schemas and threshold concepts' (Walker, 2013: 251). In other words, the Threshold Concept Framework has conflated the process of learning threshold concepts, which is characterised by confusion and frustration, with the threshold concepts themselves. These critiques of the Threshold Concept Framework do not imply that the framework is not useful, but they do imply that the Threshold Concept Framework might need to be strengthened, in particular, to avoid the conflation of learning and knowledge, and in order to attain rigorous conceptual clarity. A conceptual framework was therefore developed for this study with the intention of providing better explanatory power for understanding threshold concepts in radiation physics.

The identification of threshold concepts should not be subjective. Lecturers (as subject experts and because they are experienced in teaching key concepts in a discipline) play an important role in the identification of threshold concepts. Meyer and Land (2005) point out that lecturers have moved beyond threshold concepts, and find it difficult to teach what are now familiar concepts to them, to students. This challenge exists and, as Wilson et al. (2010) observe, a threshold concept is no longer challenging to those who have crossed the threshold. Lecturers have to remember the particular challenges that they experienced to identify potential 'troublesomeness' for students. Thus, to ensure the accurate identification of threshold concepts, there is a need for a partnership between subject lecturers, educational researchers and students. Cousin (2009:202) calls this partnership a 'Transactional Curriculum Inquiry", referring to the kinds of negotiations involved between key role players in pursuit of shared understanding of difficulties and shared ways of mastering them.

2.7 Conceptual Framework

This section provides an overview of how Legitimation Code Theory was used as both an organising and analytical framework to make sense of threshold concepts in first year radiation physics.

2.7.1 What is Legitimation Code Theory?

Legitimation Code Theory (LCT) is a sociological framework that seeks to understand the underpinning principles of how knowledge is built in disciplines, how knowledge is learned in classrooms (theory-based practice), and how knowledge is applied and developed in clinical practice. LCT was developed by Karl Maton (2000) and builds on Pierre Bourdieu's field theory (Bourdieu, 1993) and Basil Bernstein's code theory (Bernstein, 1977; 2000). It is underpinned by a Social Realist approach that understands that knowledge is 'real', that is, it has generative properties. Social Realism acknowledges the power of knowledge structures and cultures and, equally, affirms the powers of human agency and creativity (Elder-Vass, 2010). Structural and cultural contexts can support or constrain the achievement of teaching and learning, but it is how lecturers and students respond to these constraints and enablements of knowledge structures and types that can produce structural, cultural and personal transformation. An analysis of legitimation codes explores 'what is possible for whom, when, where and how, and who is able to define these possibilities, when, where and how' (Maton, 2014:18). LCT is increasingly being used as a primary framework to analyse the legitimation codes that enable or constrain knowledge building in education contexts. In this sense it is able to reveal the 'rules of the game' in different disciplines and fields by making the basis of success of teaching and learning explicit (Maton, Hood & Shay, 2016). This has important implications for higher education lecturers, as these 'rules' can then be taught and learned more explicitly, and they can be challenged and changed. LCT is multi-dimensional, offering a variety of concepts and tools to analyse practices. Each dimension explores one set of organising principles of dispositions, practices and fields, conceptualised in LCT as legitimation codes.

Since this fairly young theory emerged in the 2000s, it has grown rapidly especially after its first international conference held in 2015. Martin (2017: 27) attributes this growth to the way 'LCT combines theoretical rigour with concrete implications for practice, [which] is proving particularly attractive to scholars and lecturers in places traditionally marginalised or viewed as lower status'. The theory first emerged as a framework to study knowledge and education, and is now being used to theorise and analyse a growing range of practices across various disciplines, including education, law, politics, physics, art and science (Legitimationtheory.com, 2019).

The diversity of its application is one of the core strengths of LCT, enabling studies from different disciplines addressing a wide variety of problems, to build on one another – thus enabling cumulative knowledge building across disciplines. The South African based community of LCT scholars and studies is also growing and addressing educational concerns ranging from feedback on student writing (Van Heerden, Clarence & Bharuthram, 2017), and academic literacies in physics education (Conana, Marshall & Case, 2016) to providing insights into problem-solving in engineering (Wolff, 2018). A more extensive and ever-growing list of LCT-based studies can be found on the LCT website (http://www.legitimationcodetheory.com).

2.7.2 Why Legitimation Code Theory?

LCT has a specific focus on knowledge, knowledge building and knowledge application. A more common theoretical framework in many educational studies is social constructivist theory (e.g., Biggs & Tang, 2011), which explains the importance of students' active engagement in the learning process, and which has been very influential in university pedagogy. However, the strong emphasis that constructivist theories place on the student and the nature of the learning, means that the complexity of the concepts and topics to be learned in scientific disciplines, such as physics, are underestimated (Shumba, Ndofirepi & Gwirayi, 2012). Teaching and learning radiation physics is underpinned by conceptual knowledge and involves students in knowledge building and knowledge application. This study therefore draws on the explanatory power of Legitimation Code Theory (LCT), as an appropriate theoretical framework to study the knowledge rich field of radiation physics teaching and learning in higher education.

2.7.3 The Semantic Dimension

LCT offers many 'tools' for the analysis of knowledge practices. In this study the dimension of Semantics (Maton, 2014) was drawn on to analyse how threshold concepts in radiation physics were enacted not only in the curriculum but also in pedagogies to facilitate competent and safe clinical practice.

Semantics describes knowledge in terms of its organising principles (Maton, 2016). The key concepts used in Semantics are semantic gravity (SG) and semantic density (SD). Semantic gravity is defined as the extent to which meaning 'is related to its context of acquisition or use' (Maton, 2016: 242); the stronger the semantic gravity, the more context-dependent the knowledge will be; the weaker the semantic gravity, the more context-independent and abstract the knowledge will be. Semantic density refers to the complexity of the knowledge. The stronger the semantic density, the more complex the concepts will be, typically as a result of condensing many meanings into increasingly complex concepts. The weaker the semantic density, the less complex concepts will be. When varying strengths of semantic gravity and semantic density are combined on a semantic plane, four semantic codes are generated. These are illustrated in Figure 2.1.

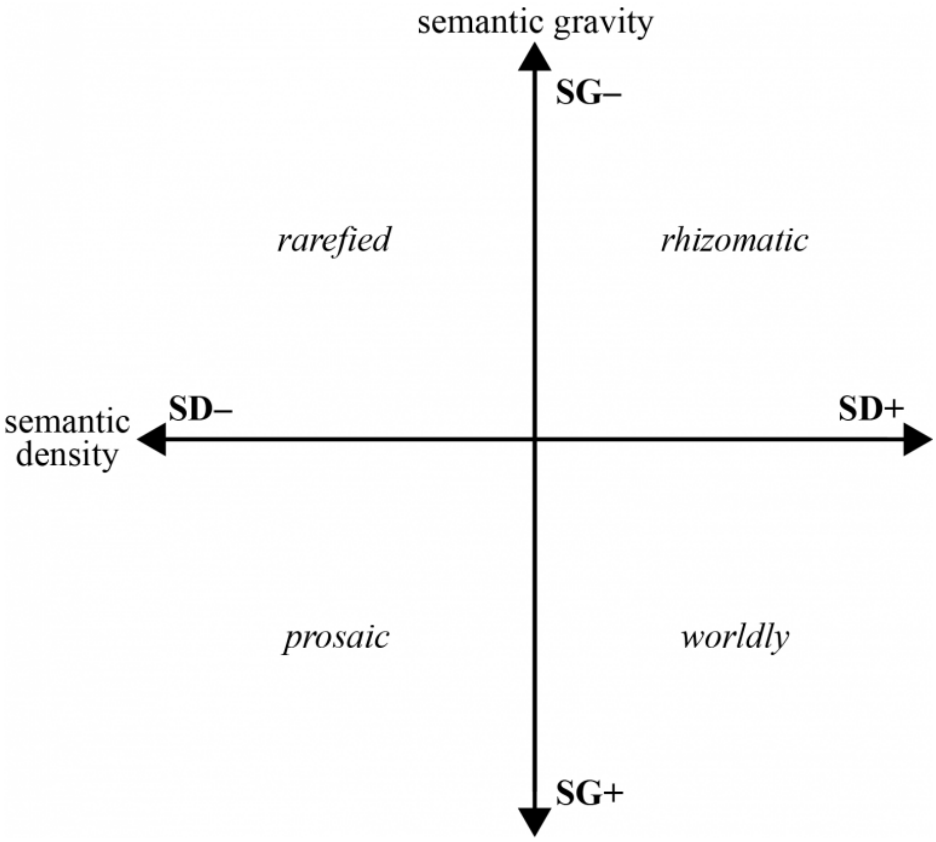


Figure 2.1 The Semantic plane (Maton, 2014: 131)

Semantic codes are useful for understanding and analysing how contextual dependence and conceptual complexity are evidenced in different knowledge forms and in knowledge based practice. Maton (2016) summarises these principal modalities as follows:

- *rhizomatic codes* (SG–, SD+), where the basis of achievement comprises relatively context-independent and complex stances;
- *prosaic codes* (SG+, SD–), where legitimacy accrues to relatively context-dependent and simpler stances;
- *rarefied codes* (SG–, SD–), where legitimacy is based on relatively context-independent stances that condense fewer meanings; and
- *worldly codes* (SG+, SD+), where legitimacy is accorded to relatively context-dependent stances that condense manifold meanings (Maton, 2016: 16).

Semantic codes represent a set of organising principles that underpin knowledge structures and practices. Once these codes have been revealed through analysis, the movements of knowledge practices across the semantic range can then be mapped using semantic profiles. Profiling is a useful analytical tool for showing shifts in practices over time.

2.7.4 Why Semantics?

Radiation physics is the applied science that underpins radiation therapy practice. Concepts from the LCT's Semantics dimension provide useful tools for thinking about radiation physics knowledge structure and practices. For Bernstein, physics epitomised a hierarchical knowledge structure; which he described as comprising a 'coherent, explicit and systematically principled structure, hierarchically organised' (Bernstein, 2000: 160). Bernstein describes horizontal knowledge structures as 'a set of strategies which are local, segmentally organised, context specific and dependent' (2000, 158). Maton suggests that the descriptors 'vertical' and 'horizontal' are 'ideal types' and that most disciplines and fields comprise varying degrees of both vertical and horizontal knowledge structures (2009: 45). In the context of this thesis, the knowledge structures of radiation can be described as 'hierarchical' (Bernstein, 2000: 158) or 'vertical' (2000: 157) because the concepts build on one another. For example, one cannot understand the concept of ionising radiation without first understanding the concept of radiation classification, which in turn is built on the concept of the atom, and so on.

Bernstein referred to disciplinary fields, such as physics, as 'singulars', in contrast to 'regions', a term he used to refer to disciplines that are based on the conceptual logic of singulars, but that face externally towards the field of practice. Radiation physics, usually described as a 'applied discipline' (Khan & Gibbons, 2014), could also be described as a 'region'. While radiation physics derives its internal logic from physics, it is applied to guide practice in fields such as medical physics and radiation therapy. Shay (2013) argues that while ‘singulars’ and ‘regions’ are useful starting points, these ‘types’ have been ‘over-dichotomized’ (2013: 6). The semantic plane (Figure 2.1) offers continua that allow for possibilities and varieties of verticality in horizontal knowledge structures, as well as horizontality in vertical knowledge structures.

Semantic density refers to the extent to which meaning is concentrated or condensed within symbols (a term, concept, phrase, expression, gesture, etc.) (Maton, 2014). Radiation physics has stronger semantic density (SD+), because meaning is condensed within the nominalisations and multiple representations (graphical, symbolic, diagrammatic, mathematical, etc.) that characterise the field. Defining the nature of semantic density in radiation physics makes visible its hierarchical knowledge structures. For example, the concept of the Inverse Square Law assumes knowledge of a number of underlying concepts and principles, such as geometric progression and Coulomb’s Law. Radiation physics contains many abstract, decontextualised concepts and principles that have a weaker semantic gravity (SG-); in such cases meaning is less dependent on its context. In radiation therapy, the abstract principles are applied to a variety of specific contexts, with stronger semantic gravity (SG+). For example, the explanatory power of an abstract physics concept, such ‘ionisation’, can be applied to dosimetry.

In a discipline such as physics, semantic gravity and semantic density often tend to be inversely related on a semantic continuum (Conana, Marshall & Case, 2020). Abstract, decontextualised concepts have weaker semantic gravity, but tend to be represented in condensed symbolic form, with stronger semantic density. For example, Newton’s Second Law has weaker semantic gravity, ‘being an abstract and generic principle, holding for all physical situations that are possible in the everyday world’ (Conana et al., 2020: 171), but has stronger semantic density, as it condenses meanings and prior concepts.

Radiation physics can be simplified in pedagogy, such as using a can of spray paint to illustrate the principle of the Inverse Square Law, thus weakening the semantic density and strengthening the semantic gravity. In the world of the classroom, Maton (2014) argues that cumulative learning is enabled through the strengthening and weakening of semantic gravity and semantic density. These recurrent shifts in context-dependent and context-independent meanings form a ‘semantic wave’ (Maton, 2014: 143). In the case of radiation physics, ‘semantic waving’ entails explicit shifts between concrete analogies, such as the can of spray paint and abstract, generalised physics principles. It would also entail explicitly ‘fleshing out’ concepts, that is, increasing the semantic gravity and reducing the semantic density, and then explaining the general concept or principle, that is, reducing the semantic gravity and increasing the semantic density. Semantic waves can thus reveal the underpinning principles of curriculum and pedagogy through a study of the shifts between stronger and weaker forms of semantic density and semantic gravity. For example, a lecture on the Inverse Square Law might start with a concrete scenario of students' spray painting sheets of cardboard from different distances, followed by a comparison and discussion of the results. Following this practical demonstration, the lecturer would shift towards a more abstract, generalised concept of geometric progression. The weakening of semantic gravity (from concrete scenario to abstract concept) would be accompanied by a strengthening of semantic density: the 'spray paint scenario' would be condensed into various representations, such as a report on an experiment or a scientific diagram. The Inverse Square Law would finally be explained mathematically, such as: 'why the intensity decreases as 1/r2 rather than as 1/r or 1/r3, or even as 1/ √r, where r is the distance from the source' (Voudoukis and Oikonomidis 2017: 23). The analytical method of semantic profiling (Maton, 2014) enables researchers to plot changes in the strengths of semantic gravity and semantic density over time. The semantic profile can be used to map a classroom episode, part of a lecture, a series of lectures, or an entire curriculum.

It is the specialised context of application that poses challenges to applied disciplines, as well as the representation of their curricula and pedagogies with a semantic wave. The semantic wave (demonstrating the rising strength of semantic gravity and the weakening of semantic density in certain learning contexts and events) is not always applicable in contexts of complex application, such as radiation therapy. In such contexts the relationship between semantic gravity and semantic density is not always inversely related on the semantic continuum. In an engineering context, Winberg, Winberg, Jacobs, Garraway and Engel-Hills (2016) found that the 'complexity of the context and the problems that arise from it pose strong cognitive challenges' (2016: 389). LCT recognises that in specialised contexts semantic density is not decreased by rises in contextual embedding. Thus a new tool, 'epistemic semantic gravity' (ESG) (Martin, Maton & Doran, 2019) analytically distinguishes between the 'everyday' contexts that are often used in teaching and the varying degrees of context dependency and complexity in formal specialist contexts. Epistemic semantic gravity describes the ways in which knowledge and practices relate to specialised contexts, such a clinical environment. Epistemic semantic gravity can be stronger or weaker along a continuum that is similar to semantic gravity. Thus stronger epistemic-semantic gravity (ESG+) describes knowledge and practices in specialised contexts of use, while weaker epistemic semantic gravity (ESG-) reflects instances where meaning is less dependent on a specialised context of use. An example of weaker epistemic semantic gravity could be general patient care, which traverses many different specialised health science and medical fields of practice, while administering therapeutic radiation doses exemplifies stronger epistemic semantic gravity as it is specific to the field of radiation therapy.

The semantic range in this study included how radiation physics is represented and explained in the classroom, and how it is applied in clinical practice. These sites of knowledge 'recontextualisation' (Bernstein, 1990) were studied for the purpose of understanding how teaching and learning facilitates both cumulative knowledge building and preparation for competent, professional practice. The semantic density range is particularly important for understanding how radiation physics knowledge is represented in the first year curriculum. The semantic gravity range is particularly pertinent for understanding how radiation physics is explained in pedagogy (Conana et al., 2020) and acquired by students (Georgiou, 2016). In professional education, the context of application, that is the sites where the knowledge is applied, is ever present, although its presence is not always foregrounded (Tan, Van der Molen & Schmidt, 2017). The clinical sites of application, even though they are not strongly present in first year radiation physics, are represented. The field of application, is described in terms of epistemic semantic gravity, which refers to the complexity of the clinical environment and treatments administered to patients.

Table 2.1 summarises the concepts of semantic density, semantic gravity and epistemic semantic gravity that provide an analytical framework for examining curricular and pedagogical practices in radiation physics for the purpose of cumulative knowledge building and competent professional practice.

Table 2.1: The semantic range of radiation physics

Semantic density	**Representation**	**Semantic gravity**	**Explanation**	**Epistemic semantic gravity**	**Application** (treatment and care)
SD 4	Mathematical	SG 1	Principles/theories	ESG 4	Planning/problem solving
SD 3	Disciplinary	SG 2	Analytic, Logical	ESG 3	Advanced clinical practice
SD 2	Scientific	SG 3	Academic	ESG 2	Specialised treatment
SD 1	Basic/simplified	SG 4	Familiar/concrete	ESG 1	General patient care

Instead of using plus and minus signs to denote the relative strengths and weakness in the semantic range, numbers have been used, for example, SD1, SD2, SD3, SD4 to denote specific kinds of increases or decreases in semantic density, semantic gravity and epistemic semantic gravity. Conana et al.'s (2020) levels of semantic density were adapted for this study. The levels, from the least semantically dense to the most semantically dense, are as follows: 'verbal, pictorial, disciplinary and mathematical' (Conana et al. 2020: 157). These levels were adapted for the study of radiation physics concepts as in Table 2.1 under ‘representation’. The semantic density levels range from simplified representations of concepts to representations that are more academic in nature, to discipline-specific scientific representations and finally to highly abstract mathematical representations.

The semantic gravity levels range from contexts that are familiar, such as using the analogy of spray paint to explain the Inverse Square Law, to contexts that are more academic, such as experiments, to explanations and analyses that are increasingly decontextualized and abstract. The levels were adapted for radiation physics from Georgiou’s three levels of semantic gravity, namely: characteristics of objects, explanations of physical objects and processes, and physical principles, laws, concepts, or theories ‘without reference to a specific situation’ (Georgiou, 2016: 185).

The epistemic semantic gravity range was derived from the scope of work of radiation therapists in the curriculum documents (described in more detail in Chapter Three and analysed in Chapter Five). Understandings of patient treatment and care in the specialised context of radiation therapy is an ethical position, and in South Africa, a mandated code of conduct for radiation therapists, as well as core competences for practitioners. Epistemic semantic gravity ranges from simplified or basic contexts, such as straightforward clinical practice and patient care, to the comfort and well-being of the patient during a complicated clinical procedure. In more specialised forms of practice in radiation therapy the epistemic semantic gravity increases, such as when a radiation therapist administers and measures the dose of treatments. Epistemic semantic gravity increases even more in more complex clinical environments (described as ‘advanced clinical practice’ in some curriculum documents) as well as simulations and actual clinical experience. Finally, the highest level epistemic semantic gravity refers to the complex tasks of treatment planning, problem solving, attending to novel and complex cases, and developing innovative practices.

2.8 A translation device for Semantics and the Threshold Concept Framework

In the above discussion it was shown how LCT explains the semantic range for radiation physics, from the representation of concepts, to the explanation of concepts, to the application of concepts in practice. An additional step was to propose a relationship between Semantics and threshold concepts. Table 2.2 is a translation device that shows how threshold concepts and the Semantic range of radiation physics, might provide a strengthened external language of description and a framework to address the research question. Table 2.2 proposes that threshold concepts might be found in the radiation physics range that has strong semantic density and stronger epistemic semantic gravity, but weaker semantic gravity. The translation device suggests that threshold concepts offer a high level of challenge to students, and are likely to be found where semantic density and epistemic semantic gravity are stronger, and were semantic gravity is weaker.

Table 2.2: A 'translation device' for aligning the Threshold Concept Framework with Semantics

Semantic density	**Representation**	**Semantic gravity**	**Explanation**	**Epistemic semantic gravity**	**Application** (treatment and care)	***Threshold concepts***
SD 4	Mathematical	SG 1	Principles/theories	ESG 4	Planning/problem solving	*Threshold concepts*
SD 3	Disciplinary	SG 2	Analytic, Logical	ESG 3	Advanced clinical practice	
SD 2	Scientific	SG 3	Academic	ESG 2	Specialised treatment	*Non-threshold concepts*
SD 1	Basic/simplified	SG 4	Familiar/concrete	ESG 1	General patient care	

Locating threshold concepts across the semantic range that is shaded in Table 2.2 suggests that threshold concepts are likely to be found where semantic gravity is low but where epistemic semantic gravity is high. The translation device also starts to suggest how the semantic range might be controlled by strengthening and weakening the semantic gravity and epistemic semantic gravity for the purpose of 'unpacking' and 'repacking' a threshold concept in the process of teaching and learning.

A translation device is methodologically important as it creates a framework by which 'profiles can be drawn with precision, down to the individual word, image, body movement or sound' (Martin et al., 2019: 103). The translation device in Table 2.2. is the first step towards providing an accurate semantic profile of threshold concepts in first year radiation physics. Once the data for the research study had been collected, the alignment of the Threshold Concept Framework with Semantics was further developed into an external language of description in Chapter Four.

2.9 Conclusion

This chapter started with a review of the literature on threshold concepts following a description where the Threshold Concept Framework was contextualised for radiation physics. The chapter provided a rationale for why LCT's Semantics was suited to explore the knowledge practices around threshold concepts in radiation physics. After a brief introduction to Semantics, examples from current literature showed how the complementary strengths of these theories create a knowledge base for this inquiry. A brief overview of the limited literature available on threshold concepts in radiation physics signals a further need to explore the complexity of these concepts in more detail. After a discussion of the rationale for using computer-based simulation in health professions education, an innovative educational tool, the Virtual Environment for Radiotherapy Training (VERT), was introduced as a means to complement theory-based and clinical practices. This chapter concluded with a conceptual framework that informed the methodology and methods used to gather empirical data for this inquiry.

CHAPTER THREE

RESEARCH METHODOLOGY: A CASE STUDY OF RADIATION PHYSICS

3.1 Introduction

The previous chapters indicated that there is both an empirical and theoretical gap in the knowledge base of how threshold concepts in radiation physics underpin radiation therapy practice. Engagement with the literature has highlighted that students and staff find learning and teaching challenging, but ‘bread-and-butter’ concepts, difficult. However, it is still unknown how the acquisition of what Cousin (2009) calls the ‘jewels in the curriculum’ is transferred and applied to clinical practice. It also showed how simulation-based education has evolved as a complementary pedagogy in the training of health care professionals and how various educational tools had effectively contributed to the transfer and application of key clinical skills. However, there is still a need to understand how virtual clinical environments are used to construct and ‘build’ knowledge in particular ways.

This chapter therefore provides the detail of how threshold concepts in radiation physics were identified, taught and learned by first year students registered for the Bachelor of Science in Radiation Therapy qualification. It also provides details of how this group of students acquired, transferred and applied the knowledge of threshold concepts in clinical practice. The aim of this inquiry is followed by four objectives to achieve the overall aim, followed by the research sub-questions. A justification for the use of case study research in a qualitative paradigm is followed by a description of the methodological approach used to engage with documents, and with student and staff participants in an ethical manner to produce quality data for analysis. Data collection events and the various stages of empirical and theoretical analyses are explained. Strategies used to ensure data quality as well as ethical issues and principles are also addressed. The chapter concludes with a summary of the research process.

3.2 The ‘real world’ problem

The intention of this study was to contribute to improved practice and better patient care by understanding the relationship between threshold concepts in the radiation physics curriculum, and radiation therapy practice in the clinical workplace. Currently, various curricular practices and pedagogical methods and techniques are used to teach concepts in health care, but it is unknown if there are successful curricular and pedagogical approaches that enable first year students to successfully learn threshold concepts customised for radiation therapy. It is also unknown what learning approaches will result in students attaining an improved grasp of key, 'building-block' threshold concepts. Such understanding (internalisation and transfer of knowledge) is crucial to build on or scaffold new concepts throughout the academic study period, and is also needed for the successful transfer and application of threshold concepts in the clinical setting.

3.3 From 'real world' problem to research problem

The larger 'real world' problem was focused to establish the research problem. The research problem involved a focus on the first year curriculum, first year students and their early preparation for practice. The research problem, that is the focus of the study, is how threshold concepts in the first year radiation physics relate to students' preparation for radiation therapy practice. The overarching research question guiding this study is: What is the relationship between threshold concepts in the radiation physics curriculum and radiation therapy practice?

3.4 Aim and objectives of the research

In the following sub-section, the research aim and objectives are discussed.

3.4.1 Aim

The research aim was to contribute to an understanding of threshold concepts in the first year radiation physics curriculum and pedagogical approaches used for the purpose of preparation towards competent and safe clinical practice.

3.4.2 Research objectives

The following objectives were intended to address the main aim of understanding the relationship between theory and practice in radiation therapy:

a) To *identify* threshold concepts in the first year radiation physics curriculum;
b) To *investigate* how first year lecturers and clinical educators taught these concepts;
c) To *understand* how students learned these concepts;

d) To *explore* the transfer of knowledge and application of these concepts in radiation therapy practice.

The following sub-questions were posed to achieve these objectives:

1. What were the main threshold concepts in the radiation physics curriculum?
2. How did first year radiation physics lecturers and clinical educators teach these concepts?
3. How did first year students learn these concepts?
4. How were the acquired threshold concepts transferred and applied in radiation therapy practice?

By addressing these questions, this study offered a new way of conceptualising knowledge building in health professions education. This provides a theoretical basis – supported by empirical evidence – to develop pedagogical tools and techniques to enhance student learning.

3.5 A case study approach to radiation physics

The idea of placing physics or an aspect of physics at the heart of a case study is an approach that seeks to understand elements of physics from multiple perspectives. For example, Baker and Blackburn (2005), in *The pendulum: a case study in Physics*, studied understandings of pendulum motion from a variety of perspectives. Similarly, Jimoyiannis and Komis (2001) studied trajectory motion from different perspectives in order to understand better how computer simulation might support students' learning of this physics topic. A case study approach was used to investigate medical physics in recent research on radiography quality control (Carver et al., 2018). The justification for centring the case study research on radiation physics, as well as the design of the case study, draw on a history of physics or elements of physics in case study research design in a particular context, using multiple perspectives of the phenomenon.

The explanatory nature of the research questions situates the inquiry in a qualitative paradigm. According to Babbie and Mouton (2001), qualitative methods provide insight into the meaning of underlying empirical data in an area of study – in this case radiation physics. These methods enabled a phenomenon, such as understanding the relationship and transfer of knowledge between theory and clinical practice, to be studied in its entirety in a real-life context in order to create meaning.

Schwandt and Gates (2018) support the reality that there is no single understanding of a 'case study', or what constitutes a 'case', and highlight the various interpretations and definitions used across various disciplines and fields of study. Ragin's (1992) classification of a 'case' as an empirical unit (radiation physics) is used and therefore seen as an 'object' that is empirically real and bounded to its context. For clarity, the 'case' or 'case study' refers to in this thesis referred to how radiation physics is understood by the different research participants in their contexts.

An important question to ask is 'What is this [inquiry] a case of?' in order to focus the attention on distinguishing the phenomenon of interest (threshold concepts) from the studied unit (radiation physics). The answer is that this thesis reports on a case, which is threshold concepts as experienced by the first year students registered in the 2018 academic year for the Bachelor of Science in Radiation Therapy at a selected University of Technology, with reference groups comprising second to fourth year students, lecturers and clinical educators; as well as the curriculum documents used to endorse the programme. Simons' (2009) definition was adopted [and adapted] which states that a case study is an in-depth exploration from multiple perspectives of the complexity and uniqueness of a particular unit (i.e. threshold concepts in radiation physics) in a real-life context (Bachelor of Science in Radiation Therapy programme). The primary purpose was to enable in-depth understanding of a phenomenon (i.e. threshold concepts in radiation physics) so as to generate knowledge and inform professional practice (radiation therapy clinical practice). This purpose is further justified by Miles's (2015) argument that a case study generates accounts of practice in educational research, '…which provide knowledge of experience that has conceptual contribution to research understandings of practice' (2015:309). The author also noted that the connections made between the case and the reader's experiences has the power to inform everyday educational practices.

As a case study, this inquiry therefore provides a rich example of context-dependent knowledge that contributes to the understanding of the researcher and the reader. This view is supported by Rule and John (2011) who state that case study research is not an 'easy option', and should not result in superficial and formulaic research, but should rather be seen as an opportunity to provide rich insights into a particular situation, event, classroom or group of people. Case study methods are therefore systematic and in depth to investigate a particular instance in its context in order to generate knowledge. It is this systematic and in-depth description that this case study aims to achieve. The points addressed in this section speak to the common misunderstandings about case studies as noted by Flyvbjerg (2006) and later demystified by Silverman (2014).

There are certain strengths and limitations to using single case-based research within a qualitative paradigm, which are discussed in the following section.

3.6 Strengths and limitations of using a single case

Frequent criticisms of case study research include the use of a small study sample and that findings cannot be generalised. The main aim of this inquiry was to create a deep understanding of knowledge transfer and application within a specific theory-practice relationship. There was no intention to generalise the contribution of this inquiry, but rather to offer theoretical insights in conceptualising the relationship between theory and practice when learning threshold concepts in radiation physics. The main characteristic of this case is that it focused on a student cohort which allowed for a high level of detail to be extracted. The researcher combined data from different sources to achieve an in-depth understanding of the relationship between theory and practice. Walford (2001) noted that a case is significant only in the context of a particular theory, and '… logical inferences therefore replaced statistical inferences' (2001:156).

In addition to generating a rich amount of data, the study sample drew on students, lecturers and clinical educators' sharing of experiences of how they understood this theory-practice relationship. A platform was therefore created for knowledge sharing, which served as the foundation for knowledge building between the university and clinical practice.

Rule and John (2001:21) noted the following possible reasons for single case-based research:

- The case is an outstanding example of its kind,
- It can be studied in great depth,
- The researcher has easy access to the case – which was the situation in this study,
- The researcher has experience of the case as a participant and thus has 'insider knowledge' – the researcher was a former student at the university, a clinical staff member who worked at both clinical sites and used to teach in the academic programme.

However, the above-mentioned authors (2001:21) also cautioned against some limitations of single-case research:

- The findings of the study cannot be generalised to other cases or contexts – which is not the aim of this inquiry, although a thick description of the research process and context of the case is provided which makes the methods and findings transferable to similar contexts,

- There is no comparative dimension within the study – Walford (2001), noted that when case studies are used, the choice must relate to specific research questions which are answerable by studying the needed features of the case,
- The bias of the researcher might restrict or distort the findings in unhelpful ways, especially if the researcher has 'insider knowledge' of, and prior assumptions about the case – this was minimised by using semi-structured interview guides.

Careful consideration and alignment of the main research question with the features of the case allowed for identifying and choosing the best suited participant group to address the research questions.

The ongoing debate about the credibility and limitations of the case study in comparison with other qualitative approaches was noted. Understandings of and reporting on case studies as a methodology versus the methods used to collect qualitative data was inconsistent across the literature. Too much flexibility associated with the approach might be overwhelming and the cause of confusion to novice researchers, and often leads to inconsistent applications which limit the streamlined application of the methodology (Hyett, Kenny & Dickson-Swift, 2014).

3.7 Delimiting this case as a bounded system

To address the boundedness of this inquiry as a case study, Rule and John (2011:20) recommend four forms of delimitation:

Categorical – describing the unit of analysis: which was threshold concepts in radiation physics offered as a module in the Bachelor of Science in Radiation Therapy qualification;

Spatial – referring to the setting where the unit will be investigated: which was a University of Technology in the Western Cape Province of South Africa, with two tertiary hospitals as clinical placement sites;

Temporal – setting out the chronological boundaries, including a specific period: which was the 2018 academic year; and

Thematic – identifying the issues to be investigated: which was understanding the relationship between threshold concepts in the radiation physics curriculum and its application and transfer to radiation therapy practice.

3.8 Data generation strategies

The following sub-sections provide detail of the strategies used to generate robust and sufficient data required to answer the research question which focused on the relationship between the acquisition, transfer and application of threshold concepts in radiation physics between the university and clinical practice.

3.8.1 Data sources and collection methods

Various sources of data and data collection methods were used to gather and collect data relevant to the research questions. Data sources and collection methods traditionally used in case study based research were employed as summarised in Table 3.1 below:

Table 3.1 Summary of case study based data sources and collection methods

No	Data source	Justification for use	Data collection method	Justification for use
1	Curriculum documents	To identify radiation physics subject content in order to identify threshold concepts	Document sample	Reliable and accredited documents detailing the scope of the curriculum and pedagogical approaches used
2	Student assessments	To identify areas of strength and difficulty and students' interpretation of threshold concepts	Document sample	A variation of assessment results demonstrating fair, credible and reliable assessment practices
3	First year student participants	Main source of data confirming threshold concepts identified, and sharing experiences of curricular and pedagogical approaches used to learn threshold concepts	Focus group interview	An effective, cost and time saving method of data collection adding valuable insights to discussions (Frey & Fontana, 1991)
4	Second to fourth year students	Senior students reflecting on their experiences of learning threshold concepts in radiation physics	Focus group interview per year group	An effective, cost and time saving method of data collection adding valuable insights to discussions (Frey & Fontana, 1991)
5	Lecturers	To confirm the threshold concepts identified, as well	Individual interviews	In-depth method of collecting data from

		as sharing experiences of curricular and pedagogical approaches used to teach threshold concepts		experts to explore individual opinions and experiences of teaching threshold concepts
6	Clinical educators	Triangulating data gathered from student and lecturer participants and also sharing experiences of how threshold concepts are transferred and applied to radiation therapy practice	Focus group interview per clinical site	An effective, cost and time saving method of data collection adding valuable insights to discussions (Frey & Fontana, 1991)

In section 3.9 more detail is included in terms of the permissions and ethical considerations taken to protect the confidentiality of the above-mentioned research participants.

3.8.2 Site selection

According to Walford (2001), a detailed description of the research site is needed to enable transferability to and applicability of findings to similar contexts. The site selected to conduct this inquiry is the only University of Technology where a science-based Bachelor of Science is offered in South Africa (SAQA, 2018).

The radiation therapy programme offered at the university site (Site U), uses a work-integrated learning (WIL) educational approach where, from the second half of their first year, students are exposed to the clinical workplace and academic lectures in short cycles of two to four weeks at the end of the second, third and fourth terms. This work placement was developed to enable students to apply their theoretical knowledge in practical contexts for enhanced learning and improved graduate employability (Engel-Hills et al., 2010). The two tertiary hospitals in the Western Cape Province of South Africa were included. These sites serve as relevant workplace learning clinical sites accredited by the Health Professions Council of South Africa for student placement and training – referred to as Site A and Site B throughout this inquiry to protect the site and the clinical educator participants based at each site.

3.8.3 Participant selection

The main research question of this inquiry calls for an understanding of how learning between theory-based and clinical practice happens, in particular how threshold concepts in first year radiation physics are acquired, applied and transferred in clinical practice. Therefore, the voices of the lecturers and clinical staff who teach first year radiation physics, as well as the first year students were key contributions. Additional registered students across the four levels of study were asked to reflect on their experiences as first year students studying towards the Bachelor of Science in Radiation Therapy (BSc: RT). Clinical instructors were an important link between theory and practice. They were able to recontextualise the radiation physics concepts in clinical practice, where the transfer and application of threshold concepts in radiation physics are implemented and assessed. They therefore made a key contribution to this study.

The purposive sample of participants thus included:

- First year students registered for the subject Physical Science 1 of which radiation physics is a module;
- Second to fourth year students registered for the subject Physics of Radiation Therapy (2 – 4 as per the year of study) of which radiation physics is a module;
- Lecturers (including the subject lecturers, teaching assistant and clinical instructor) facilitating the subjects;
- Clinical educators responsible for and involved with the clinical liaison and assessment of all student groups (first to fourth year students) at site A and site B.

In qualitative research, the power of a study is not determined by how many participants are included in the sample, but by the appropriate contribution and participation from each participant in order to answer the research question. A scientifically calculated sample was thus not used to determine the number of student participants needed to answer the research question but rather a selection matrix was compiled to decide on the sample that best represented the population where data was collected.

Table 3.2 is the selection matrix reflecting the student population sample. From the matrix a total number of 24 students were included in the student participant group (six students per year group). The numbers in brackets in column one, refer to the total number of students registered for the course. Students were selected on the basis of their performance in the first assessment task.

Table 3.2 Student participant selection matrix

Scores → **Year group** ↓ **(Total 2018 registrations)**	**Low assessment scores (49% or less)**		**Average assessment scores (50% – 65%)**		**High assessment scores (66% and more)**	
First years **(10)** **No males registered**	Female	Female	Female	Female	Female	Female
Second years **(10)** **Three males registered**	Male	Female	Male	Female	Male	Female
Third years **(6)** **One male registered**	Female	Female	Male	Female	Female	Female
Fourth years **(10)** **One male registered**	Female	Female	Male	Female	Female	Female

Due to the limited number of staff teaching the radiation physics modules in the Bachelor of Science in Radiation Therapy programme, all lecturers (currently five, including the clinical instructor and teaching assistant, and excluding the programme coordinator) were included in the lecturer participant group. The clinical staff participant group included those staff members who were involved with student training in an official capacity at the clinical sites. In the Radiation Oncology departments at both tertiary academic hospitals in the Western Cape Province of South Africa, there are dedicated staff members appointed for the structured training of students when they are placed at these sites. Such staff are called 'student liaison staff' and included the planning area manager, treatment floor manager and one staff member from each sub-division. The number of clinical staff participants were fifteen (15), which included eight (8) staff members from clinical site A and seven (7) from clinical site B.

3.8.4 Inclusion criteria

This section details the inclusion criteria for participants:

- Staff sample:
    - All lecturers (including lecturers, the teaching assistant and clinical instructor) facilitating the radiation physics module across the four levels of study;
    - All clinical student liaison staff (staff involved with student training in an official capacity) in full-time employment at the two accredited workplace learning sites.

- Student sample:
    - First year students registered for the Bachelor of Science in Radiation Therapy qualification and registered for the subject called Physical Science 1 where radiation physics is a module during the 2018 academic year, meeting the requirements of the selection matrix described in Table 3.2;
    - Second to fourth-year students registered for the Bachelor of Science in Radiation Therapy qualification and registered for the subjects called Physics of Radiation Therapy where radiation physics is a module during the 2018 academic year, meeting the requirements of the selection matrix described in Table 3.2.

3.8.5 Exclusion criteria

- Any staff who were involved with the programme but did not facilitate the radiation physics modules during the 2018 academic year;
- Any students registered for other qualifications offered by the department (such as the Bachelor of Science in Diagnostic Radiography, Bachelor of Science in Diagnostic Ultrasound or Bachelor of Science in Nuclear Medicine Technology), even if they attended the same lectures in any level of study during 2018;
- Students who were registered for the Bachelor of Science in Radiation Therapy qualification but not registered for a subject where radiation physics was a module in 2018 (for example a student who failed Human Science and only registered for Human Science during the 2018 academic year).

3.8.6 Document sampling

The following documents were used to initially identify potential threshold concepts in the radiation physics curriculum:

- Curriculum documents (including assessments) detailing the content of the radiation physics module offered at Site U, which included the following:
    - formal curriculum approval and registration documents (from the South African Qualifications Authority (SAQA), and the Higher Education Quality Committee (HEQC);
    - one first year student guide of 2018 reflecting the planned curriculum, learning outcomes, teaching and learning strategies, and assessment methods as communicated to students;

- one of each second, third and fourth year student guides of 2018 reflecting the planned curriculum, learning outcomes, teaching and learning strategies, and assessment methods as communicated to students; and
- examples of summative theoretical assessments written by the first year students in 2018.

3.8.7 Data collection events

The realities of all activities were captured as clearly and accurately as possible by using multiple sources of evidence (Brink, Van der Walt & Van Rensburg, 2006:118). Reality is complex and that is the reason why various sources and methods were needed to capture and explain it. Richardson and St Pierre (2005:963) use the term 'crystallisation' to indicate the complex, multi-faceted nature of the topic under study. Denzin and Lincoln (2008) liken the crystallisation process to a writer telling the same tale from different points of view.

The subsequent sequence was used to gather the information needed to understand how first year students registered for the Bachelor of Science in Radiation Therapy qualification learn threshold concepts in radiation physics.

A review of the following document sample assisted to identify threshold concepts covered in the first year radiation physics module. It also enabled a theoretical classification/typology of knowledge needed to learn and understand threshold concepts in radiation physics:

- formal curriculum approval and registration documents;
  - the *Bachelor of Radiation Therapy* document (SAQA, 2018), and
  - the online submission to the HEQC – *Application form for programme accreditation*.
- the curriculum documents detailing the content of the radiation physics module in the first year student guides of 2018;
- the curriculum documents detailing the content of the radiation physics module in the second to fourth year student guides of 2018;
- samples of formative and summative theoretical assessments of first year students registered for the radiation physics module reflecting the assessment questions and a representation of low, average and high assessment scores.

Focus group interviews were conducted with first year students across the 2018 academic year. For the purpose of triangulation (Denzin & Lincoln, 2008), data were additionally collected from the second, third and fourth year groups where focus group interviews were used as reflections of their experiences with the first year radiation physics curriculum in previous years. Appendix 3.1 is the interview guide used during the focus group interviews with the student participants.

By the time of the interviews the students were familiar with the term 'threshold concept' as following Cousin's (2006) transactional curriculum inquiry approach they were participants in the threshold concept study. In the case of the first year students, the semi-structured focus group interviews were repeated quarterly. One semi-structured focus group interview was conducted with the senior groups, that is, one with second years, one with third years, and one with fourth year student participants. The questions asked in the semi-structured focus group interview are listed below:

1. Why should BSc: Radiation Therapy students learn radiation physics?
2. What is your understanding of threshold concepts in Radiation Physics?
3. What is your experience of learning threshold Radiation Physics concepts in VERT™?
4. Comment on the following statement: Knowing/mastering threshold concepts in physics improves clinical competence.
5. After your clinical rotation: What helped you to apply Radiation Physics concepts in the clinical department? What did not help you?
6. Did the sessions in VERT™ help you to apply concepts in the clinical department? What about those sessions helped/did not help?
7. What are your suggestions for teaching threshold concepts in Radiation Physics?
8. Is there anything in the Radiation Physics module that you found beneficial for your own learning and clinical practice? Please elaborate.
9. Is there anything else about learning Radiation Physics that you would like to share with the researcher?

- Question 1 was asked in order to elicit first students' evolving understanding of the role of radiation physics in their studies, as well as senior students' reflections on the same topic, given their broader perspective.
- Question 2 was intended to elicit first year students' developing understanding of threshold concepts over the academic year, as well to elicit senior students' reflections on their first learning challenges.

- Question 3 was asked to ascertain the extent to which the use of the virtual learning environment impacted students' understanding across all four levels.
- Question 4 was a verifying question to check responses to Question 1.
- Question 5 intended to probe the issue whether students were able to identify radiation physics concepts in radiation therapy practice across all levels.
- Question 6 was a verifying question for Question 3.
- Question 7 was asked to elicit students' suggestions for improving pedagogy.
- Questions 8 and 9 were general open-ended questions where students could raise issues that were not part of the semi-structured interview.

After the student semi-structured focus group interviews, individual interviews were held with all lecturers to elicit the curricular and pedagogical approaches used to deliver the radiation physics content and assessment strategies used, and to gain insights from their understandings of the role of radiation physics in radiation therapy practice. Appendix 3.2 is the interview guide used during the individual interviews with the lecturers.

Finally, data collected from the lecturer and student participant groups were triangulated using focus group interviews with clinical educators that were closely involved with student training at the clinical sites (A and B). Appendix 3.3 is the interview guide used during the focus group interviews with the clinical educators.

3.9 Ethical considerations

The Declaration of Helsinki (WMA, 2013) deals with ethical principles for medical research involving human subjects. The authors of the declaration emphasise the power relation that exists between the doctor and the patient – which equates to the lecturer-student power relation in academia and thus in this study. Attention is therefore drawn to paragraph 9 of the declaration that deals with 'responsibility', where it is stated that "It is the duty of [researchers] who are involved in … research to protect the life, health, dignity, integrity, right to self-determination, privacy and confidentiality of personal information of research subjects" (WMA, 2013: E1). The Singapore statement on research integrity (World Conference on Research Integrity, 2010) also focuses on key responsibilities that will ensure ethical research practices. This study also adheres to the recently signed and jointly issued statement on ethical research and scholarly publication practices in the South African context to ensure quality research of high integrity (Academy of Science of South Africa et al., 2019).

From an educational stance and referring to research on threshold concepts, Cousin's (2009) ethical framework assisted the researcher to pay special attention to informed consent as an ongoing process, participant confidentiality – before, during and after dissemination of findings - and anonymity of data generated during this study.

This study was approved by the Faculty of Health and Wellness Science's Research Ethics Committee (REC), with REC approval reference number: CPUT/HW-REC 2017/H40 (Appendix 3.4 is a copy of the ethics approval letter). This application included a permission letter from the Head of the Department of Medical Imaging and Therapeutic Sciences (MITS) to access documents and student assessments, and to interview lecturers and students. Permission was also granted by both clinical sites (A and B – Appendices 3.5 and 3.6 are letters of approval from each clinical site) where the clinical instructor, and student liaison staff, referred to as clinical educators in the context of this study, were interviewed.

Very specific groups of people were needed to realise the objectives of this study and to ensure a representative sample; however, participation was on a voluntary basis with a call for participation emailed to all participants. Appendix 3.7 is an example of the call for participation letter detailing the aims, purpose, and benefits of the study. The researcher acknowledges and am aware of possible participation-bias due to the lecturer-student power relation and being a colleague of the lecturer and clinical staff participants.

All participants were recruited individually via electronic mail. The informed consent letters for the staff (Appendix 3.8) and student participant (Appendix 3.9) groups were forwarded to them detailing the study aims, purpose and benefits. Participants were not given an opportunity to request a face-to-face appointment to explain the content of the consent form – this was to eliminate possible, but unintentional coercion, recruitment and participation bias. All returned (initialled, signed and dated) consent forms were stored electronically on a password protected computer. Printed copies were stored in a sealed envelope in a locked safe in a locked office at the university.

Each document and participant were assigned a study code to ensure anonymity and to keep personal information confidential. Refer to Table 3.3 for the participant profiles and Table 3.4 where the document codes are featured. No direct identifiers were kept in either electronic or printed format. Informed consent to voluntarily participate in this study was an ongoing process, and participants' willingness to participate were confirmed at the start of each data collection event. They could have withdrawn from the study, but none of them did after giving initial written consent to participate. Participants were continuously informed of how their contributions were used to answer the research questions by doing the following:

- allowing participants to listen to recordings;

- emailing transcriptions of audio recordings to verify content and check accuracy; and
- informing participants of any dissemination of findings related to this study, e.g. published journal articles, conference presentations, etc.

Table 3.3 Examples of participant codes (total number of participants in brackets)

Student participants (24)		Lecturer participants (4)	Clinical staff participants (15)	
Year 1 (6)	Y1_L1_2018	Lecturer 1	Site A	A_Plan_1 (4)
				A_Rx_1 (4)
Year 2 (6)	Y2_L1_2018	Lecturer 2	Site B	B_All_1 (7)
Year 3 (6)	Y3_L1_2018	Lecturer 3	Key: A/B = clinical site, Plan/Rx/All = work area, 1 = order in which participants responded during interviews	
Year 4 (6)	Y4_L1_2018	Lecturer 4		
Key: Y = level of study, L = order in which participants responded during interviews, 2018 = academic year when data was collected				

Table 3.4 Examples of document codes

Document studied	Document code
Qualification registration documents	DocReview_SAQA_2018
	DocReview_HEQC_2018
First year student guide	DocReview_Y1LG_2018
Second year student guide	DocReview_Y2LG_2018
Third year student guide	DocReview_Y3LG_2018
Fourth year student guide	DocReview_Y4LG_2018
Student assessments	DocReview_Assess_Physics Y1
Key: DocReview = document sample, Y1LG = designator used to code the type of document, 2018 = academic year when data was collected	

3.10 Personal orientation to the inquiry

Various sources of information such as media reports, formal evidence-based reports, and statistics on innovative pedagogy presented to stakeholders, decision-makers, lecturers, and students, indicated the relevance of this study. However, a personal motivation was needed to stay engaged and committed for the duration of the study. Observations of student learning practices in the classroom (theory-based practice) and feedback from staff in clinical practice, regarding the application of threshold concepts, were found to be unreliable and insufficient to inform changes to the curriculum, teaching and learning strategies, or assessment methods. After consulting various information sources to indicate how other lecturers make sense of student learning with respect to key and threshold concepts, it was found that there were limited reports that provided evidence-based insights and understanding. There was thus a need to investigate knowledge building in the area of teaching and learning threshold concepts in radiation physics and how those concepts manifested in professional practice. The work done towards compiling this thesis was thus a stepping stone towards improved curricular and pedagogical practices to facilitate meaningful learning and to enable successful knowledge building which in turn would result in accountable and competent professionals delivering high energy ionising radiation in a safe manner.

3.10.1 Researcher's positionality

The researcher drew on Cousin's (2009) Transactional Curriculum Inquiry. The researcher is an 'insider' in the field (as a former student, qualified radiation therapist and until recently a lecturer teaching on the programme). Bias was reduced by rigorous following of the Transactional Curriculum Inquiry methodology. Bias was also reduced by the use of an external professional transcriber who transcribed all the audio recordings of the semi-structured focus group and individual interviews. The transcriptions were done independently and off-campus. Bias was further reduced by the inclusion of 'member checks' (Denzin and Lincoln, 2008), in which all participants were provided with opportunities to make corrections if they found errors in the transcriptions.

3.11 Data evaluation and analysis

All data collected were first evaluated for relevance to answer the research sub-questions, before it was further processed and 'cleaned-up' for analysis. Responses that were not relevant to this inquiry, for example discussions where the existing programme was compared to the previous offering, were deleted from the original transcriptions during the 'clean-up'. Transcribed audio recordings of interviews with staff and student participants provided rich and complementary data of how threshold concepts in radiation physics were learnt and taught over the four years of study.

The following sub-section will report on the two-stage analysis that followed the initial identification of the unit of analysis.

3.11.1 Stage 1: Unit of analysis

The unit of analysis refers to those entities that are described and compared in an inquiry (Mouton, 1996). In the context of this thesis, the unit of analysis refers to threshold concepts in radiation physics, and in particular, to the semantic profile of the threshold concepts in radiation physics (see Section 2.7.1 on LCT). The stronger semantic density and weaker semantic gravity of radiation physics point to the potential challenges for students' learning in the discipline; while the stronger epistemic semantic gravity points to the potential of the threshold concepts for underpinning radiation therapy practice. The unit of analysis, the semantic profile of threshold concepts in first year radiation physics, was applied in the analysis of all text documentations and interview transcriptions.

3.11.2 Stage 2: In-vivo coding and empirical thematic analysis

Focus and individual interviews with students, academic staff and clinical educators were transcribed, using standard transcribing methods (Edwards & Lampert, 2014). 'Member checks' (Savin-Baden & Major, 2013: 477) were undertaken and the transcriptions were cleaned and revised before analysis. A two-step process of coding the data was undertaken, following the verification of transcripts by both interviewers and interviewees. Initially code data with *in-vivo* coding, following Saldaña's (2013) first cycle coding methods, which entailed extracting key-words from the participants' actual words (2013: 58 – 60). The second cycle of coding reframed the *in vivo* key-words in terms of the four levels and categories of semantic density, semantic gravity and epistemic semantic gravity (see Table 3.5), and more fully explained the data with reference to the conceptual and theoretical frameworks. Engagement with the data provided insights into how threshold concepts in radiation physics were understood by students, academics and clinical educators.

Table 3.5: Example of data coding

Participant	Transcription	In-vivo code	SD	SG	ESG
A_Rx_1	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 exactly … why you're doing what you're doing	no room for error blindly push buttons know exactly…	SD2 - SD2	- - -	ESG1 ESG0
A_Rx_2	Because that would make sense because 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 and what did the radiographers do on that plan in order to execute. So I think that…	Light bulb moment… amalgamate What did the radiographer do…	SD3 SD3 -	- - -	- ESG3 ESG2

All words and phrases (text) related to teaching and learning threshold concepts in radiation physics, knowledge of such concepts, and the transfer and application of those concepts in clinical practice were coded (text with similar meaning grouped together) accordingly. Thereafter, an empirical thematic analysis was conducted that included data generated from the document review, student assessments and transcribed audio recordings. See Table 3.6 for an example of an initial code tree developed from an excerpt of the data set generated by the clinical staff participant groups at both clinical sites.

Table 3.6 Excerpt of a code tree using data from clinical staff participant group

Codes and themes from all clinical staff data sets			
Level 1: All codes (from transcripts)	Level 2: Sub-themes	Level 3: Main themes	Linked to sub-question
Radiation Safety	Key concepts	Identified threshold concepts	1
ALARA principle			
Isocentre	Threshold concepts		
SSD			
Thinking 3-Dimensionally			

3.11.3 Stage 3: Translating data to theory

According to Maton and Chen (2016), qualitative analysis using LCT involves movement between abstract theory and concrete data in iterative cycles in order to gain theoretical understanding without losing track of the empirical findings. As the researcher immersed herself in the themes developed from the empirical analysis (Stage 2), she started learning the steps of the 'theory-data-dance' by returning to the Semantics dimension of LCT (as discussed in Section 2.3). The third stage of analysis went beyond the emergent themes and applied the translation device (Table 2.2 repeated below) to define more precisely the patterns emerging from the data.

Table 2.2: A 'translation device' for aligning the Threshold Concept Framework with Semantics

Semantic density	**Representation**	**Semantic gravity**	**Explanation**	**Epistemic semantic gravity**	**Application** (treatment and care)	***Threshold concepts***
SD 4	Mathematical	SG 1	Principles/theories	ESG 4	Planning/problem solving	*Threshold concepts*
SD 3	Disciplinary	SG 2	Analytic, Logical	ESG 3	Advanced clinical practice	
SD 2	Scientific	SG 3	Academic	ESG 2	Specialised treatment	*Non-threshold concepts*
SD 1	Basic/simplified	SG 4	Familiar/concrete	ESG 1	General patient care	

The four levels of semantic density, semantic gravity and epistemic semantic gravity were used to show the semantic profiles of concepts and curricular and the semantic waves of the pedagogies used in teaching radiation physics concepts.

3.12 Data quality

The following section focuses on the strategies used to ensure quality throughout this inquiry, with reference to the trustworthiness of data collected, processes followed and the credibility of interpretations and inferences made in the conclusions chapter of this thesis. Noble and Smith (2015) confer that evaluating the quality of research is essential if findings are to be applied in practice.

The 'trustworthiness' and 'credibility' of data produced by qualitative research refer to good quality research (Denzin & Lincoln, 2008). Due to the qualitative nature of the research questions, the integrity of this study is addressed by focusing on the rigour provided by the Transactional Curriculum Inquiry methodology (Cousin, 2009). The trustworthiness of the study is demonstrated by the researcher's ability to show integrity and competence throughout the study by means of in-depth planning, purposive sampling, careful selection of data sources that have relevance in terms of the research questions, and the transparent analysis process.

Trustworthiness - referring to the consistency of analytical procedures and confidence in the research findings (Denzin & Lincoln, 2008) - was demonstrated by ensuring that the research findings reflected the understanding of the participants as closely as possible by using their points of view as relevant quotations to support the researcher's interpretations. Clarity and transparency are essential requirements for the trustworthiness of any qualitative study (Noble & Smith, 2015; Baillie, 2015), hence reference to appendices such as informed consent forms and interview guides throughout this report. Original and 'cleaned' transcriptions of all voice recordings were shared with the participants to check and verify the accuracy of the transcribed text.

In order to facilitate transferability to other similar sites and more broadly within health professions education programmes, the researcher's main intention is to create an understanding of each idea referred to in this thesis, for example, threshold concepts and not to misinterpret or misrepresent the viewpoints of any participants or authors cited. The case study approach used in this inquiry allowed for rich descriptions of the case, setting and participants which in turn strengthened the rigour of the inquiry (Baillie, 2015).

3.13 Chapter summary

This chapter provided a rationale for the use of an appropriate methodology in order to identify and understand threshold concepts in radiation physics. It provided information concerning the case study design and qualitative methods used to undertake this explanatory inquiry. Table 3.8 is a summary of the research design used to investigate the relationship between acquiring, transferring and applying threshold concepts in radiation physics to radiation therapy practice. Ethical considerations and strategies used to ensure data and methodological quality and rigour were also unpacked. This methodological understanding forms the basis for developing a revised language of description to transcend the divide between theory and data (Maton & Chen, 2016). Multiple stages of in-vivo and LCT analyses of data generated during this inquiry are presented in the subsequent chapters.

Table 3.8 Summary of the research design

Research Sub-questions	Sites	Data sources (incl. participants)	Data collection methods	Data analysis methods
1. What were the main threshold concepts in the radiation physics curriculum?	Site U	Curriculum documents, study guides, theoretical assessments	Document and student assessment review	Discourse and thematic analyses drawing on the revised external language of description (semantic profiles of threshold concepts in radiation physics)
2. How did first year radiation physics lecturers and clinical educators teach these concepts?	Site U and clinical sites A and B	Student, lecturer and clinical educator participants	Semi-structured focus group interviews Semi-structured individual interviews	
3. How did first year students learn these concepts?	Site U	First year student participants	Semi-structured focus group interviews	
	Site U	Lecturer	Semi-structured individual interviews	
4. How were the acquired threshold concepts transferred and applied to radiation therapy practice?	Clinical Sites A and B	Students	Semi-structured focus group interviews	
		Lecturer	Semi-structured individual interviews	
		Clinical educator	Semi-structured focus group interviews	
		Lecturer	Semi-structured individual interviews	
		Clinical educator	Semi-structured focus group interviews	

CHAPTER FOUR

LANGUAGES OF DESCRIPTION FOR THRESHOLD CONCEPTS

4.1 Introduction: Describing First Year Radiation Physics

The focus of Chapter Four is the concepts in first year radiation physics from the multiple perspectives of students, university lecturers and clinical educators for the purpose of further developing the external language of description. This thesis is a case study of radiation physics. It traces the journey of radiation physics from concepts in curriculum documents, to the classroom, and out into the field of radiation therapy practice. The case study of first year radiation physics thus begins with a description of what the discipline is, from different participants' viewpoints. The purpose of this in-depth look at the characteristics of radiation physics is intended to further develop the conceptual framework introduced in Chapter Two, and to develop a language of description for identifying the threshold concepts that characterise first year radiation physics.

4.2 Many Languages of Description

Participants' descriptions of first year radiation physics were dependent on their contexts. Their understanding was determined by whether they were lecturers of first year radiation physics, first year students learning the subject, more senior students reflecting on their learning in their first year, or clinical educators, most of whom were practising radiation therapists.

Educational theorists and researchers have developed more specialist languages for describing disciplinary areas and for student learning, for example, the Threshold Concept Framework (Meyer & Land, 2003; 2005). There are also more abstract theories, such as social realism, of which LCT is an example, that provide even more specialised languages of description. Radiation physics has not been extensively studied in the educational research literature, thus neither the Threshold Concept Framework nor LCT specifically addresses issues in radiation physics as an academic subject. For this reason, it was important to explore the research participants' different ways of describing radiation physics in more detail. Their understandings of first year radiation physics were of particular value in further developing the translation device developed in Chapter Two. Figure 4.1 provides a schematic representation of the languages of description analysed in Chapter Four. The outer ring of the circle represents the empirical language of description, which refers to the ways in which students, lecturers and clinical educators describe radiation physics. The second circle represents the Threshold Concept Framework that was developed to explain areas of difficulty in a curriculum. It is known in Sociology of Education studies as the 'external language of description' (Bernstein, 1996: 136). An external language of description should be able to describe the empirical domain in a theoretically consistent and logical way. At the centre is the high level theory, known as the 'internal language of description'. Its function is to extend and strengthen the external language of description, and to ensure its coherence.

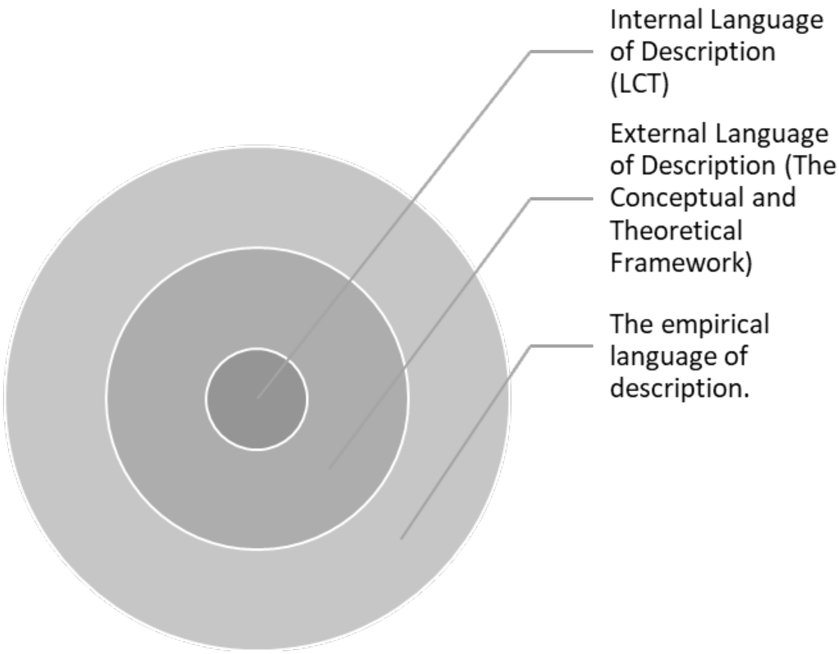


Figure 4.1 Levels of description of first year radiation physics

4.3 Empirical Language of Description: Radiation physics in the 'real world'

The participants of the study, namely the students, the lecturers and the clinical educators, are in the 'real world' or empirical domain (the outer ring of Fig. 4.1). They describe first year radiation physics from the vantage point of their own experience.

4.3.1 Students' perspectives on first year Radiation physics

The students in this study 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 (Y3_L3_2018)

A large part of the difficulties associated with radiation physics was its abstract nature; first year students used words like ‘up there’ (Y1_L3_2018) or ‘in the air’ (Y1_L6_2018) 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 (Y1_L3_2018).

> But in Physics, I always feel it’s – out of the air just here (Y1_L6_2018).

First year students did not find radiation physics relevant to their chosen profession of radiation therapy. They noted that the subject was more appropriate for ‘Medical Physics students’ (Y3_L7_2018) or even ‘Harvard University Physics’ (Y3_L4_2018). For one of the student interviewees, radiation physics was simply ‘way too physics-full…’ (Y1_L4_2018).

What emerges from the first year students’ experience of radiation physics is that they found the discipline challenging and not relevant to their practice. They did not understand the role of radiation physics in underpinning radiation therapy practice.

4.3.2 Lecturers’ perspectives on first year Radiation physics

The lecturers, who were either physicists or radiation therapists, did not perceive 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 recognised it as an underpinning radiation therapy practice. The Physicists described radiation physics in the specialised language of the discipline, while the radiation therapists understood radiation physics 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 x, y and z’, ‘bending magnets’, ‘waveguides’, ‘anodes’, ‘isocentre’, ‘collimation’, ‘virtual wedges’, and ‘head of the machine’ (Lecturer 4). They key role of radiation physics in underpinning practice was explained by a lecturer as a ‘high stakes’ issue:

> The stakes are high, 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 … and the first year’s level is quite critical because it sets their standard ... (Lecturer 3).

On the other hand, 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 about a mode of enquiry' (Lecturer 2). However, the physicists could also understand radiation physics and radiation therapy as almost interchangeable:

> Radiation, how do we protect ourselves from it…? How do we utilise 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 and also … basically, radiation protection (Lecturer 2).

In some cases, radiation physics was understood as a discipline with its own characteristics and properties – 'It is what it is, what it is' (Lecturer 1), but in most cases it was understood in relation to radiation therapy. Lecturer 1 described radiation physics as a foundation for 'pre-clinical' skills development:

> I think the pre-clinical skills is understanding those concepts (Lecturer 1).

Some of the lecturers sequenced their teaching of radiation physics, as Lecturer 1 explains: 'I teach in a way that I learnt 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 three-point 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 where one thing leads into the other and it's the process that you would walk every day in the department or should walk every day in the department (Lecturer 1).

Lecturer 1 has conflated radiation physics and radiation therapy to the extent that they are no longer separate entities in her understanding.

4.3.3 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 exactly … why you're doing what you're doing (A_Rx_1).

The clinical educators were aware that students had acquired considerable knowledge of radiation physics over the period of their studies. They described this as having 'head knowledge of radiation and what it entails' (A_Rx_1). They were, however, sceptical of students' ability to apply the knowledge learned in the clinical context:

> I think knowledge-wise there is. They can answer the question. They know exactly … but the practical application … (A_Rx_4).

As A_Plan_4, elaborated, '…that comes with experience'.

While acknowledging the need for students to understand concepts in radiation physics, they valued practical experience in the clinical environment more highly.

4.4 An Initial External Language of Description for Radiation Physics

Having studied the participants' different understandings of first year radiation physics from their various positions and experiences, an initial attempt was made to develop a consistent and systematic understanding of radiation physics, drawing on the Threshold Concept Framework (the second circle in Figure 4.1). This framework provided an external language of description, that is, it stepped back from the subjective experiences and positions of the research participants and 'framed' their descriptions with the identified characteristics of threshold concepts. The external language of description, thus changed the empirical language of description:

> … the external language of description, encompassing changes originated by the empirical, leads to changes … In this way, the three levels constitute active, dynamic instruments that undertake changes in a real research process (Morais, 2002: 564).

4.4.1 (Not entirely) Bounded

The Threshold Concept Framework suggests that threshold concepts have a ‘bounded’ nature; it is this discipline-specific quality that makes a concept difficult to learn and difficult to teach (Meyer & Land, 2003; 2005). The first year radiation physics lecturers were not in agreement about exactly how ‘bounded’ the concepts of radiation physics were. On the one hand radiation physics was recognised as a discipline in its own right. On the other hand, 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 … even when I ask the students now, “What’s the x, y and z?” They go … “Mm … ja … it’s that thing on the graph.” That’s where the concept starts. It starts with that, “Mm … ja … it’s that graph thing that we did” …those are concepts that are taught in Physics and so it does start there (Lecturer 1).

When radiation physics is understood to originate from physics, it is bounded because it belongs to physics. In another version, its concepts are derived from practice, as one of the participants 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 realised is independent of them having learnt all this other physics. If they knew how the radioactive decay little equation worked even before we called it that, we could immediately start describing radioactive decay. And then we go later on, into all the different types of reactions (Lecturer 3).

This not-entirely-bounded nature of radiation physics characterises many of its concepts. The students identified with a 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 ‘[teach] like how he would to Medical Physics students (Y3_L7_2018) or as if he was teaching ‘Harvard University Physics’ (Y3_L4_2018).

4.4.2 Integrative (conceptual and practical)

The integrative nature of threshold concepts is the sense of 'revealing the previously hidden interrelatedness of things' (Meyer & Land, 2005: 377) applied to many of the concepts in radiation physics. Threshold concepts make connections between other concepts, and their realisation is often referred to as a 'light-bulb' or 'a-ha' moment (Cousin, 2009). Lecturers spoke about 'conceptual understanding…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, as in the quotation below:

> It's impossible too for someone to understand [radiation physics], really understand it, like the little equations and so on without first understanding it conceptually. It's better, you know, we focus on conceptual understanding. If they don't have the conceptual understanding you never quite understand 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 into practice. A first year student explained her developing understanding in terms of integrating theory and practice (rather than concept-building):

> 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 because you know all these bits and pieces of information but you never really puzzle it together (Y1_L6_2018).

4.4.3 (Temporarily) Troublesome

The 'troublesome' nature of radiation physics was most acute for the first year students who were encountering the discipline for the first time. It was a discipline that was very different from what they had learned at school. Initially, concepts in radiation physics to them seemed, as Perkins put it, 'counter-intuitive, alien or seemingly incoherent' (2006:7). The troublesomeness of radiation physics was temporary, and senior students, lecturers and clinical educators had all mastered the once-troublesome concepts. Many could, however, remember some of the difficulties that they had experienced. A senior student, reflecting on her first year experience, 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, we've never gotten like any notes beforehand or while doing it. So it's very difficult to – now [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 and a lot of the time they don't use visuals a lot. Then it makes it also difficult because now [the lecturer is] just like talking in the air … Ja, so that makes it difficult (Y3_L6_2018).

In her description of what made radiation physics difficult for her, the student hints a possible pedagogy in which prior knowledge building, visuals and more concrete example might make the abstract content knowledge of radiation physics more accessible.

4.4.4 Liminality

Meyer and Land (2006) use the term 'liminality' in the sense of a 'rite of passage' that the student has to undergo before being accepted into the disciplinary community. Cousin (2006a) describes how students often become 'stuck' and oscillate between understanding and misunderstanding. Several 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 she's going to ask you is how are you going to bring in your first beam? How are you going to place your first beam? What do you know at first year? I think our approach now because we shelter our students as well, things are – we are kind of softer to what the staff used to be before. They were cruel and … I needed to go read physics background before I was rostered (B_All_7).

Land (2011) proposes that if the liminal space is not traversed, the student will only be able to perform in a 'ritualised manner'. This description is echoed in the 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, I don't know if it's an issue of critical thinking you know. For them, theory and practical, 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 … I'm told to do this, do this, do this. This is how we do it. Because sometimes I ask a question, you do this, but why? Because that's the difference between somebody who studied for this because I can take anybody from the students, say do you want to train that [inaudible] but you need to understand why am I doing it … (A_Rx_2).

4.4.5 Irreversible

The idea of irreversibility was explained by the senior students as a gradual process of cumulative learning and gaining insights:

> Radiation physics … then it just gets … how can I put it … gets more clarity … with every single time I got introduced to it again (Y2_L4_2018).

For many lecturers, for whom the concepts of radiation physics had long been internalised 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 mid-line 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. So that – and I don't think it's something that you can really explain once or twice or thrice and expect them to understand. 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).

4.4.6 Reconstitutive

The inclusion of 'reconstitutive' as a threshold concept characteristic (Meyer & Land, 2005) 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:

> Because that would make sense because 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 and what did the [radiation therapists] do on that plan in order to execute (Lecturer 1).

4.4.7 Discursive

The 'discursive' dimension was also a later addition to the Threshold Concept Framework (Meyer & Land, 2005), to indicate that the crossing of a threshold concept would be likely to incorporate an enhanced and extended use of the language of the discipline. 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 lay-men'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 start to use the disciplinary and professional discourse, as shown in the exchange between the interviewer and first year student, who had returned from the first clinical rotation:

Interviewer:	Just – what did you see and how did you do it?
Y1_L8_2018:	Oh, firstly you put the patient on the bed. Then you align the midline…
Interviewer:	What else after the midline?
Y1_L8_2018:	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.

4.4.8 Transformative (knowledge and identity)

A threshold concept, once understood, is said to enable 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 students, these transformative shifts tended to happen in the clinical environment, rather than in the radiation physics classroom. A first year student, recently back from her first clinical experience described 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 learnt from there (Y1_L10_2018)

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 (A_Rx_1).

In other words, they might have the concept of a sep (separation), but it is unlikely to become an internalised, irreversible or transformative concept unless they have extended clinical experience. The clinical educators 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 realise but they can't do it or they don't do it correctly and then you try to help and they're not always very open to suggestion (A_Rx_2).

Reaching the point of transformative understanding and 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 we can't actually have the mind-set that we used to have with students prior to this course because it's completely different. And we only, I think what we want to see in a fourth year, we're possibly only going to see when they do community service (B_All_6).

4.5 An Internal Language of Description for Radiation Physics

The value of the Threshold Concept Framework, as can been seen above, has been to systematise some of the randomness that arose from the empirical circle by overlaying a logical framework. However, the Threshold Concept Framework does not entirely explain the nature of radiation physics and its threshold and non-threshold concepts. For example, the framework conflates the knowledge structure of the concept with the experience of the concept. While the characteristics of being ‘bounded’ and ‘integrative’ seem to describe the concept; the descriptors of ‘troublesome’, ‘irreversible’, ‘transformative’ describe the experience and attainments of learning. These terms are subjective and difficult to measure as they are neither precise nor measurable (Nicola-Richmond et al., 2018). The Threshold Concept Framework has been debated in the literature and its theoretical inconsistencies have been pointed out (e.g., Barradell, 2013). These limitations do not mean that the Threshold Concept Framework is without value. This is where an internal language of description (the inner circle of Figure 4.1) can be used to strengthen the external language of description.

In Chapter Two, LCT was introduced. LCT was chosen as a knowledge based theory that was appropriate for the analysis of threshold concepts in the first year radiation physics curriculum, as well as for investigating its relation to clinical practice and for understanding the ways in which learning radiation physics was (or could be) facilitated. The particular dimension chosen, Semantics, provided an analytical lens for understanding the semantic profiles of threshold concepts in radiation physics as a disciplinary field, for understanding how semantic gravity and semantic density increased and decreased in curricula and pedagogy, as well as for understanding how radiation physics underpinned radiation therapy practice, through the strengthening and weakening of epistemic semantic gravity.

Through the analytical lens of Semantics, radiation physics is seen as having a stronger semantic density and a weaker semantic gravity (Figure 4.2). The threshold concepts embedded in radiation physics could be seen as increases in sematic density and decreases in semantic gravity that create ‘epistemological obstacles’ (Meyer & Land, 2005: 377) to learning. In other words, in those areas where the semantic density increases and semantic gravity decreases, students who are learning the discipline are experiencing them as ‘troublesome’. Students then (usually temporarily) enter the liminal zone in which confusion reigns (Figure 4.2). The liminal zone can be described as an area of relatively low semantic density and semantic gravity as students misunderstand complex concepts. In this case study, the zone is not one of low levels of challenge, but one of misunderstanding and error.

As the students become able to access and understand the stronger semantic density of the threshold concept, they cross the threshold into clarity. When they venture into the clinical environment, they move into an area of high epistemic semantic gravity. In doing so, they have to move from an area of weaker semantic gravity to one of stronger epistemic semantic gravity as they apply radiation physics in skilled and specialised practice. The students will also have to acquire the stronger epistemic semantic gravity associated with patient care more generally. All these aspects need to be taken into account by radiation physics lecturers and clinical educators who have to teach the difficult concepts of radiation physics and understand their role in underpinning radiation therapy.

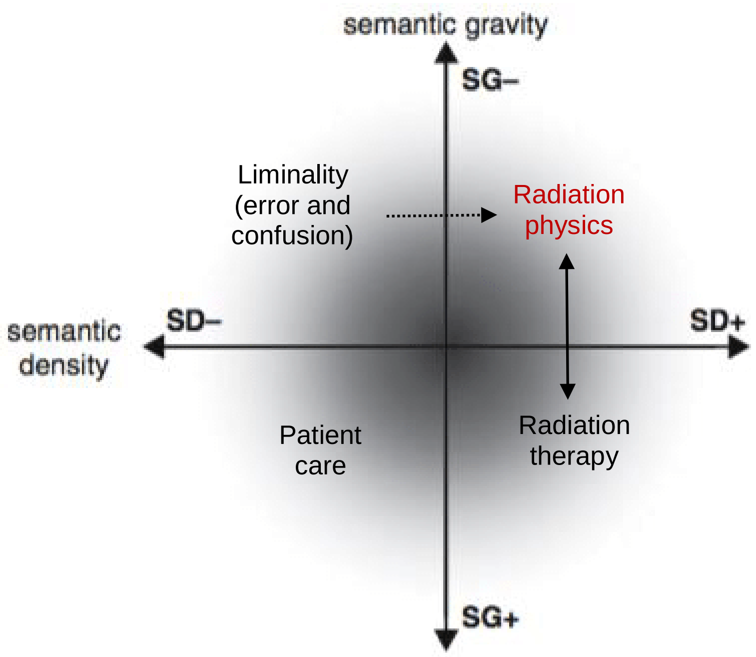


Figure 4.2 The Semantic Plane for Radiation Physics adapted from Maton (2014)

4.6 A revised External Language of Description for Radiation Physics

When the internal language of description (LCT) 'dialogues' with the initial external language of description (as was starting to happen in the paragraph above in which semantic density, semantic gravity and epistemic semantic gravity were used to 're-frame' the Threshold Concept Framework) a revised language of external description was developed that has improved explanatory power. Inconsistencies in the initial Threshold Concept Framework, such as the conflation of knowledge and processes of knowing, can be addressed. The revised external language of description that draws on the concepts of semantic density, semantic gravity and epistemic semantic gravity can now distinguish concepts of radiation physics and the ways in which radiation physics is experienced by different participants. This is explained by Bernstein (1996) as follows:

> Briefly, a language of description is a translation device whereby one language is transformed into another. We can distinguish between internal and external languages of description. The internal language of description refers to the syntax whereby a conceptual language is created. The external language of description refers to the syntax whereby the internal language can describe something other than itself (Bernstein, 1996: 135-6).

The revised external language of description is able to 'describe something other than itself' in this case, radiation physics. The revised language of description is more coherent and more logical than the initial external language of description because it has, as Bernstein (2000) further explains, a 'higher degree of applicability':

> The external language of description is constituted by propositions and models derived from the internal language of description, now with a higher degree of applicability. It is the external language of description that activates the internal language of description (Bernstein, 2000:168).

4.6.1 Boundedness or disciplinarity

In the revised external language of description, the notion of 'boundedness' is enhanced with the more precise descriptors of semantic density, semantic gravity and epistemic semantic gravity. Radiation physics has stronger semantic density and weaker semantic gravity. In threshold concepts the semantic density increases. What also starts to make sense, in terms of the revised external language of description is why the nature of radiation physics was not consistently described in terms of disciplinary knowledge, why it was often explained in terms of radiation therapy practice, and why it was often sequenced with the logic of practice in teaching. With reference to the Semantic plane (Figure 4.2), radiation therapy draws down what it needs from radiation physics for the specialised treatment of patients, while radiation physics has an external gaze towards radiation therapy as a field of practice. Patients are always at the centre of practice. Thus it makes sense for radiation therapists who teach radiation physics to understand it in terms of practice, that is, epistemic semantic gravity, 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 amongst 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] … it's the must have?
Senior Student:	It has nothing to do with physics, but I would say patient care is always number one (Y3_L3_2018).

The revised external language of description revealed that radiation physics can have a dual nature. It always has stronger semantic density, and stronger epistemic semantic gravity, but can have stronger or weaker sematic gravity.

4.6.2 Integrative, vertical and horizontal

In LCT terms, the integrative nature of both non-threshold and threshold concepts in radiation physics refers to their vertical knowledge structure (Bernstein, 1999), which means that their concepts are vertical and cumulative; one concept is built on the other. It is difficult, if not impossible, for students to acquire more advanced concepts, particularly threshold concepts, if there are conceptual gaps in their understanding. As a radiation physics lecturer explained:

> I think it's got to do with conceptualisation of basic principles that they are taught. Some people can't understand actually what we are doing (Lecturer 3).

4.6.2.1 Integrating practice

Radiation physics is so closely tied to radiation therapy, and its integrative nature enables it to describe practice in particular ways. Like thermodynamics which is the physics of mechanical engineering, and describes the physics of mechanics (Cartwright, 1983), so radiation physics is also an applied discipline that describes the physics of radiation treatment. This could be understood as horizontal integration.

4.6.3 Troublesomeness – the complexity of the vertical knowledge structures

The troublesomeness experienced by students and the knowledge structures that make the discipline and its concepts troublesome should not be conflated. Radiation physics uses three-dimensional geometry, a complex form of geometry containing complex concepts. These three dimensional concepts that are embedded in radiation physics can lead to students experiencing difficulties:

> But 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 with a, a lung with say maybe in the middle lobe, somewhere in the middle. You know it's important to spare the other lung those kind of little stuff and that comes with experience. So I think maybe they should start a little bit earlier with the clinical tuts on the planning part. Maybe just simple stuff like gynae … you know, just to get you know, where must a field go? How must it be labelled? Those simple type of things they struggle with (Lecturer 1).

The integrative, vertical and cumulative nature of radiation physics accounts for threshold concepts in radiation physics. These threshold concepts (as well as complex, vertical and cumulative non-threshold concepts) explains its 'troublesomeness' as a discipline. Radiation physics is densely packed with non-threshold and threshold concepts. It has ever-increasing semantic density comprising multiple non-threshold and threshold concepts, each of which needs to be mastered by the students in order for them to move to the next one.

4.6.4 Liminality: confusion in traversing the semantic plane

Being in a state of 'liminality' is a characteristic of students learning threshold concepts. Thus 'liminal' describes the students' confusion, and is not a descriptor of a threshold concept. Land describes the liminal state as 'approximate to a kind of mimicry or lack of authenticity' (Land 2011). This state is identified by the lecturer quoted below who describes a student as a 'robot', 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).

Students will inevitably spend time in a state of confusion, in which they will experience difficulties in understanding, discussing, and writing. With reference to the semantic plane (Figure 2.1), liminality could be understood as an expression of 'rarefaction' (SG-, SD-), that is a space of weaker semantic gravity (SG-), or a disorienting decontextualization, and weaker semantic density (SD-), or reduction in meaning. Liminality is consequently evident in students' inadequate contextualization or transfer of concepts to practice, as well as their oversimplification or misunderstanding of concepts. The liminal space should be a safe space for students to learn from their mistakes (Land, 2011), but practice based on an incorrect understanding of radiation physics concepts would have dire consequences for patient care.

For the above reason, it is important that students move from 'rarefaction' (SG-, SD-) towards the 'rhizomatic' plane of stronger semantic density (SD+), or clarified and more concentrated meaning, and the 'worldly' plane of stronger contextual relevance. The recursive movement from the rarefied plane towards the rhizomatic plane and the worldly plane as shown in Figure 4.2. Liminality could be understood, with reference to Semantics, as the processes involved in undergoing code shifts from the rarefied to the rhizomatic plane (e.g., from SG-, SD- → SG-, SD+) and from the rhizomatic to the worldly plane (SG-, SD+ → SG+, SD+), as shown in Figure 4.2.

4.6.5 Irreversible understandings, but constant concepts

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). In this description Clouder (2005) conflates knowledge structures with the learning process. Walker (2013), in her critique of the Threshold Concept Framework, suggests that the framework is a cognitive framework, rather than a framework for describing concepts; she notes 'a great deal of conceptual overlap between schemas and threshold concepts' (Walker, 2013: 251). In the revised external language of description, threshold concepts are not understood to be irreversible – while they are subject to the strengthening and weakening of semantic density, semantic gravity and epistemic semantic gravity, none of these shifts is 'irreversible'.

4.6.6 Reconstitutive

Initially, Meyer and Land (2005) understood that it was students' thinking that was 'reconstituted' following the crossing of the threshold concept:

> What is being emphasised [in reconstitutiveness] is the inter-relatedness of the learner's identity with thinking and language (Meyer and Land, 2005: 375).

In a later work, however, Land and colleagues (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. Together these features bring about the required new understanding. As a consequence of this new understanding the learner crosses a conceptual boundary into a new conceptual space and enters a post liminal state in which both learning and the learner are transformed. This is an irreversible transformation and is marked by a changed use of discourse. These latter effects – the crossing of conceptual boundaries, transformation, irreversibility and changed discourse – can be characterised as consequential features of the threshold concept (Land, Meyer & Baillie, 2010: iii).

Although the above description conflates the threshold concept with the learner and the process of learning, there is a claim that ontological/epistemological shifts are evident in concepts. In LCT terms, a 'reconstitution' of the threshold concept would involve strengthening or weakening of semantic density, semantic gravity and epistemic semantic gravity as part of the process of recontextualising radiation physics for pedagogy or for practice. This suggests that disciplines can shift towards practice, which is characteristic of applied disciplines in particular. This 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 pre-clinical skills then translate into good practice when they do clinical skills so that they understand when I'm doing this set up, I need to apply the x, y and z that I learnt to understand where this patient needs to shift on the bed. 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 the above description, Lecturer 1 understands radiation physics, relation to practice in a number of ways. It is described as a set of pre-clinical skills that underpin the clinical skills. Radiation physics is seen as '…those bases…' that enable students to understand the planning principles and the patient set-up. In LCT terms, Lecturer 1 identifies the semantic density of radiation physics in the epistemic semantic gravity of radiation therapy practice.

4.6.7 Discursive: specialist languages

Meyer and Land (2005) 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. This extension of language might be acquired, for example, from that in use within a specific discipline, language community or community of practice, or it might, of course, be self-generated. It might involve natural language, formal language or symbolic language (Meyer & Land, 2005: 374).

Thus the language of radiation physics would require a stronger semantic density and weaker semantic gravity in the academic language of the classroom. A specialised language of practice is also required, stronger epistemic semantic gravity is evident in the specialised language of professional practice. First year students would find it difficult to remember the specialised terms and specialised ways of communicating disciplinary knowledge, and would initially show this through weaker semantic density in radiation physics, but would acquire the disciplinary discourse over time. They would also acquire the appropriate discourses for the clinical environment, when communicating with patients, using jargon with colleagues, or more formal communication with other professionals (Wyrley-Birch, 2010).

4.6.8 Transformative

In the process of learning, the learner changes, as Land and colleagues (2010) explain: 'the outcome of transformative learning … is that the contents 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 'transformative', high levels of understanding and high levels of practice can be attained. In LCT terms, this involves the attainment of stronger semantic density, weaker semantic gravity, and stronger epistemic semantic gravity. This was expressed 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 (Y1_L11_2018).

4.7 Conclusion

Table 4.1 summarises the revised external language of description for radiation physics, drawing on the analysis covered in Chapter 4 and the translation device (Table 2.2). The 'bounded' or disciplinary nature of radiation physics is described, in particular how threshold concepts in radiation physics emerge. The 'integrative' tendency of radiation physics, due to its hierarchical knowledge structure and its role in underpinning practice is understood as an important aspect of threshold concepts. The 'troublesome' nature of threshold concepts is explained as rises in semantic density and epistemic semantic gravity, but the weakening in semantic gravity. 'Liminality', when both the semantic density and semantic gravity are too low, were explained as code shifts across the Semantic Plane. Irreversibility was excluded from the revised framework as it describes the state of attainment of the threshold concept, rather than the nature of the threshold concept. It also explains the 'distance' between experts and novices, and this is helpful in understanding pedagogy, but not helpful for understanding threshold concepts. The reconstitutive nature of threshold concepts in radiation physics is similar to its 'integrative' tendency, but in the case of radiation physics applied more specifically to its underpinning of radiation therapy practice and the reciprocal relationship between semantic density and epistemic semantic gravity; simultaneous rises in both semantic density and epistemic semantic gravity create threshold concepts. The specialist scientific and mathematical languages and other 'discursive' practices are aligned with the semantic profile of radiation physics, that is, they mirror the levels of semantic density and epistemic semantic gravity. Attaining a threshold concept is potentially transformative, as it implies a high level of understanding and a concomitant high level of professional practice.

Table 4.1 The Revised External Language of Description

Initial External Language of Description	**The revised External Language of Description**	**Semantic codes for threshold concepts**	**Examples from the Data**
Bounded	The disciplinary characteristic of radiation physics is stronger SD, weaker SG, and stronger ESG. Increases in SD and ESG create threshold concepts	SD3/4 SG1 ESG3/4	*Physics is not really something that you can animate because it's theory. It is what it is, what it is … you're teaching a concept (Lecturer 4).*
Integrative	Concepts are vertically integrated and cumulative in radiation physics, but concepts can also be applied in practice, creating a range of both stronger SD and stronger and weaker ESG.	SD3/4 SG1 ESG0/1/2/3/4	*'if you don't actually understand the concept, you can't put a picture together of what is' (Y3_L3_2018).* *'…the linking of their book-based knowledge into clinical practice (A_Rx_1).*
Troublesome	'Troublesomeness' is experienced as SD strengthens when threshold concepts are encountered, while SG is low. ESG can vary in strength in threshold concepts.	SD3/4 SG1 ESG0/1/23/4	*When they [clinical staff] mention SUP and moving from the reference to the isocentre…calculating that could be confusing at times (Y1_L6_2018).*
Liminality	When students misunderstand threshold concepts SD and ESG might be too low for accurate representation, or SG might be so high it obscures meaning.	SD0 SG4 ESG0	*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 (Y3_L3_2018).*
Irreversible	Threshold concepts in radiation physics are not irreversible, their basic state is constant. Irreversibility describes the learning process.	-	*Radiation physics … then it just gets … how can I put it … gets more clarity … with every single time I got introduced to it again (Y2_L4_2018).*
Reconstitutive	Radiation physics, at higher levels of SD can reconstitute itself in practice, or as underpinning practice, evident in the reciprocal relationship between SD and ESG at higher levels.	SD3/4 ESG3/4 SG1	*when the light-bulb moment comes, when you can amalgamate why you're doing that in planning and how you got the end result (B_All_2).*
Discursive	Discursive practices in an academic setting express stronger SD, while in the clinical setting will have stronger ESG as well.	SD3/4 ESG3/4 SG1	*I think the difference between SSD and the different setups of the fixed Iso and the Iso on the patient itself (Y1_L5_2018).*
Transformative	Transformation is understood as attaining the highest level of understanding (SD4) and an equally high level of competence professional practice (ESG4).	SD4 SG1 ESG4	*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 …(Y1_L10_2018).*

In this chapter a revised external language of description for threshold concepts in radiation physics was developed. The new external language of description bridged the discursive gap between the internal language of description, LCT's Semantics and the initial external language of description provided by the Threshold Concept Framework. In the next chapter, the focus is on the first year radiation physics curriculum.

CHAPTER FIVE

IDENTIFYING THRESHOLD CONCEPTS IN THE FIRST YEAR RADIATION PHYSICS CURRICULUM

5.1 Introduction: Unpacking Radiation physics for Radiation Therapists

The focus of Chapter Four was the development of an external language of description for threshold concepts in radiation physics, drawing on LCT's Semantics dimension. This chapter focuses on the identification of threshold concepts in radiation physics within the first year Physical Science curriculum. Physical Science 1 is a subject within the Bachelor of Science in Radiation Therapy qualification. It comprises three modules, namely Physical Science 1 A (which is an introduction to general Physics), Chemistry for Radiation Therapists (which is a short introduction to the structure and properties of atoms), and Physical Sciences 1 B (which introduces radiation physics).

The first section of Chapter Five takes an in-depth look at the first year radiation physics curriculum, drawing on the external language of description to explain its logic. This analysis focuses on the first year Physical Sciences curriculum, drawing on Bernstein's (1977) view of curriculum as the organisation of knowledge. Attention was given to selection, sequencing, pacing:

- Selection: What was included and why?
- Sequence: How important was the order in which concepts are introduced?
- Pacing: How was time allocated in the curriculum?

The sections that follow explain how the threshold concepts were identified in curriculum documents and students' assessments. The final section explains the threshold concepts that are embedded in this curriculum, drawing on the external language of description. Focusing attention on the threshold concepts requires the explanatory power of the external language of description. The chapter thus further refines the set of theoretical tools for conceptualising threshold concepts. Finally, the chapter highlights some implications towards a pedagogy for threshold concepts in radiation physics.

5.2 Selection, sequencing and pacing in the first year radiation physics curriculum

The Bachelor of Science in Radiation Therapy qualification curriculum was benchmarked against international curricula offered by a range of providers (including the International Atomic Energy Agency, the European Society for Radiotherapy and Oncology's curriculum for radiation therapists (Eriksen et al., 2012), and the University of Wisconsin), as well as South African institutions (including Durban University of Technology and the Central University of Technology) offering a similar 'classic curriculum' (Khan & Gibbons, 2014). The content selected for inclusion in a curriculum and the ways in which it is sequenced and timed reveals the knowledge that is valued by the curriculum developers. With regard to curriculum at the level of the whole qualification, the underpinning logic is the logic of practice:

> [The qualification] enables the professional to competently apply an integration of theory … practical experience and appropriate skills to the solution of well-defined and abstract problems in Radiation therapy (DocReview_SAQA, 2018).

The terminology used throughout the curriculum documents emphasises the intention of the programme to develop students towards becoming competent professionals, which includes their ability to translate theory into practice. In LCT terms, the curriculum documents emphasised both semantic density in the form of the underpinning science and epistemic sematic gravity in the therapy focus across the overall qualification. The whole qualification could thus be described as having both strong semantic density and strong epistemic semantic gravity. Semantic gravity did not appear in official curriculum documents as there was no place for the 'everyday' in the formal qualification description.

Focussing on the role of physics in the Bachelor of Science in Radiation Therapy qualification, there is considerable curricular space (and time) allocated to the study of Physics – as Table 5.1 shows. In the first two years, radiation physics is a module in the subjects of Physical Science 1 and 2. Physical Sciences 1 and 2 are pre-requisites for the Physics of Radiation therapy 3 and 4. Radiation physics is a strong component of these subjects. The 'hierarchical knowledge structures present in physics are often mirrored in correspondingly hierarchical curriculum structures' (Conana et al. 2020). In the case of the physics curriculum across the four years of the qualification (Table 5.1), the curriculum structure is hierarchical, with the junior level courses building conceptually towards the more theoretical and abstract senior level courses.

Table 5.1 Summary of alignment of radiation physics content across the four levels of the BSc: Radiation Therapy

Study level	Subject name	Selection of topics in radiation physics	Alignment
First year	Physical Science 1	Physics of Radiation	Radiation
Second year	Physical Science 2	Particle Physics, X-rays, Introduction to Radiation therapy equipment	X-rays
Third year	Physics of Radiation therapy 3	Dosimetry of the radiation beam	Dosimetry
Fourth year	Physics of Radiation therapy 4	Specialised Radiation therapy equipment, planning, dosimetry and quality control	Radiation therapy equipment and quality control

The physics content starts off with general physics, for example, in the first year study guide the modules covered were listed as Classical Physics, Modern Physics and the Physics of Medical Imaging. The Physics of Radiation, a key learning topic, was situated in the Modern Physics module (DocReview_Y1LG_2018). Increasingly, radiation physics, as represented in the curriculum, relates strongly to clinical practice. Bernstein (1977) calls this process one of re-contextualisation:

> This process of selection, abstraction and re-focusing leads to re-contextualizing (Bernstein, 1977: 29).

Re-contextualisation starts in the first year, but more obviously so in the third and fourth years. The Physics of Radiation Therapy 3 subject's purpose explicitly states that the subject focuses on:

> …the theory underpinning the knowledge of radiotherapy physics in order that the various radiation therapy modalities and radiotherapy needed, integrates the theoretical knowledge with the practical applications in the clinical work situation (DocReview_Y3LG_2018).

As the study level increases, so the level of complexity of the radiation physics concepts also increases. The concepts also become increasingly specialised. The third year student guide states that:

> …the implementation of the theoretical knowledge and the Physics of Radiation therapy 3 can be integrated with Radiation Therapy Practice 3 (DocReview_Y3LG_2018).

There is an underpinning relationship between the physics curriculum and the clinical subjects. Physics concepts are initially introduced as abstract theory in Physical Science 1 and 2, and then more strongly applied to practice in Radiation Therapy Practice 3. The increasing focus on practice and the shift from 'classic' physics to radiation physics across the curriculum could be understood as increases in both semantic density and epistemic semantic gravity.

The underpinning science subject in first year of the Bachelor of Science in Radiation therapy, is Physical Science 1. The subject starts with an introduction to classic physics, Physical Science 1 A, while the basics of radiation physics is introduced in Physical Science 1 B. There are other complementary subjects that relate to Physics:

> The Physical Sciences 1 cluster consists of Physics 1A, Physics 1B, Chemistry 1A modules, and elements of Medical Imaging and Oncology (MIO) and Radiographic Technology 1. The introduction to Physical Sciences 1 for Radiography underpins the Physics principles encountered in current and cutting edge medical imaging and prepares students for future imaging technologies. The course aims to develop the necessary:
>
> - Content knowledge,
> - Conceptual and cognitive skills,
> - Contextual articulation of Physics (and chemistry) with radiography, and
> - Problem-solving skills applied to real-world, field-of-practice situations (DocReview_Y1LG_2018).

Curricular selection '…is essentially a selection from the culture of a society' (Ellis, 2006). What is important in radiation therapy is practice – both current and potential future practice. The first part of the curriculum Physics 1 A builds students' understanding of general physics principles and 'thinking tools', while the second part, Physics I B lays the ground work for skilful practice through the 'contextual articulation of Physics (and chemistry) with Radiography' (refer to Appendix 3.10 for the Physical Science 1 section of the first year learner guide). Table 5.2 shows the strong focus on the knowledge practices used in the profession as stated in the general curriculum documents:

Table 5.2 The First Year Physical Science Curriculum (DocReview_Y1LG_2018)

Physics selections	Key themes
PHYSICS 1 A	
1. Mechanics	- Physics of Motion

2. Kinematics	- Why should we care about motion? - Linear Motion - How to describe motion
3. Force	- Physics of Forces
4. Dynamics	- Forces cause acceleration - Resultant Forces - Newton's 3 Laws of Motion - Gravity
5. Energy	- Physics of Energy
6. Work, Energy, Power	- Energy of a System - Conservation of Energy
7. Linear Momentum	- Conservation of Momentum
8. Rotational Motion	- Physics of Rotational Motion
9. Rotation and Torque	- Conservation of Angular - Momentum
10. Geometric Optics	- Physics of Light (1)
11. Reflection and refraction	- Light as a Ray - Concept of Reflection - Concept of Refraction
	- Physics of Electricity & Magnetism
12. Electro-statics	- Nature of Electrical Charge - Behaviour of Electrical Charge - Concept of Electric Fields
13. Electric current	- Flow of Charge - Basic Circuits - Electricity and the Body
14. Magnetism	- Nature of Magnetism
15. Electro-magnetic induction	- Concept and Application of Electrical Induction
CHEMISTRY FOR RADIOGRAPGHY	
16. Chemistry selections	- Atoms and Elements - Molecules and Compounds - Chemical Bonding - Chemical Reactions and Quantities
PHYSICS 1B	
17. Properties of Matter	- Atomic Nature
18. Solids, Liquids, Plasmas	- Solids, Liquids, Plasmas
19. Heat energy	- Temperature, Heat and Expansion - Heat Transfer - Change of Phase - Thermodynamics
20. Sound	- Physics of Sound
21. Vibrations and waves	- Energy transmitted through a wave
22. Sound	- Nature of sound
23. Light as a wave	- Physics of Light (2)
24. Properties of Light	- Light as electromagnetic waves
25. Colour	- The colours we see
26. Light behaving as a wave	- Light as waves: effects
27. Light emission	- Ways in which light is emitted
	- Modern Physics
28. Light as Quanta	- Physics of Light (3)
29. Quantum nature of light	- Light as quantised photons
30. Atomic and Nuclear Physics	- Physics of Radiation

31. The Atom and the quantum	- Atoms - Quantum Mechanics
32. The Atomic Nucleus and Radioactivity	- Radioactivity - Radiation
33. Clinical Radio-isotope decay	- Clinically useful radionuclides and radio isotopes used in Medical Imaging - Decays in the human body
34. Nuclear fission and fusion	- What is fission and fusion? - Fission and fusion reactions.
35. Radiation protection Physics	- Introduction to radiation protection
36. Introduction to Medical Imaging	- Physics of Medical Imagining
37. Convergence of acquired Physics knowledge to imaging applications	- Acquired Physics Knowledge to Imaging Applications - Overview of main imaging modalities, Image production and appearance

In any physics curriculum there is likely to be different ideas about what is important (Ellery, 2017). Since the curriculum was developed by both physics lecturers and radiation therapy lecturers and practitioners, it is inevitable that different approaches would be evident in the curricular selections. Table 5.2 above, however, predominantly shows the influence of the hierarchical structure of physics (Bernstein, 2000; Muller, 2015) in the first year Physical Sciences curriculum. Bernstein (2000) uses 'knowledge structure' to explain the manner in which knowledge accumulates or is produced. Bernstein (2000) characterises differences between the disciplines using the metaphors of 'hierarchical' and 'horizontal' knowledge structures (see Section 2.7.4). Physics is one of the disciplines that is:

> broadly characterized as hierarchical, in other words, they grow cumulatively, by subsumption of phenomena into increasingly higher-order explanatory principles/laws (Shay, Wolff & Clarence-Fincham, 2016: 77).

For example, general and basic concepts in the Physics of Light (e.g., reflection and refraction) are developed and extended into more complex concepts of light (e.g., light as a wave, light as quantised photons). Other concepts are similarly integrated and subsumed across the Physical Sciences curriculum. Bernstein (2000) uses physics as an example of 'hierarchical knowledge', that is, it is produced through concepts that build upon one another towards increasingly higher levels of complexity and abstraction. This is particularly the case in Module 1 A, which could be said to have stronger semantic density and weaker semantic gravity, as well as weaker epistemic semantic gravity.

However, in Module 1 B (topics 17 – 37) the curriculum points more clearly towards the Physics of Radiation and its role in underpinning practice. This is graphically illustrated as a semantic profile in Figure 5.1. The x-axis represents the 37 topics of the Physical Sciences curriculum, and the y-axis indicates the four levels of semantic density, semantic gravity and epistemic semantic gravity. The physics concepts follow the physics hierarchy, moving from atoms to quantum mechanics, to radioactivity and radiation. This indicated as SD1 in Figure 5.1 because the semantic density of the general physics curriculum is relatively less dense than the semantic density of the specialised radiation physics curriculum (SD1 – SD4). From topic 17 onwards, elements from radiation therapy practice, such as radiation protection and radioactive decay in the human body make an appearance, and in LCT terms, indicate a rise in epistemic semantic gravity (ESG1 – ESG4). The semantic gravity (that is, the ‘everyday’) is not apparent and is represented as a low flat line (the dashed line in Figure 5.1), indicating the absence of context and abstract nature of the curriculum documents. The role of radiation physics in underpinning radiation therapy practice is evident in the steep rise in epistemic semantic gravity (the dotted line), following the greater focus on radiation therapy practice after topic 29. Figure 5.1 provides the semantic profile of the first year physics curriculum, showing the typical physics semantic profile of stronger semantic density and weaker semantic gravity. From topic 17 onwards, the applied discipline of radiation physics is introduced. Figure 5.1 shows the greater detail and complexity of the radiation physics curriculum documents by the rises in semantic density and the steep rise in the epistemic semantic gravity over the final topics.

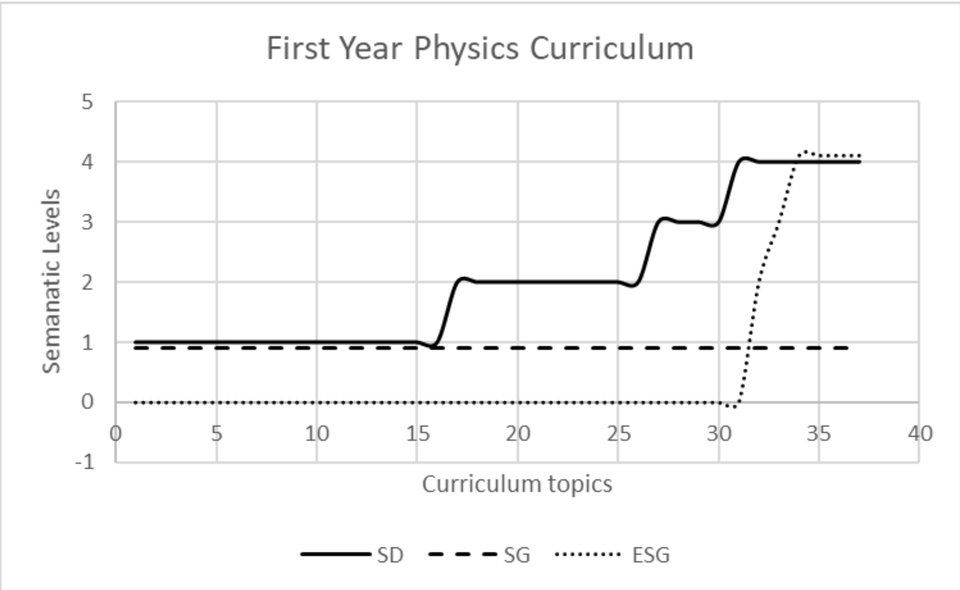


Figure 5.1 The Semantic Profile of the First Year Physics Curriculum (The radiation physics module begins at topic 17).

As described in Section 3.7.6, curriculum documents such as qualification registration documents and student guides (also known as course readers) were studied in order to understand how radiation physics concepts were structured within the first year curriculum, with a view to identifying threshold concepts that might be potential sticking points in the curriculum. As an academic subject, radiation physics draws from core disciplines such as mathematics and physics and feeds into other academic subject. Studying the radiation physics curriculum documents revealed a range of concepts that students were required to master, such as atomic and nuclear structure, radiation quantities and units, classification of radiation, properties of radiation, and so on.

Table 5.3 The Semantic range across the Physical Science 1 curriculum

Semantic range			Modules	Descriptors	Examples
SD3-4	SG0	ESG3-4	Physics 1 A	Mechanics, Kinematics, Force, Dynamics, Energy, Work, Energy, Power, Linear Momentum, Rotational Motion, Rotation and Torque, Geometric Optics, Reflection and Refraction, Electro-statics, Electric current, Magnetism, Electro-magnetic induction	- Light as a Ray - Concept of Reflection - Concept of Refraction
SD1	SG0	ESG0	Chemistry for Radiography	Chemistry of the atoms and molecules.	- Atoms and Elements - Molecules and Compounds - Chemical Bonding - Chemical Reactions and Quantities
SD1	SG0	ESG1-3	Physics 1 B	Properties of Matter, Solids, Liquids, Plasmas, Heat energy, Sound, Vibrations and Waves, Light as a Wave, Properties of Light, Colour, Light emission, Light as Quanta, Quantum nature of light, Atomic and Nuclear Physics, The Atom and the quantum, The Atomic Nucleus and Radioactivity, Clinical Radio-isotope decay, Nuclear Fission and Fusion, Radiation Protection Physics, Introduction to Medical Imaging, Convergence of acquired Physics knowledge to imaging applications	- Clinically useful radionuclides and radio isotopes used in Medical Imaging - Introduction to radiation protection - Physics of Medical Imagining - Acquired Physics Knowledge to Imaging Applications - Overview of main imaging Modalities Image production and appearance

5.3 What was valued in the assessment of first year Radiation physics?

From a study of the curriculum documents alone, it was not possible to identify which of the concepts included in the radiation physics curriculum could be considered to be threshold concepts. While there were clearly many complex concepts, it was difficult to determine which concepts would offer the greatest levels of challenge. For this reason, an examination of assessment documents was undertaken.

Section 1A of the Physical Science 1 curriculum was assessed through the Basics of Physics course (Rowlands, 2018) offered as a Massive Online Open Course (MOOC), available at: https://www.mooc-list.com/course/basic-Physics-open2study. Below is an excerpt from the first year student guide where the MOOC was introduced and Figure 5.2 is a snapshot of its Homepage.

> You will be required to complete three MOOCs for the year.
>
> 1. The MOOC Project consists of 4 parts:
>   1.1. Familiarise yourself with start/end dates, and duration of the MOOC.
>   1.2 Enrol for the MOOC.
>   1.3 Participate in, and complete the MOOC.
>   1.4 Print out your certificate of completion and hand in the hard-copy timeously.
> 2. Three MOOCs are required for the year, one for each of the following:
>   2.1 Physics 1a
>   2.2 Physics 1b
>   2.3 Chemistry 1a.
> 3. The final weighting of the MOOCs towards each of the above is:
>   3.1 Physics 1a: 20% towards the second semester mark.
>   3.2 Physics 1b: 20% towards the second semester mark.
>   3.3 Chemistry 1a: 20% of the overall final mark.
> 4. The list of MOOCs which you are required to do will be published in the first term. Procedures for submission of the certificate of completion will be published at a later date. The following general rules apply:
>   4.1 You are expected to work independently on your MOOC.
>   4.2 Late submissions of your certificate of completion will be penalised at 5% per day.
> 5. The process towards a successful MOOC Project involves the following steps:
>   5.1 Consult with your lecturer/discipline coordinator frequently.

5.2 Notify your lecturer/discipline coordinator timeously of any problems encountered.

5.3 Observe timelines (DocReview_Y1LG_2018).

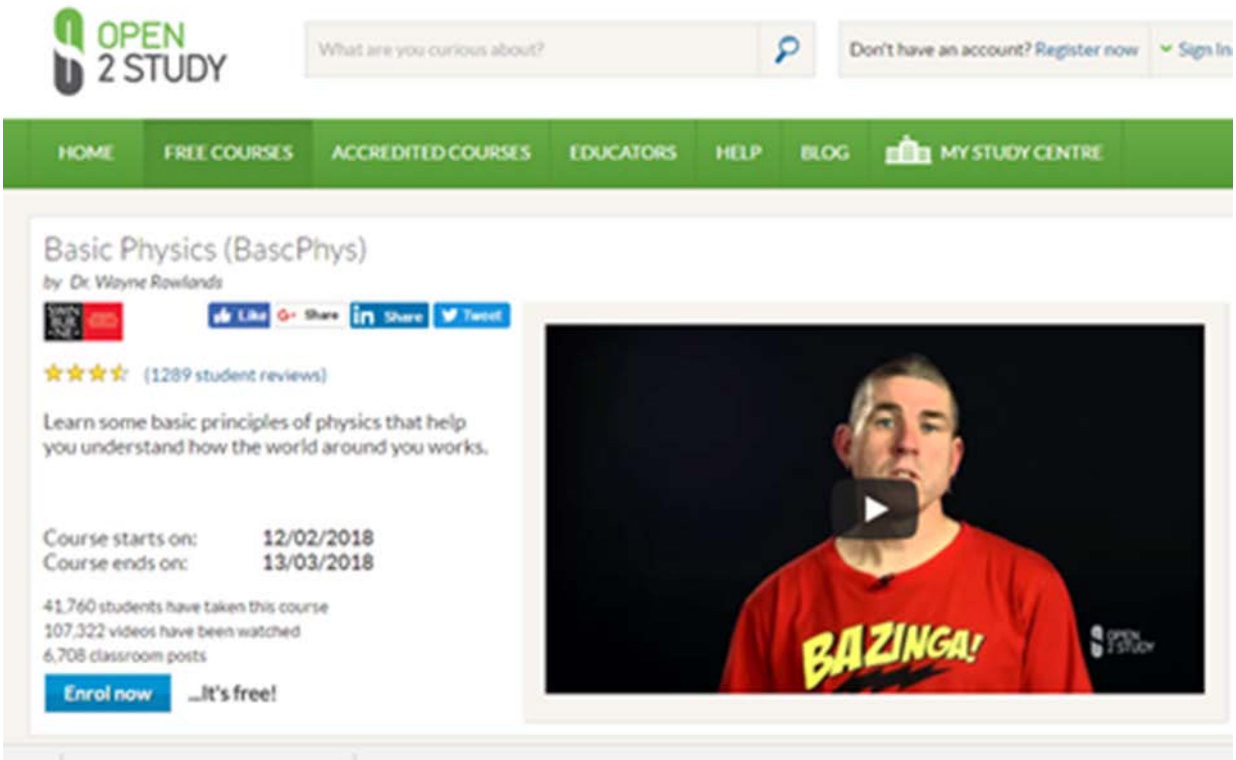


Figure 5.2 The Basic Physics MOOC (image from https://Open2Study.com)

The focus of the study is radiation physics; thus in in order to determine more accurately where students were experiencing difficulties in this section, that is Module 1 B of the Physical Science 1 course, a study of students' mark records, assignments, tests and examinations was undertaken. While analysing these documents it became clear that concepts that posed a high level of challenge included: radiation quantities and units, the classification of radiation, the properties of radiation, especially ionising radiation and the classification of ionising photon radiation, the isocentre, beam divergence, and the Inverse Square Law. These concepts were thus identified as potential threshold concepts.

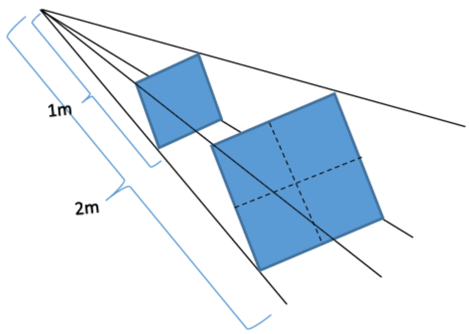
Examples of assessment tasks in radiation physics (i.e., Module 1 B of the Physical Sciences 1 curriculum) include the following example of a formative assessment task, a worksheet (Figure 5.3) to assess students' understanding of the Inverse Square Law:

Pair up with a classmate and answer the following:

1. How is the inverse square law applied in your chosen discipline?
   In radiation therapy the inverse square law plays a role in the reduction of radiation. It is known that the farther distance from the source you are, the less you are exposed. An example of this in radiotherapy is the maze-like corridor they build in the treatment room.

2. State the inverse square law by describing the relationship of x-ray quantity to distance.
   The x-ray quantity is inversely proportional to the square distance from the source. Thus, as the distance from the source increases, the intensity or x-ray quantity will decrease exponentially.

3. Draw a line diagram illustrating the change in radiation beam intensity if a patient is moved from 1m to 2m away from the x-ray tube. The initial intensity of the beam is 1.5 Gy.



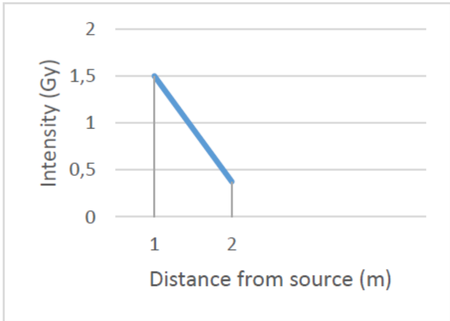


Figure 5.3 Questions from a worksheet used to assess students' understanding of the Inverse Square Law

A close study of the text and diagrams of the assignment above suggest that students are likely to find the task challenging. The semantic profile of the assessment task is shown in Figure 5.4:

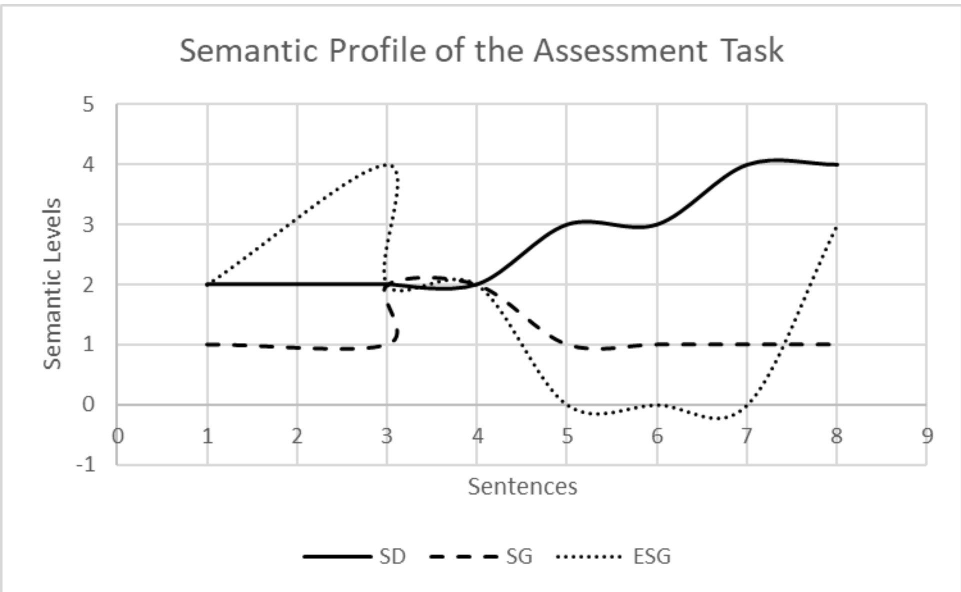


Figure 5.4 Semantic profile of the assessment task.

The x-axis represents the number of sentences in the task, and the y-axis represents levels of semantic density, semantic gravity and epistemic semantic gravity. The task is introduced in a relatively decontextualized way (SG1), although reference is made to specialised practice in the clinical context (ESG2). Students are required to explain the Inverse Square Law (SD3). After the scenario is given, the semantic density rises again, indicating the increasing level of challenge – culminating in the use of a mathematical representation (SD4). While the semantic gravity (dashed line) strengthens slightly in the form of the scenario, it soon drops to its usual low flat line, indicating the high level of abstraction (despite some contextualisation). The epistemic semantic gravity rises as the task is applied, and then falls as the task becomes more abstract and mathematical. There is no indication of a semantic wave that might enable cumulative knowledge building. For example, a more deliberate pacing of semantic gravity and sematic density, with a simple clinical task, involving basic epistemic semantic gravity, to which students' understanding of the Inverse Square Law is applied.

In a written test (Figures 5.5 and 5.6) questions were posed to first year students to determine their understanding of Ionisation and the Inverse Square Law:

Describe and use labelled diagrams to compare and contrast 'Ionisation' and 'Excitation'.

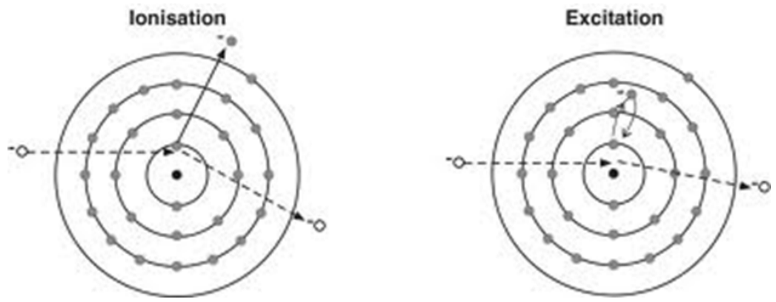


Figure 5.5 Assessment task for Ionisation and Excitation

Calculate the intensity of the radiation received by the second dog in the image below [use: $I_1/I_2 = (d_2/d_1)^2$].

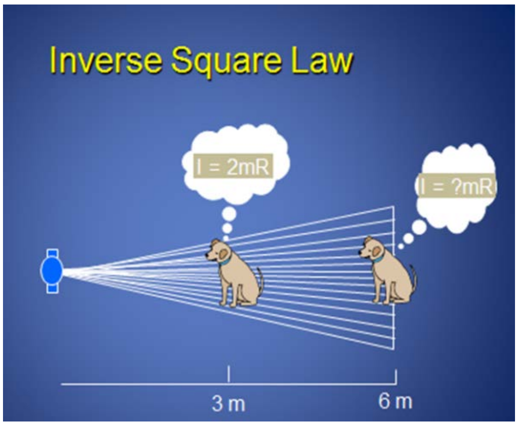


Figure 5.6 Assessment task for the Inverse Square Law

The semantic profile of Figure 5.5 and Figure 5.6 is a high semantic density flat line and low semantic gravity and epistemic semantic gravity flat lines, which is common in test questions. For first year students a semantic wave profile would be more likely to elicit more thought through responses.

The students' responses to the assignment (Figure 5.3) and test questions (Figures 5.5 and 5.6) showed their confusion between the concepts of ionisation and excitation, and well as their difficulties with the Inverse Square Law. Similar difficulties were experienced by students in their assessment with regard to the classification of radiation and the properties of radiation, although the latter concepts were not as challenging to students as the three concepts that more directly underpin radiation therapy practice.

A simulated clinical assessment, which is a task involving strengthened epistemic semantic gravity, comprising the preparation of a virtual patient for treatment, was used to ascertain first year students' knowledge of the isocentre. The purpose of the assessment task was to ensure that students could distinguish between the geometric isocentre and the treatment isocentre, as well as move from the reference to the treatment isocentre. The scenario below is an example of how their understanding of the isocentre (located in the centre of the tumour and demonstrated by means of an 'iso-shift' on the 'patient') was assessed:

> Mrs. X has been diagnosed with cancer of the cervix and is receiving radical external beam Radiation therapy to the pelvis.
>
> Using the anatomy loaded on the VERT system,
>
> Your Task is:

- Move to the reference axis provided
- Shift from the reference to the isocentre using the measurements provided (Time allowed: 15 minutes)

Most students made the distinction between the geometric isocentre and the treatment isocentre, and has effectively demonstrated that they have gained access to mastery of concepts and of a key distinction of a conceptual and practice configuration characterised by ESG3. The main difficulty was moving from the reference to the treatment isocentre, that is the increase in semantic density (SD4) – this indicate the possibility of the isocentre as a threshold concept. The reason why it is potentially a threshold concept is that it exists as a mathematical representation, thus a high level of semantic density, a low flat line of semantic gravity, and a high level of epistemic semantic gravity. The difficulties experienced by the students suggest that it is these intersections of stronger semantic density and stronger epistemic semantic gravity with a low flat line of semantic gravity that creates a threshold concept.

5.4 Threshold Concepts in the first year radiation physics curriculum

By studying the radiation physics curriculum documents, the student guides and the assessment tasks, 17 concepts were identified (Table 5.4). These concepts were defined in terms of 1) those relatively easy to define and apply within both theory-based and clinical contexts, 2) those that were difficult to define, but not to apply, and 3) those that were both very difficult to define and to apply. The identification of threshold concepts in a radiation physics curriculum poses many challenges (Hudson, Engel-Hills & Winberg, 2018).

The curriculum registration documents specify the clinical competence required by graduates, the end goal was therefore known. The documents communicating the delivered and enacted curricula over the four years provided the road map to get to the end goal.

Table 5.4 lists the concepts identified across the different documents studied, showing how the threshold concepts in first year radiation physics were identified:

Table 5.4 Radiation physics: Topics of Learning and Students' Difficulties

	Learning topics in Physical Sciences 1B	Areas of Difficulty and in which learning topic(s) they reside
1	Properties of Matter	
2	Solids, Liquids, Plasmas	
3	Heat energy	

4	Sound, Vibrations and Waves	
5	Light as a Wave	
6	Properties of Light, Colour	
7	Light emission	
8	Light as Quanta	
9	Quantum nature of light	Classification of Radiation
10	Atomic and Nuclear Physics	
11	The Atom and the quantum	Properties of Radiation
12	The Atomic Nucleus and Radioactivity	
13	Clinical Radio-isotope decay	
14	Nuclear Fission and Fusion	
15	Radiation Protection Physics	Ionisation; The Isocentre; The Inverse Square Law.
16	Introduction to Medical Imaging	
17	Convergence of acquired Physics knowledge to imaging applications.	

The five areas in which students experienced difficulty comprised concepts that were at the top of the semantic density rise in the first year radiation physics curriculum (see Table 5.3 and Figure 5.1) – but they are also the first year concepts that are most related to radiation therapy practice.

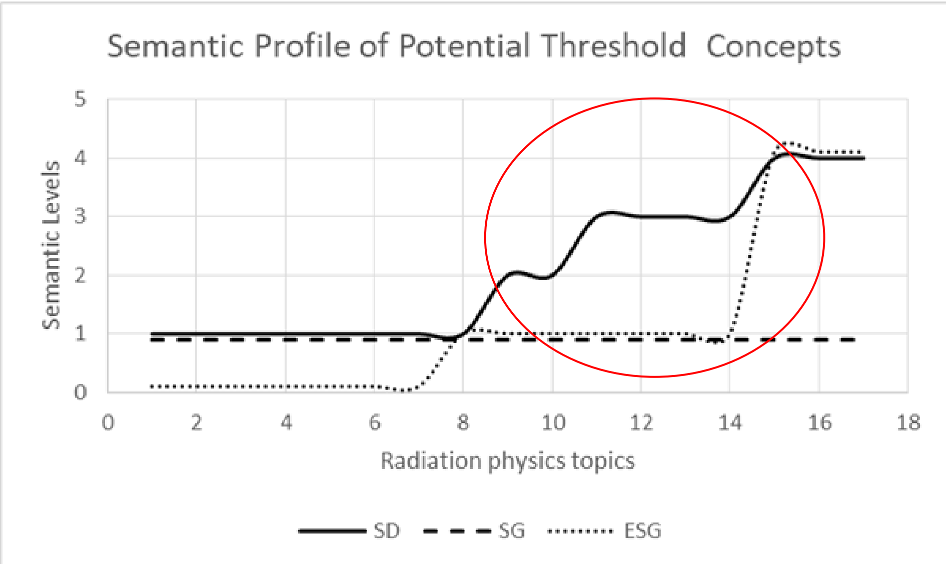


Figure 5.7 Semantic profile of potential threshold concepts in the first year radiation physics module

Figure 5.7 is a semantic profile of the key topics in the first year radiation physics module. The x-axis represents the 17 key topics covered in the module. The rises in semantic density across topics 9 – 17 (SD2 - SD4), the radiation physics section (Module 1 B), the flat line of semantic gravity (SG1) (in the official curriculum documents), and the rise in clinical application, epistemic semantic gravity (ESG1 – ESG4), suggests that the circled area is where threshold concepts would be found, such as 1) the properties of radiation, 2) the classification of radiation, 3) ionisation, 4) the isocentre and 5) the Inverse Square Law.

The rise in epistemic semantic gravity is particularly noticeable for the last three threshold concepts, namely ionisation, the isocentre and the Inverse Square Law. These concepts represent considerable challenges to students, but are critical, as they underpin competent and safe practice in radiation therapy.

The concomitant rise in semantic density and epistemic semantic gravity as the concepts turn toward practice was confirmed in a semi-structured focus group interview with the first year students who identified these concepts as the most challenging. Figure 5.8 is a photograph of the classroom board, following the focus group interview on the concepts impacting practice.

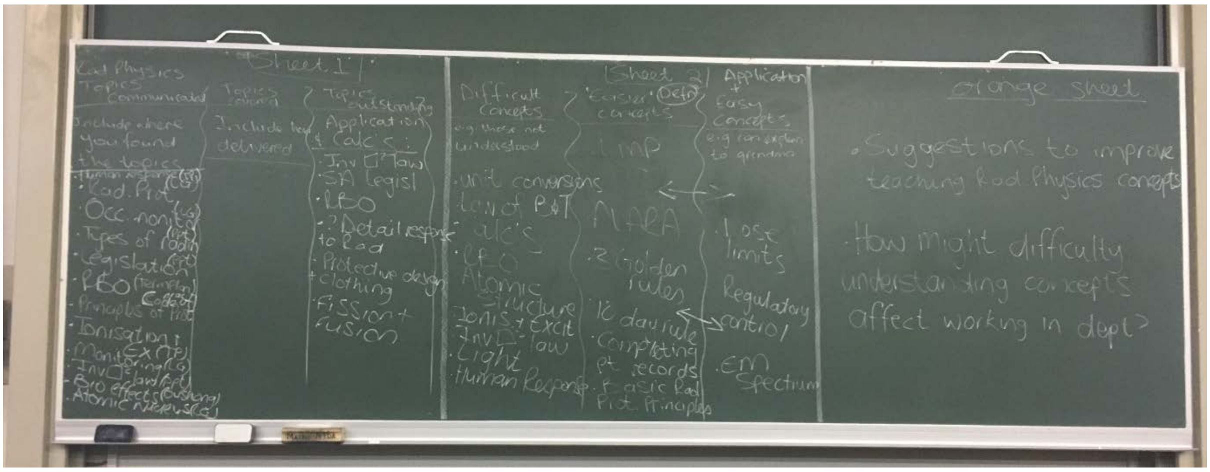


Figure 5.8 Student responses to 'How might difficulty understanding concepts affect working in [the clinical department]?'

Table 5.5 is a transcription of the photograph used in figure 5.8 (adapted from Hudson, Engel-Hills & Winberg, 2018).

Table 5.5 A transcription of the photograph in figure 5.8

Easy (to define and apply)	Difficult (to define, not to apply)	Very Difficult (to define and apply)
Dose limits Electromagnetic spectrum As Low As Reasonably Achievable (ALARA) Time, distance shielding rule	Basic radiation protection principles	Radiation conversion Radiobiology concepts Atomic structure Ionisation and Excitation Inverse Square Law
Dose limits Electromagnetic	10-day rule Completing patient	Unit conversions Radiation conversion

spectrum ALARA Time, distance shielding rule Last menstrual period (LMP) Regulatory control	records Basic radiation protection principles	Calculations Radiobiology concepts Atomic structure Ionisation and Excitation Inverse Square Law
-	-	Unit conversions Radiation conversion Calculations Radiobiology concepts Atomic structure Ionisation and Excitation Inverse Square Law
Dose limits Electromagnetic spectrum ALARA Time, distance shielding rule LMP Regulatory control	-	Unit conversions Radiation conversion Calculations Radiobiology concepts Atomic structure Ionisation and Excitation Inverse Square Law
Dose limits Electromagnetic spectrum ALARA Time, distance shielding rule LMP Regulatory control	-	Unit conversions Radiation conversion Calculations Radiobiology concepts Atomic structure Ionisation and Excitation Inverse Square Law

Amongst the concepts defined by the students as 'very difficult to apply and define' are the five threshold concepts. Other concepts mentioned by the students are building blocks of the five threshold concepts, such as Calculations and Atomic structure.

In the section below, the five threshold concepts are analysed. The threshold concepts are interrelated, and all are the underpinning concepts of radiation therapy practice. While the concepts are separated here for analytical purposes, students have to engage with many of these concepts simultaneously. These overlaps across the threshold concepts add to their 'troublesomeness'.

5.4.1 The classification of radiation

The first threshold concept identified, the classification of radiation, is the end point of a process of cumulative knowledge building, including concepts from chemistry (e.g., atoms, elements, molecules, compounds, chemical bonding, reactions and quantities) and concepts from radiation physics (e.g., waves, photons, radioactivity, radiation). The growing complexity of the concepts are described in LCT terms as rises in semantic density.

Students are expected to understand the difference between ionising and non-ionising radiation, as well as understand the classifications of direct and indirect ionising radiation, as indicated in Figure 5.9. This classification is unique to the discipline of radiation physics; in the language of threshold concepts it is 'bounded'. Ionising radiation is outside of students' experience and not included in the school physics curriculum. In addition, the classification of radiation introduces many specialised and new terms, such as α-particles, β-particles, X-rays and γ-rays. The new terminology is associated with the rise in semantic density and the 'discursive' element of the threshold concept.

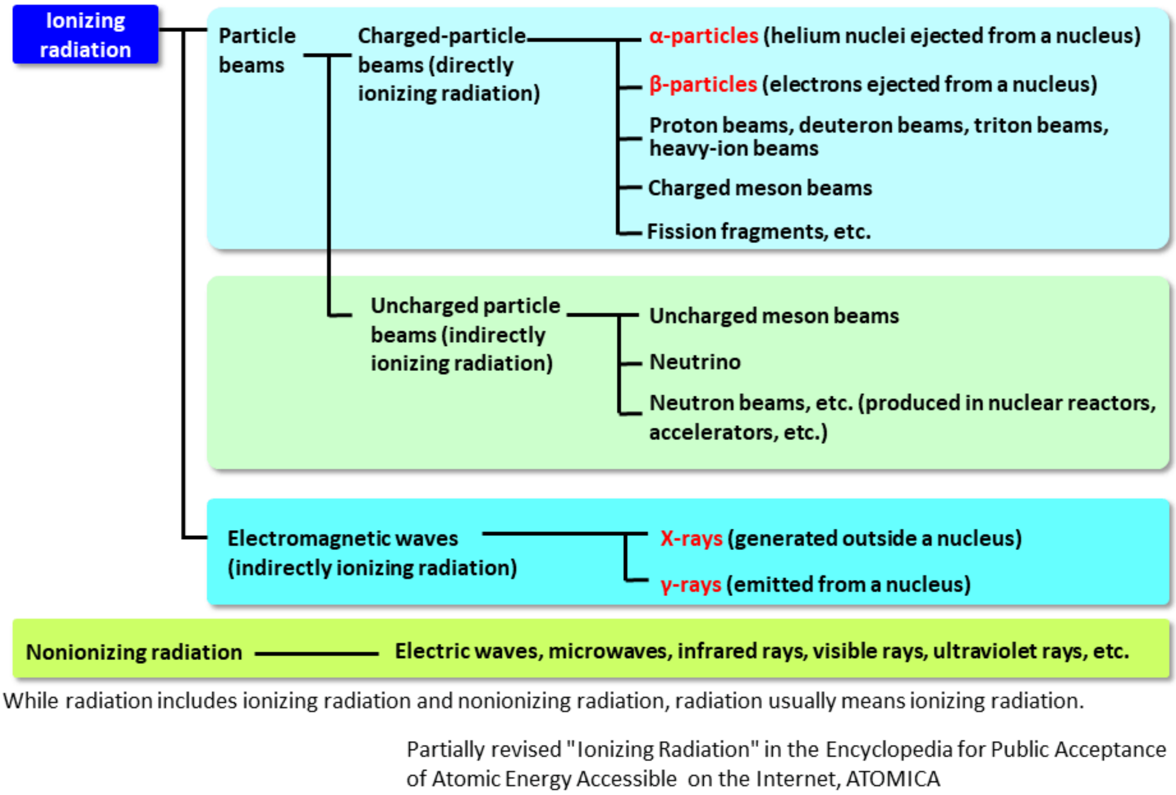


Figure 5.9 Classification of Radiation (Ministry of the Environment, Government of Japan, 2016)

5.4.2 The properties of radiation

As the radiation physics curriculum hones in on clinically useful radionuclides and the radio isotopes used in Medical Imaging, there is a markedly strong increase in semantic density and condensation of meaning. Concepts in the properties of radiation are built on prior concepts of the atom, radioactivity and radiation decay. Students need to understand the that the properties of radiation are dependent on the energy of the radiated particles. Radioactive materials emit α, β, or γ radiation, comprising helium nuclei, electrons or positrons, and photons, respectively. Other sources include X-rays from medical radiography examinations and muons, mesons, positrons, neutrons and other particles. The complexity of these concepts is demonstrated as 'spikes' in the semantic density that characterise threshold concepts. Figure 5.10 provides an idea of the complex classifications.

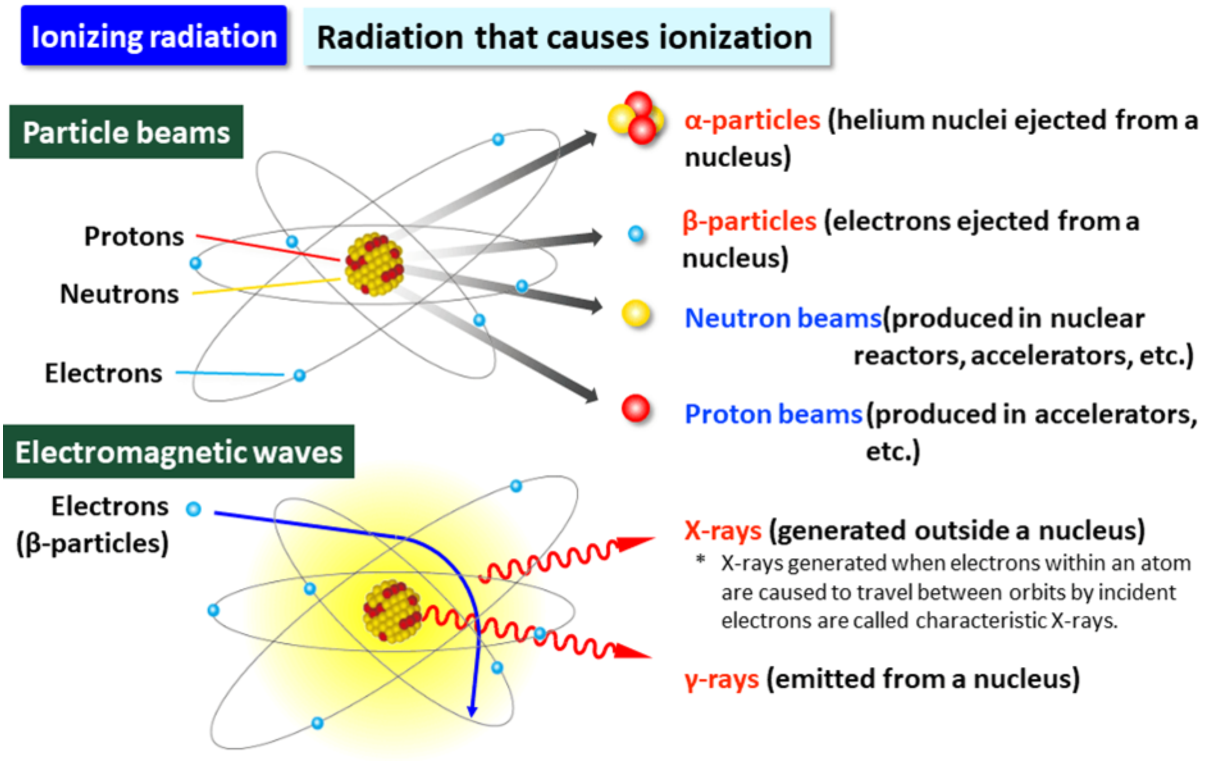


Figure 5.10 Properties of Ionising Radiation (Ministry of the Environment, Government of Japan, 2016)

The properties of radiation build on the prior threshold concept of the categories of radiation. The extract below is taken from a classic textbook on radiation physics:

> The term radiation applies to the emission and propagation of energy through space or a material medium. By particle radiation, we mean energy propagated by traveling corpuscles that have a definite rest mass and within limits have a definite momentum and defined position at any instant. However, the distinction between particle radiation and electromagnetic waves, both of which represent modes of energy travel, became less sharp when, in 1925, de Broglie introduced a hypothesis concerning the dual nature of matter. He theorized that not only do photons (electromagnetic waves) sometimes appear to behave like particles (exhibit momentum) but also material particles such as electrons, protons, and atoms have

some type of wave motion associated with them (show refraction and other wave-like properties) (Kahn & Gibbons, 2014: 6).

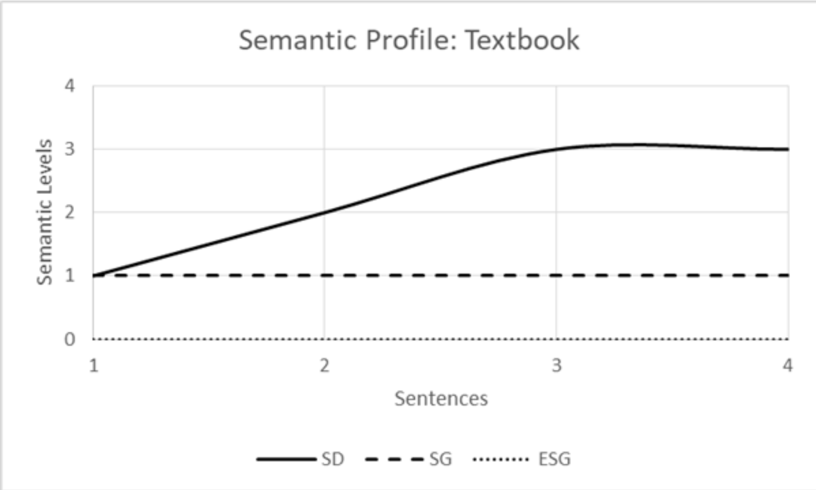


Figure 5.11 Semantic profile of a text book extract

Figure 5.11 shows the rising semantic density (SD1 – SD3) and a flat line of low semantic gravity (SG1) due to the highly abstract nature of the text. There is also a low flat line of epistemic semantic gravity (ESG0), due to the absence of the clinical context. The extract explains the complex and abstract nature of the properties of radiation, derived from the theory of the dual nature of matter. In fully understanding the properties of radiation, students have to understand radiation both as a wave and as a particle. The complex, abstract and theory-based nature of the properties of radiation, and the concomitant rise in the semantic density, suggest that the properties of radiation is a threshold concept. The properties of radiation include a number of specialist terms that also characterise threshold concepts. Students need to understand the properties of radiation and correctly use the terminology of radionuclides such as Radium-226, Cesium-137, and Cobalt-60 – all of which are sources of γ-rays for beam radiation. These γ-rays are emitted from the radionuclides as they undergo radioactive decay. Note that while complex, the semantic density has not reached SD4, as there is no mathematical representation in this extract.

5.4.3 Ionisation

Ionisation refers to any process by which electrically neutral atoms or molecules are converted to electrically charged atoms or molecules, known as ions. In the radiation physics curriculum, it represents another 'spike' in semantic density, due to its abstract nature and increased complexity. Ionisation needed to be partially understood in the previous threshold concepts of the classification of radiation and the properties of radiation. The 'integrative' nature of the threshold concept is exemplified by ionisation as a concept, which appears across the radiation physics curriculum in increasing levels of complexity. Going into ionisation in more depth reveals additional layers of complexity:

> Ionisation is the process by which a neutral atom acquires a positive or a negative charge. Ionising radiations can strip electrons from atoms as they travel through media. An atom from which electron has been removed is a positive ion. In some cases, the stripped electron may subsequently combine with a neutral atom to form a negative ion. The combination of a positively charged ion and a negatively charged ion (usually a free electron) is called an ion pair. Charged particles such as electrons, protons, and a-particles are known as directly ionising radiation; provided they have sufficient kinetic energy to produce ionisation by collision as they penetrate matter. The energy of the incident particle is lost in a large number of small increments along the ionisation track in the medium, with an occasional interaction in which the ejected electron receives sufficient energy to produce a secondary track of its own, known as a d-ray. If, on the other hand, the energy lost by the incident particle is not sufficient to eject an electron from the atom but is used to raise the electrons to higher-energy levels, the process is termed excitation. Uncharged particles such as neutrons and photons are indirectly ionising radiation because they liberate directly ionising particles from matter when they interact with matter. Ionising photons interact with the atoms of a material or absorber to produce high-speed electrons by three major processes: Photoelectric effect, Compton effect, and Pair Production. Before considering each process in detail, we shall discuss the mathematical aspects of radiation absorption (Khan & Gibbons, 2014: 58).

The complex description above has a similar semantic profile – a high line of semantic density, which will increase when 'the mathematical aspects' are discussed. Semantic gravity is not present in the highly abstract text. These concepts are somewhat simplified in Figure 5.12, which shows the effects of ionisation through illustration, which provides some context, thus a slight increase in semantic gravity.

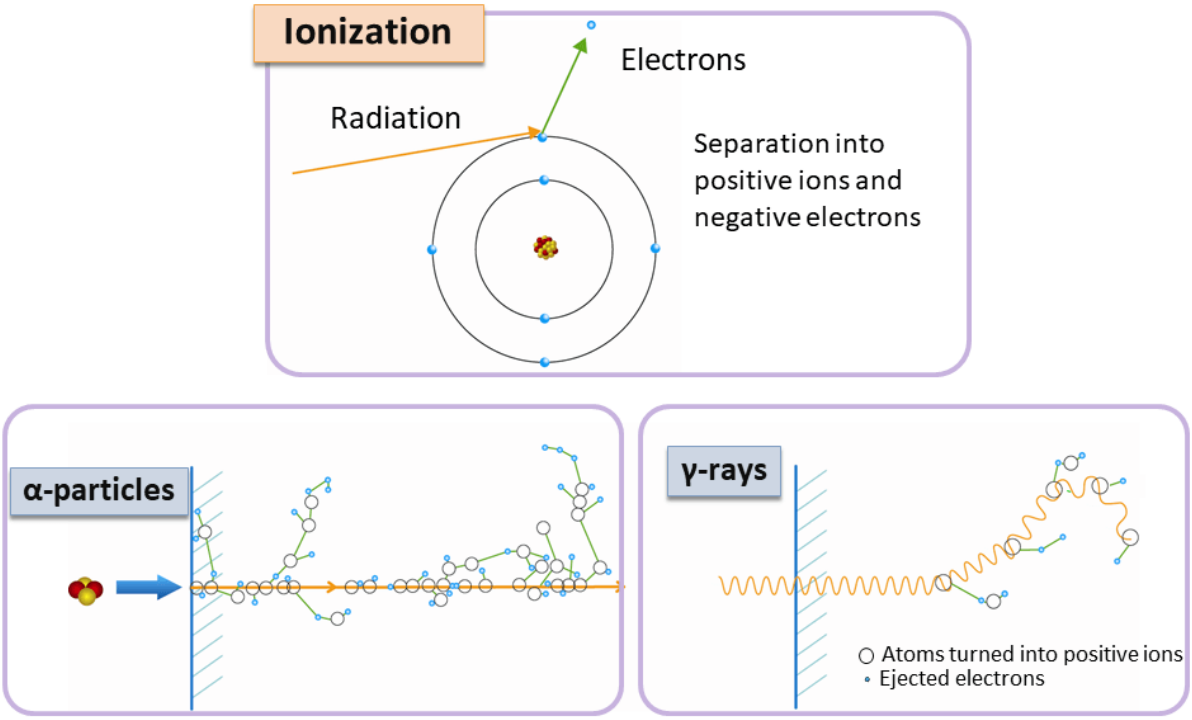


Figure 5.12 Ionisation (Ministry of the Environment, Government of Japan, 2016)

Ionisation is one of the principal ways that radiation in the form of charged particles, X-rays, and γ-rays transfer their energy to matter. Ionising radiation can ionise atoms and molecules, and break chemical bonds – and is thus harmful to living organisms. It is the dangerous nature of ionisation and the care that must be taken by the radiation therapist in the treatment of patients that make an understanding of ionisation fundamental to safe practice.

5.4.4 The isocentre

The last two threshold concepts represent more clearly the 'turn' of the radiation physics curriculum towards radiation therapy practice. In the 'practice turn' the weaker epistemic semantic gravity is strengthened. The concept of the isocentre underpins safe practice. Figure 5.13 represents a treatment bed, comprising a collimator (radiation source) and gantry (rotation device). As the gantry rotates, the collimator axis (which is assumed to be coincident with the central axis of the radiation beam) moves in a vertical plane. The point of intersection of the collimator axis and the axis of rotation of the gantry is known as the isocentre (Khan & Gibbons, 2014: 47).

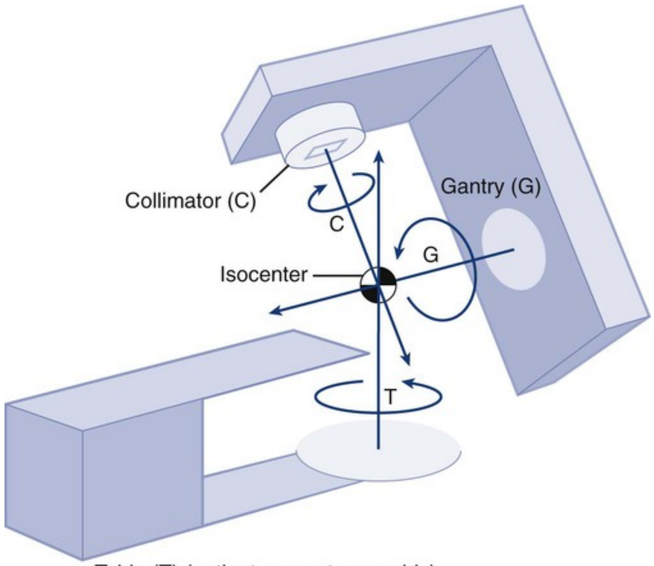


Figure 5.13 Threshold concepts in practice (from Bourland, 2016:96)

The radiation isocentre (in contrast to the mechanical isocentre) is the point in space where radiation beams intersect when the gantry is rotated while the radiation beam is switched on. The rise in the sematic density (SD4) in the concept of the isocentre is due to the complex mathematics and physics calculations that are needed to identify the isocentre. The rise of the semantic density (SD4) as well as the advanced level of clinical practice implied (ESG4).

5.4.5 The Inverse Square Law

Understanding the Inverse Square Law for ionising radiation is one of the fundamental radiation physics concepts underpinning radiation therapy practice. It demonstrates the 'integrative' nature of the threshold concept, building on prior concepts of mathematics, and integrating concepts from general physics, chemistry and radiation physics, in particular ionising radiation. At the base of the Inverse Square Law in radiation physics is the mathematical concept of geometric progression. This indicates a high level of semantic density (SD4). Additional concepts are drawn on to create the Inverse Square Law in radiation physics, such as Coulomb's Law. It is typical of applied disciplines (that is, disciplines that are more focussed on an area of practice) to draw on concepts from the pure disciplines, but to modify and adapt them in ways that make them more useful for practice.

The threshold concept of the Inverse Square Law integrates prior concepts, such as the ‘isocentre’ and ‘beam divergence’. Its relation to advanced clinical practice (ESG4) is a part of what makes it both integrated and troublesome is the different sets of calculations involved: the isocentre is plotted using three-dimensional geometry (x, y and z axes); beam diversion is calculated using arithmetical progression; radiation effect uses the Inverse Square Law, a geometric progression. The investigation into threshold concepts for radiation physics thus highlights the importance of the sequencing of topics from a student learning perspective: from types of radiation to properties of radiation, to interaction with matter, shielding, radiation protection and dosimetry for practice.

5.5 Conclusion

Table 5.6 shows the strengthening of semantic density across the five threshold concepts. In the last three threshold concepts (ionisation, the isocentre and the Inverse Square Law) a strengthening of the epistemic semantic gravity is noted.

Table 5.6 Threshold concepts in first year radiation physics

Threshold concepts	Semantic Codes	Explanation	Example from the data
The classification of radiation	SD3, SG1, ESG0	The classification of radiation builds on prior concepts from Chemistry (e.g., Atoms, elements, molecules, compounds, chemical bonding, reactions and quantities) and concepts from radiation physics (e.g., waves, photons, radioactivity, radiation). It thus integrates prior concepts and has a specialised terminology. It's 'troublesomeness', can be explained as an increase semantic density from general science (SD2) to a more disciplinary and specialised applied science (SD3).	*Oh, okay. I just think it's very complex and you need to do so much reading in order to kind of understand and even then I think there's a lot of grey areas that's not filled in* (Y3_L7_2018).
The properties of radiation	SD3, SG1, ESG0	The properties of radiation subsume prior concepts of the atom, radioactivity and radiation, thus has integrative tendencies that typify threshold concepts. As it builds on the base of the classification of radiation, there is a strong increase in the semantic density (SD3).	*…you can throw a lot of concepts around but if you don't actually understand the concept, you can't put a picture together of what is being, what he's trying to get to you* (A_Rx_2).
Ionisation	SD3, SG1, ESG2	Ionisation vertically integrates two prior threshold concepts, namely categories of radiation and properties of radiation, which strengthens the semantic density (SG3). The concept of ionisation is key to safe practice, demonstrating an increase in epistemic semantic gravity (ESG2).	*No, just for example, we learnt how to get an X-ray but we have never even touched on how this radiation really works or even with Nuclear Medicine, I don't know, we haven't really done much on that you know* (Y1_L3_2018).
The isocentre	SD4, SG1, ESG3	The isocentre is a concept that integrates and builds on prior concepts, strengthening the semantic density (SD4). Its close association with radiation therapy practice, therefore also strengthened epistemic semantic gravity (ESG3).	*And they expect you to ask questions but they don't tell you anything. They're just like 'Oh, give the khoki.' They draw stuff but they don't explain like, 'Okay so those are the shifts we're going to apply to go to the isocentre. They don't say anything so you're standing, doing calculations, like what are you calculating? I don't understand. What is anterior, add and subtracting…So, it doesn't make sense. So, what do I ask if I don't know what you're doing?* (Y3_L1_2018).
The Inverse Square Law	SD4, SG1, ESG3	The Inverse Square Law integrates concepts across disciplines (Mathematics, Chemistry and Physics). The concepts drawn from different disciplines demonstrate a 'spike' in the semantic density (SD4). The concept underpins and relates to the practice of Radiation therapy, and therefore strengthening epistemic semantic gravity (ESG3).	*…they need to tell you …'But listen, I don't know how to do this calculation. This is a problem with the Inverse Square Law. Please help me' and if you assess them later and find it's still the case, ask maybe [a clinical education] to help you*…(A_Rx_1).

The last three threshold concepts are notable for stronger semantic density and stronger epistemic semantic gravity. The threshold concepts are all interconnected, but sequenced in a way that withholds some of their complexity to allow the semantic density to increase more gradually. For example, in the classification of radiation, the concept of ionisation is introduced as a non-threshold concept; in other words, as a simplified concept, to enable focus on the threshold concept of the classification of radiation. Ionisation is present in the properties of radiation, for example the properties of ionising and non-ionising radiation, but the focus is one the properties of radiation more generally in the next threshold concept. When the focus turns to ionisation as a threshold concept, it can be explained in all its complexity. The last three concepts, ionisation, the isocentre and the Inverse Square Law are all strongly interrelated and underpin the practice of radiation therapy.

The semantic profiles in this chapter alert us to the interrelationships between the threshold concepts on the one hand, but also to the fact that each may be understood separately. For practice it is necessary that the concepts are integrated. A clinical educator described the need to 'join the dots':

> I think for me it's the linking of their book-based knowledge into clinical practice. They can't find the link between the two. So, I know that they understand the concepts, but they can't see it in reality if that makes any sense and when they're busy doing it they can't relate the two. You know what I mean? So, like say they're measuring a sep on a scan the understanding that you [measure] to the slice from ant to post and that they just don't – I don't know if any of you agree with me, 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 (A_Rx_1).

It is through pedagogy that the 'dots', in this case the threshold concepts, will need to be connected. This will be the focus of the next chapter.

In this chapter, five concepts were identified through the document analysis. These concepts were classified using the external language of description developed in Chapter 4. The curriculum documents showed the 'bounded' or discipline-specific nature of the potential threshold concepts, including their specialised discourses. The study found that radiation physics threshold concepts have an integrating tendency. They integrate prior concepts from the field of radiation physics, but they also subsume concepts from other disciplines, such as mathematics, general physics and chemistry. Radiation physics was characterised as having hierarchical knowledge structures that grow cumulatively by subsumption of non-threshold concepts and threshold concepts into increasingly complex concepts. The potential threshold concepts thus comprised multiple layers, each indicating increases in semantic density, and in the case of the last three concepts, increases in epistemic semantic gravity. Their complexity was a key indicator of their 'troublesomeness'.

The study of curriculum documents and assessment tasks confirmed the potential of the five identified concepts to be threshold concepts, as they all have 'troublesome' characteristics. The study has gone beyond merely confirming the troublesome nature of threshold concepts, but has additionally explored the nature of the troublesomeness of the threshold concept, identifying that it is an increase in semantic density, and that it subsumes prior concepts to form the complex layers. The major contribution from the curriculum documents and assessment tasks, is that the layering of both threshold and non-threshold concepts that are drawn from prior concepts in radiation physics or from other disciplines such as mathematics, general physics and chemistry, potentially creates threshold concepts in radiation physics.

Using the Semantic dimension of LCT as an external language of description enabled insights into the nature of threshold concepts. LCT as an analytical framework allowed for disciplinary knowledge in radiation physics and its close relationship to radiation therapy to be foregrounded. It made explicit the knowledge that underpins threshold concepts; and has implications for effective teaching and successful learning of threshold concepts in radiation physics, in particular the semantic wave. The curriculum documents and assessment tasks show that there is a clear focus on 'specialist knowledge' in radiation physics.

The challenge for the radiation physics curriculum and the assessment tasks for students is how to make complex abstract concepts clear and how to illuminate the 'differential internal epistemic and pedagogical architecture that students have to negotiate' (Muller, 2015: 415). Muller (2015) argues, with reference to Science, Technology, Engineering and Mathematics (STEM) disciplines, that the rapid growth in the specialisation of knowledge in these disciplines will require greater explicitness in future curricula:

> Demands for access to, and demands for, STEM knowledges and practical know-how will also escalate, bringing larger and more diverse constituencies into the universities (Muller, 2015: 415).

While this chapter focused on understanding the challenges, the next chapter will focus on addressing the challenges. How these concepts were 'experienced' by student and staff participants will be discussed in the next chapter that focuses on teaching and learning threshold concepts in radiation physics towards the underpinning of competent and safe radiation therapy practice.

CHAPTER SIX

TOWARDS A PEDAGOGY FOR THRESHOLD CONCEPTS

6.1 Introduction

In Chapter Five the first year radiation physics curriculum and assessment tasks were studied and analysed for the purpose of identifying threshold concepts and explaining their properties. Five threshold concepts were identified: 1) the classification of radiation, 2) the properties of radiation, 3) ionisation, 4) the isocentre and 5) the Inverse Square Law. The revised external language of description and the translation device (Table 2.1) were used to explain the characteristics of the concepts in terms of strengthening and weakening the semantic density, the semantic gravity, and the epistemic semantic gravity.

In this chapter, the focus is on how the five threshold concepts were taught by radiation physics lecturers, and how the pedagogies were experienced by students. The first year radiation physics lecturers' explained how they taught the five threshold concepts in interviews and students provided their perceptions of the pedagogies in semi-structured focus group interviews. This chapter analyses the semantic profiles of the pedagogies and explains the effect of the pedagogical approaches on students' understanding. An analysis of how the pedagogical relationship between lecturers and students effected teaching and learning events and processes that seek to grant students access to threshold concepts, is undertaken. Trends in the analysis were summarised to exemplify pedagogies for threshold concepts in first year radiation physics. The inverse relationship between semantic density and semantic gravity was clear in effective pedagogies. The importance of epistemic semantic gravity in teaching radiation physics emerged from the study, in particular in the pedagogy of concepts such as ionisation, the isocentre and the Inverse Square Law. The chapter concludes with implications for a pedagogy of threshold concepts in radiation physics for competent and safe radiation therapy practice.

6.2 Pedagogies specified in Physical Sciences 1 Documents

The teaching methods used in the Bachelor of Science in Radiation Therapy programme, as reported in curriculum documents and student guides, did not specify the details of the pedagogy to be used, only the required mix of teaching and learning experiences for course accreditation, such as face-to-face lectures, tutorials, group work, audio-visual media, simulations and discussion groups. Additional teaching activities were listed in student guides, including: electronic media, presentations, problem-based learning, Learning

Management System Tools (e.g. Blackboard and Google Drive), practical demonstrations, DVD's, videos, web-based tools (i.e. virtual software), and Massive Open Online Courses (MOOCs). A category specified as one of the modes used to implement the curriculum was 'Learning Activities', which included the Learning Management System, web-based activities, group work, oral presentations, poster design, technical writing, model building and educational visits. The mix of teaching and learning methods and activities described in the curriculum was similar over the four years. In the next section, the focus is on identifying a specific pedagogy for threshold concepts in first year radiation physics.

6.3 Pedagogies for Threshold Concepts in First Year Radiation Physics

In this section, the pedagogies used in the radiation physics module are studied in detail, with a view to understanding the practices that supported students' learning of the threshold concepts in first year radiation physics that were identified in Chapter 5.

6.3.1 Teaching and Learning the Classification of Radiation

Concepts that have to do with atoms and sub-atomic particles are necessarily abstract as we cannot observe or directly manipulate them. Therefore, because radiation is not visible, and far removed from everyday experience, 'formal reasoning' is required to understand the classification of radiation (Johnson & Hafele, 2010). Understanding radiation involves abstract reasoning and the abstraction is increased when in the concept of the classification of different types of radiation, since classification involves comparing or relating abstract concepts, while having no direct experience of them. The classification of radiation thus involves multiple abstract ideas and, in LCT terms, represents stronger semantic density and weaker semantic gravity. One of the radiation physics lecturer's pedagogical approach to teaching a complex radiation physics concept was to 'scaffold' the concept, which is explained as follows:

> We start scaffolding [the classification of radiation] before we get to that. That we started in bits and pieces, like putting the pieces together long before they got to that point. So, when they got to that point, they could understand certain things … (Lecturer 3).

The sequences of Figures (from Figure 6.1 to Figure 6.3) show how the concept of the classification of radiation might be scaffolded, that is, initially simplified with a cartoon-like drawing (Figure 6.1) that simplifies the concept and reduces the number of radiation sources to enable students to grasp the basic idea. The semantic density is usually stronger in a threshold concept, but is in this example is considerably weakened in the initial scaffolding. Stronger semantic gravity is evident in the concrete representations of the barriers (paper, metal, lead, and water) and the comic-like ‘splat’ of the α-rays, β-rays, etc. against the barriers.

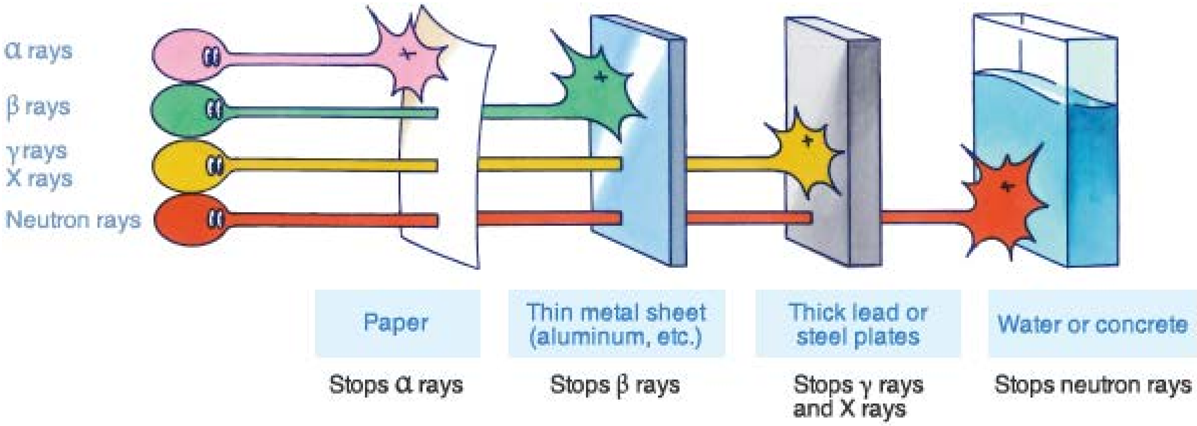


Figure 6.1 Using visuals to make the abstract more concrete (image from https://socratic.org/)

In the next step of the scaffolding process, semantic density is strengthened and semantic gravity is weakened. More sources of radiation are introduced (Figure 6.2), and a more scientific representation of the wavelengths and their relationship to increases in energy is shown. Photographs are used to illustrate the different types of radiation to anchor the abstract concept with concrete and contextual examples of the radiation sources that will be more familiar to students. The photographs have the effect of reducing the semantic density of the classification concept, while more scientific diagrams and text starts to re-build its complexity.

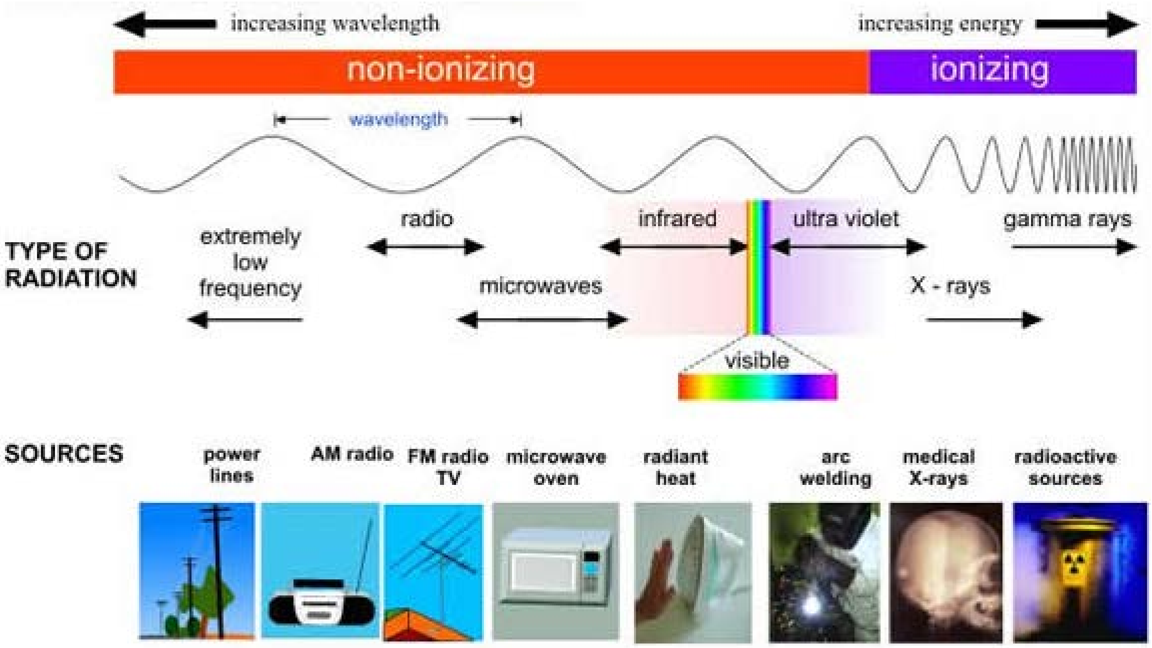


Figure 6.2 The Electromagnetic Spectrum (image from https://socratic.org/)

The next step of the scaffolding pedagogy involves increasing the complexity of the concept, such as the differences between ionising and non-ionising radiation. The effects of radiation are including, such how ionising radiation 'damages DNA'.

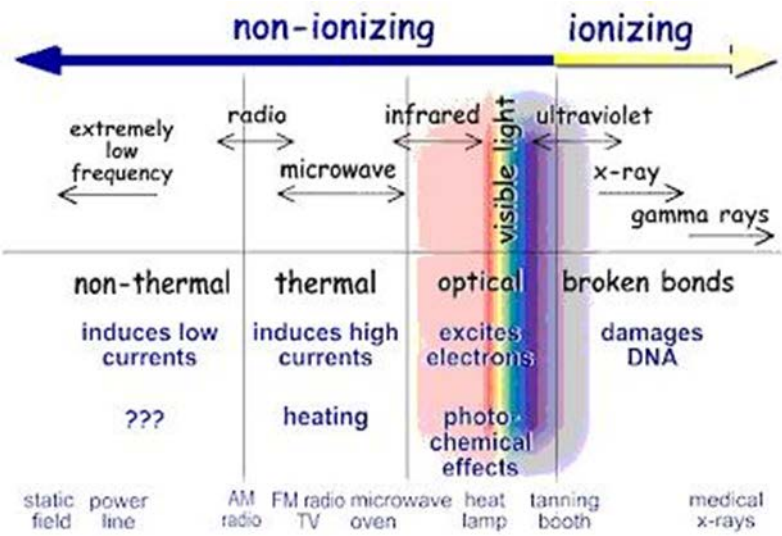


Figure 6.3 Moving from concrete to abstract reasoning in the classification of radiation (image from https://socratic.org/)

As shown in Figure 6.3, a table is used, with fewer visual details to support students' shift from the concrete to the abstract, while introducing ideas about ionising radiation. The semantic density of the concept is restored and the semantic gravity reduced.

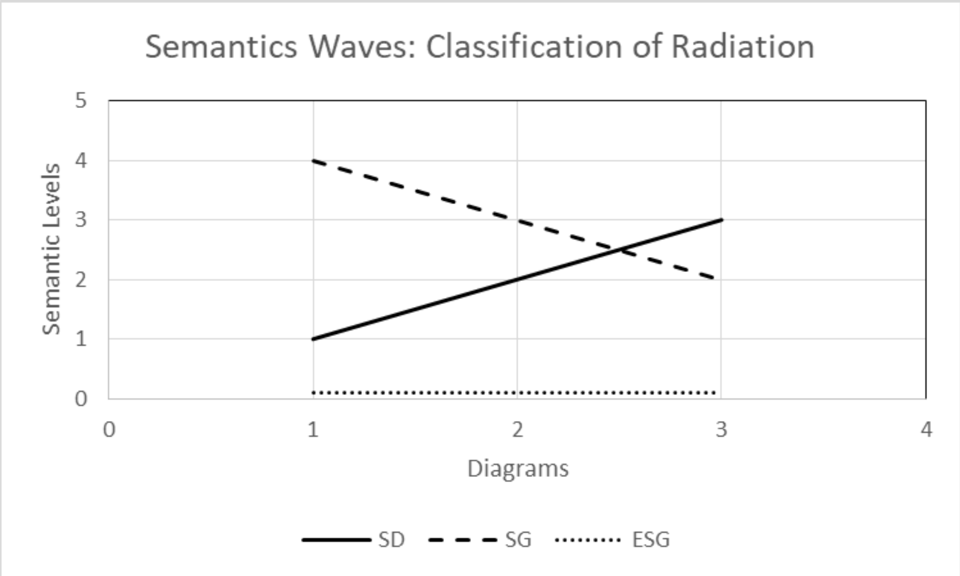


Figure 6.4: Semantic waves in teaching the classification of radiation

Figure 6.4 is semantic profile of the pedagogy implied in the sequence of three diagrams, Figures 6.1, 6.2 and 6.3, which are represented by the data points on the x-axis. The first diagram simplifies the semantic density (SD1), while strengthening the semantic gravity through the comic-like presentation and the use of familiar objects (SG4). In the second diagram semantic density is strengthened (SD2) through the use of more scientific terms and images (SD2), while the semantic gravity is weakened through the more academic style of representation (SG2). In the third diagram more a more radiation physics-specific illustration is used that strengthens the semantic density (SD3) and weakens the semantic gravity (SG2) towards a more analytical level. A typical semantic wave emerges in which the inverse relationship between semantic density and semantic gravity is seen. As the semantic gravity weakens, and the diagrams become more decontextualised and abstract, the semantic density increases. The epistemic semantic gravity is represented by the dotted flat line at the base of the graph (ESG0), as the clinical environment is not present in the concept and the ways in which it is explained. As Lecturer 1 notes:

> I think it starts off in physics. … It's not just a practical application. It starts with your baseline physics … (Lecturer 1).

6.3.2 Teaching and Learning the Properties of Radiation

The properties of radiation, which are complex to teach and to learn, as is typical of threshold concepts, was taught through analogies. This is because the properties of radiation can be compared to the properties of other materials. The properties of radiation comprise many layers. For example, teaching radioactive decay, that is, the amount of a radionuclide that decreases over time causing radioactivity to weaken, has additional embedded concepts such as the 'half-life', that is, the time required for radioactivity to weaken and reduce to half. Built into the half-life concept is the idea of geometric progression and decrease.

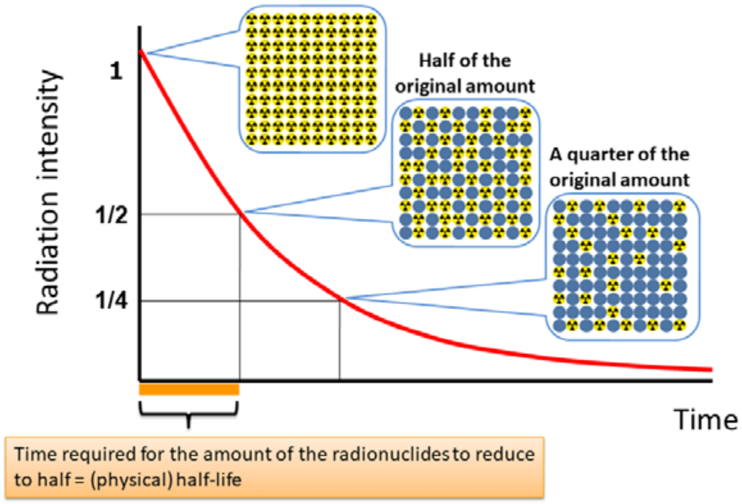


Figure 6.5 Radiation Decay (image from the Ministry of the Environment, Government of Japan, 2016)

The concept of the half-life is usually illustrated by means of a graph in which the horizontal axis represents elapsed time and the vertical axis represents radiation intensity. The resultant curve demonstrates the exponential radioactivity decreases (Figure 6.5). The representation of radiation decay in Figure 6.5 has a relatively stronger semantic density and relatively weaker semantic gravity.

The lecturers were of the opinion that they could scaffold the concept 'the decay processes, half-life' (Lecturer 3), by introducing the concept of 'decay' in a more familiar way. They did this by giving the students bottles of Coca Cola™, getting them to open the bottle, shake it and pour it into a glass, thus producing lots of bubbles. The students worked in groups to time the process of bubble 'decay' as well as to measure the level of the bubbles as they popped. They then plotted the 'decay' on graphs, creating exponential curves. The lectures explained that they 'have a lot of analogies … photos, coke, bubbles in the Coke (Lecturer 3) and in this case used 'a glass of Coke to explain radioactive decay' (Lecturer 2).

[The first year students are] extremely attentive when you show them the analogy. We use, like the glass of Coke, they watch it and they could see as the bubbles came, the graph went like that [indicates curve]. Because you timed it over a few seconds by hand (Lecturer 3).

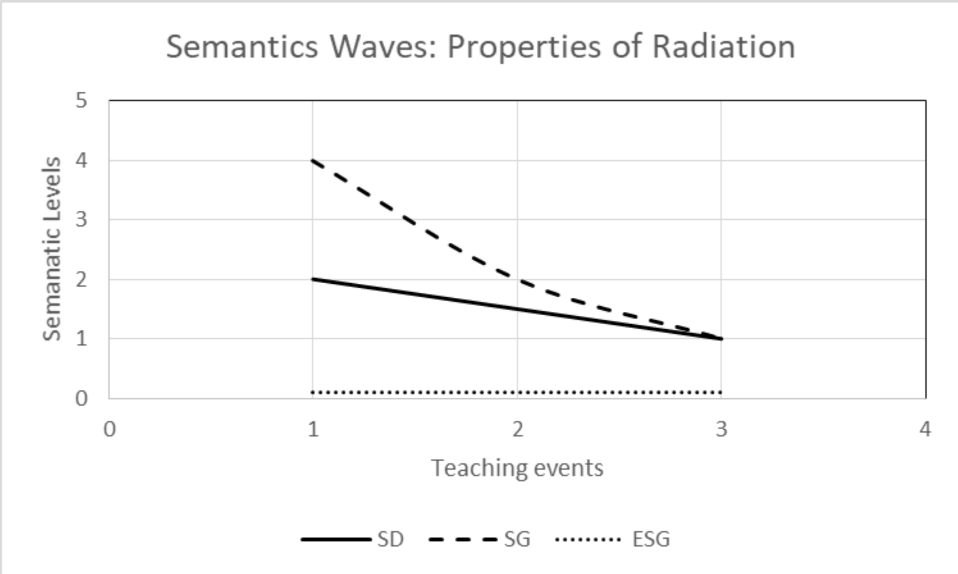


Figure 6.6: Semantic wave for the 'Coke analogy' of Radiation decay

Figure 6.6 is the semantic profile of the 'Coke analogy' and shows weakening of the semantic density (SD1) by introducing stronger semantic gravity (SG4) in the form of the familiar carbonated soft drink. The teaching events on the x-axis refers to the three lessons where the analogy was used. The 'bubbles in the Coke' analogy weakened the semantic density through the use of familiar materials (Coca Cola™) and by creating an environment of fun and enjoyment – which is not often associated with learning threshold concepts. The temporary weakening of semantic density helped the students to understand the concept of decay, at a basic level, as Lecturer 1 put it:

Understanding what your basic definitions are (Lecturer 1).

The graph in Figure 6.6 is useful as a start to the learning process, but is not desirable for cumulative learning; it illustrates what Maton (2016) calls a 'down escalator' showing an increased level of semantic gravity and weakening the semantic density. The effect of a rapid drop in the semantic density can lead students to believe they understand a concept, even if they have not grasped its full complexity. The lecturers would need to rebuild the concept and strengthen the semantic density into a semantic wave similar to the profile in

Figure 6.4, in order to build cumulative learning. They would need to abandon the coke experiment to explain in more detail how the properties of radiation and the half-lives are dependent on the types of radionuclides. Students would need to understand and apply the mathematical formula for working out radiation decay. The process of building cumulative learning through initially weakening semantic density and then re-building it, that time and considerable care, as the lecturers understood:

> So, we're teaching the basics of what a log is and the ABC's and gradually scaffold it up to that radioactive decay formula and then, you don't even call it that to start with. You just get them to understand. But then immediately after that what our strategy was, we went straight to radioactive decay after the tools and skills modules. So, that was the next thing we did after that (Lecturer 3).

6.3.3 Teaching and Learning Ionisation

Many students experience difficulty in understanding the concept of ionisation energy (Tan et al., 2008). This is a concern because the concepts of ionisation and ionising energy are foundational for understanding atomic structure, periodic trends and the energetics of reactions (Taber, 2003). The difficulty of the concept has to do with its highly abstract and complex nature:

> For example, to explain various trends in ionisation energy, students need to consider a variety of factors such as nuclear charge, electron–nucleus separation, the type of orbital occupied by an electron and whether the orbital is occupied by one or two electrons. To make it even more complicated, some of these factors may work in opposing directions and the students need to decide which are the dominant factors for a given situation (Tan et al., 2019).

In their study of students' conceptions and misconceptions in Chemistry, Wiji and Mulyani (2018) found that only 6% of the first year class were able to conceptualise ionisation clearly. Understanding ionisation is crucial for future radiation therapists, as their practice is the therapeutic administration of ionising radiation:

> The Radiation Therapist is involved in the planning and/or dose calculation and accurate administration of various forms of ionising radiation for the treatment and care of patients with malignant and benign neoplasms, according to a prescription of a Radiation Oncologist (SAQA, 2018).

When students, as shown in the exchange between first years in a focus group interview, acknowledge their own difficulties in understanding; it is a particular concern.

Y1_L3_2018:	No, just for example, we learnt how to get an X-ray but we have never even touched on how this radiation really works or even with Nuclear Medicine, I don't know, we haven't really done much on that you know, since we do all the disciplines so…
Y1_L1_2018:	And we did the Technetium in Physics but now we know it's actually part of Nuclear Medicine.
Y1_L4_2018:	Nothing really comes together – it's like a lot of information and you have to like piece it back again together at the end.
Y1_L3_2018:	Nothing is linked.
Y1_L2_2018:	I was going to say like it's all over the place you just have to figure out yourself.

These first year students show that they are stuck in the liminal space of confusion and misunderstanding, as yet unable to achieve higher levels of semantic density. Understanding concepts that are not physically seen in clinical practice, such as the radiation dose to bodily structures inside the patient, increase the semantic density of the concept of ionising radiation.

The lecturers interviewed used VERT to make visible the structures and process that are not possible to observe. The VERT training package includes an extension called 'VERT Physics' that can be used to demonstrate concepts such as ionisation, the isocentre, beam divergence, and the Inverse Square Law (Beavis & Ward, 2012).

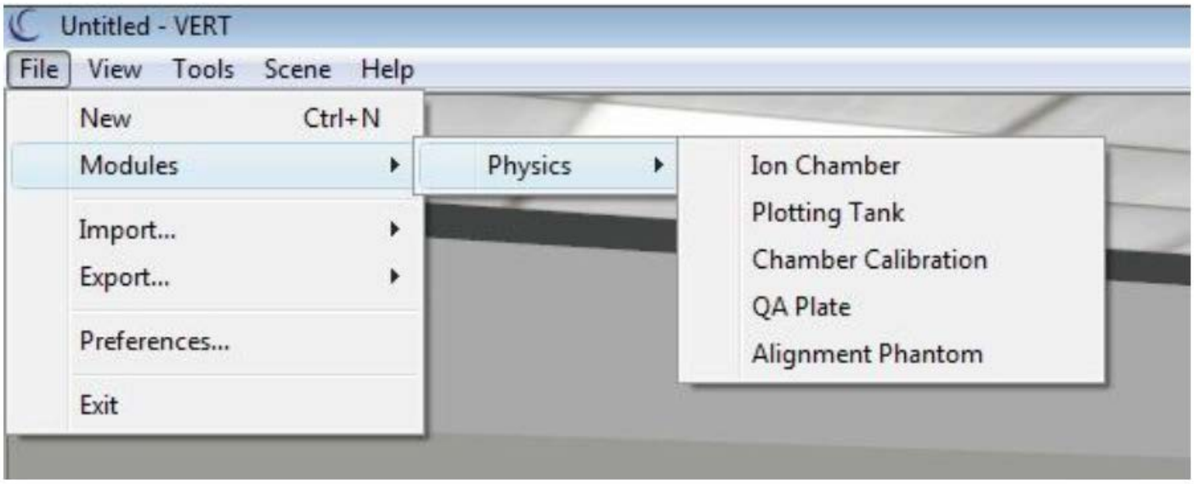


Figure 6.7 List of options available in VERT Physics

The VERT software package includes a three-dimensional (3D) effect that enables a better visual understanding of the dose distribution, consideration for organs at risk and therefore an improved understanding of the patient's side effect profile. Osterhölm, Framholt and Nordentoft (2010) reported that students experienced their training as less pressured when they learned in a 'patient free' environment. Osterhölm et al. (2010) also noted that the students' understanding of the clinical techniques improved when they could 'see' inside the patient and understand the dose in relation to the 3D representation of the anatomy of the patient. In Figure 6.8, the radiation beam is shown, penetrating a tumour in the prostate (area marked in red) and its effect on the surrounding normal tissue (the bladder situated anteriorly and the rectum posteriorly to the prostate). What is apparent is the stronger epistemic semantic gravity of the specialised field of practice (ESG2). The legend/key on the right side of the image, indicates the dose delivered in cGy, which gives students information on the amount of dose delivered to the patient in one radiation beam. The dose calculation indicates the high level of semantic density (SD4). While VERT contextualises, it does not simplify by using an 'everyday' or familiar context, thus semantic gravity is weakened to an analytical level (SG2).

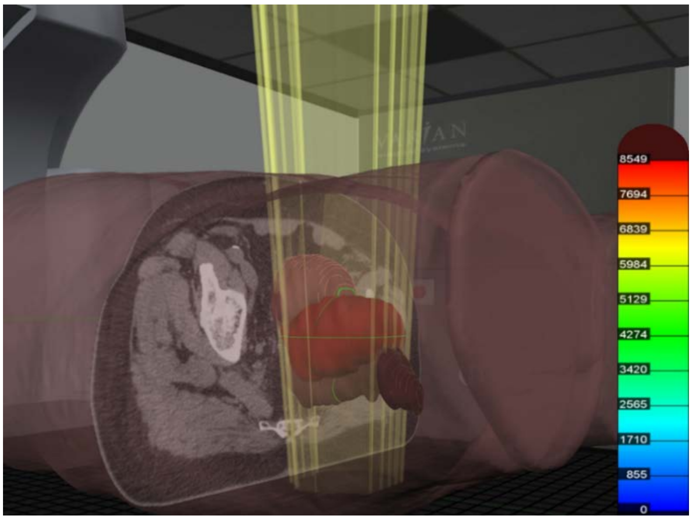


Figure 6.8 Seeing the ionising radiation dose with VERT

A first year student explained how seeing what was normally invisible helped her understanding:

> … there's an actual X, Y and Z axis that they put on the body and then you can see okay this is this and … so you can see it visually in front of you on the patient (Y1_L3_2018).

Tan and colleagues (2019) found a virtual learning environment similarly helpful in developing chemistry students' understanding of ionisation; and, in particular, point to the benefits of repetition in a virtual online learning environment. Demonstrating a complex concept on VERT is not a 'once off' event. VERT provided a platform where students could learn from their mistakes without changing calibrations or causing harm to patients. Senior students reported that the 'Ion chamber' option (see Figure 6.7) was used most to visualise the effect of changing the energy of the radiation beam.

> We struggled to understand and then she gave us the chance to take the thing ourselves and then you change the energy and you see what's happening (Y3_L3_2018).

Students valued the ability to repeat the setting up process on VERT, and felt that even more opportunities to repeat such processes were needed:

…these classes that we had [using VERT] it helped, and I feel like we should do that more often in physics especially with the PDDs [percentage depth doses] … (Y3_L2_2018).

While VERT is helpful in easing the incline of the semantic density ascent, stronger semantic density (SD4), in the form dose calculations, is achieved. By strengthening the semantic density, the concept of ionising radiation and the associated dose calculations is understood more accurately. The weaker semantic gravity (SG2) enables such strengthening of the semantic density. The stronger epistemic semantic gravity (ESG3) of advanced practice increases the level of challenge in terms of specialised equipment, virtual patients who have internal organs that need to be protected, and a tumour that requires treatment. Figure 6.8 demonstrates how the ionising radiation dose covers the tumour volume (structure in red).

Figure 6.9 is a semantic profile of teaching ionisation with VERT. The semantic density is slightly reduced by the virtual clinical context and, by making visible the invisible. The simulated context and the stronger semantic gravity reduce the semantic density temporarily, allowing students to build their understanding of the concept, before the semantic density is strengthened through dose calculations. The resultant semantic wave, which combines both semantic gravity and epistemic semantic gravity approximates to Maton's (2014) ideal semantic wave for cumulative knowledge building.

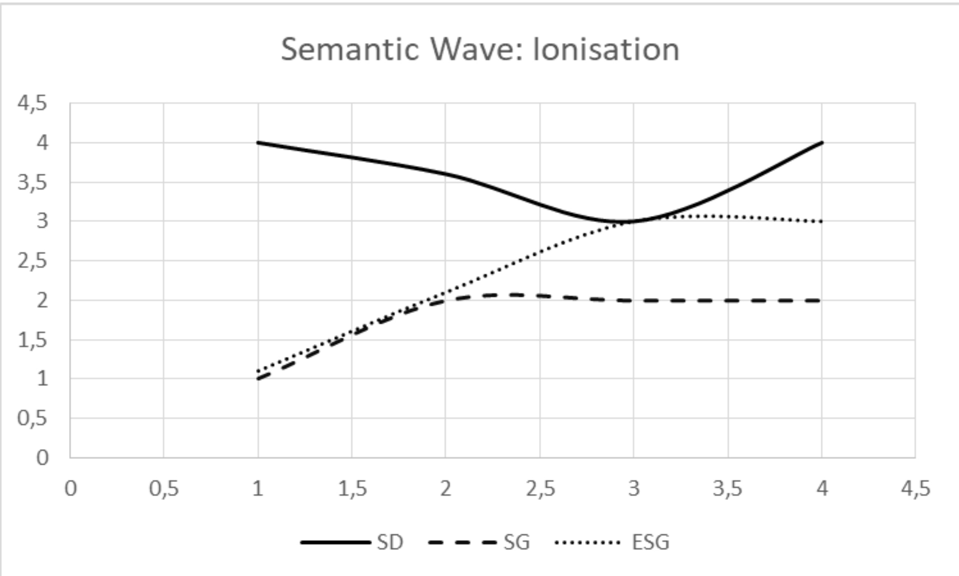


Figure 6.9 A semantic wave for teaching ionisation with VERT

VERT enabled students to see the ionising radiation that is present but invisible in clinical practice. The ability to see the effect of the radiation dose on an organ at risk introduces the safe use of radiation from the beginning of the course. Students could see the effect on the internal organs of what seemed like a small misalignment on the virtual patient's 'skin'. Senior students, reflecting back on their first year, understood the importance of conceptual clarity with regard to the key underpinning concepts on which their practice is based:

> … people don't really understand the magnitude of what they're actually working with … so … the ALARA … no lead here or there, lead here and there but why, you know? What happens? What are the effects … you know? If we don't do that, what's going to happen? We don't see radiation. So, now it's easy to leave room for mistakes or leave small gaps in between because you don't see it (Y3_L7_2018).

ALARA (As Low As Reasonably Achievable) is a safety principle designed to minimise radiation doses and releases of radioactive materials. In LCT terms, the student argues the need for a deep understanding of radiation physics in the interest of safe radiation therapy practice. In LCT terms, she argues for strengthening the semantic density in order to achieve a concomitant increase in epistemic semantic gravity.

The use of VERT enabled the pedagogical approach of repetition, as the following lecturer explained:

> … we use VERT to demonstrate those same principles [ionisation]. So then I will refresh what we have done and practise those concepts over and over and over by repeating it to make sure that they get it (Lecturer 1).

While learning in the virtual environment, or on a laptop, is helpful in enabling students to 'see the invisible'; it is important that students use the virtual environment as a support to their understanding of the complex and abstract concept of ionising radiation. An important aspect of the ease of repetition in the virtual environment is the confidence that it gives to students:

> …you just feel more confident after working on the VERT and then you come in real life and you also have to all these things. It just makes it easier. You're not so scared (Y1_L9_2018).

6.3.4 Teaching and Learning the Isocentre

With regard to teaching the concept of the isocentre, the virtual clinical environment created by VERT was found to be particularly beneficial:

> I wish that all of the disciplines could have something like VERT to teach with. I just think it helps make the penny drop … you talk about it and you question them and you have this whole interaction … and then seeing that actually in play, is that final little bit of cementing that foundation … I think it has to be the new way of teaching as much as we have to stick to textbooks and all of those things, we have to also now think of being more visual and hand-on with our teaching to help the theory be brought across (Lecturer 1).

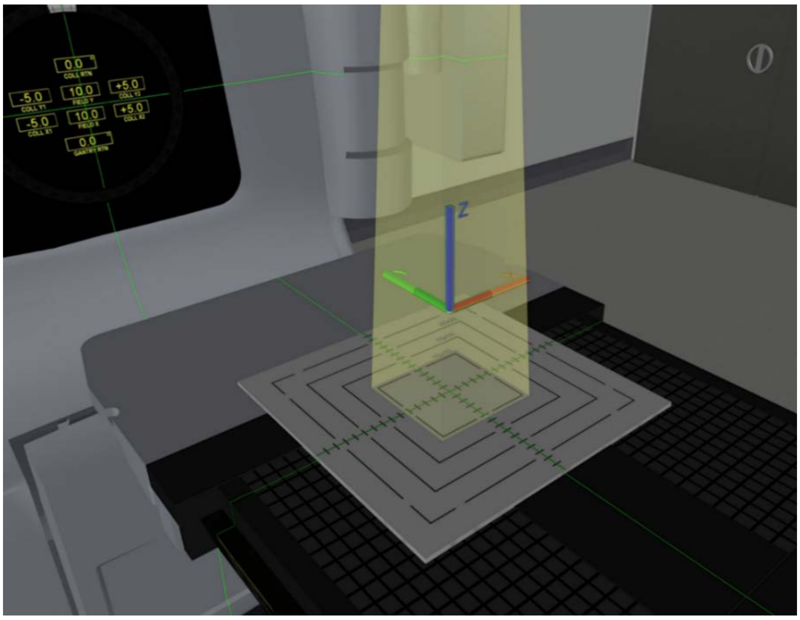


Figure 6.10 Demonstrating the isocentre and beam divergence using VERT

Figure 6.10 shows is one of the representations of the isocentre, using VERT. The semantic profile teaching the isocentre with VERT would be similar to the semantic wave illustrated in Figure 6.9. The semantic density (SD4) is high due to the graphical mathematical calculations required. In Figure 6.10 VERT provides a simplified treatment bed, thus reducing some of the complexity of the clinical environment (ESG2). In Figure 6.10 only the beam is made visible; there is no virtual patient or internal organs to be protected. Students' learning in thus scaffolded by simplifying the epistemic semantic gravity. Students found that making the invisible visible, while simplifying the context, had a positive effect on their understanding of the isocentre, as the following first year student explains:

> Seeing for example the referencing and the isocentre, a bit more how – actually understanding what they're doing and being able to maybe even try it yourself (Y1_L1_2018)

The first year student quoted above describes how seeing 'a bit more' (but not the full complexity of the clinical environment) supported cumulative learning. The student quoted below similarly confirms how 'just seeing it more' made a considerable difference to her level of understanding:

> When they mention like SUP and moving from the reference to the isocentre – the calculating of that could be confusing at times. So just seeing it more allows us to understand better (Y1_L2_2018)

While Figure 6.10 is a representation of the isocentre that reduces much of the epistemic semantic gravity, the representation in Figure 6.11 strengthens the epistemic semantic gravity (ESG3) by orientating first year students to the layout of the treatment room, showing the linear accelerator and positioning a virtual patient on the treatment couch using the set-up lasers. Taken together, Figures 6.10 and 6.11 form a rising semantic wave that appropriately reduces and strengthens the semantic density and epistemic semantic gravity to support cumulative learning. The difference between the simplified context in Figure 6.10 and the more complex context in Figure 6.11 shows that progressively strengthening of epistemic semantic gravity has no effect on the semantic density. The treatment environment is complex and the calculations are complex.

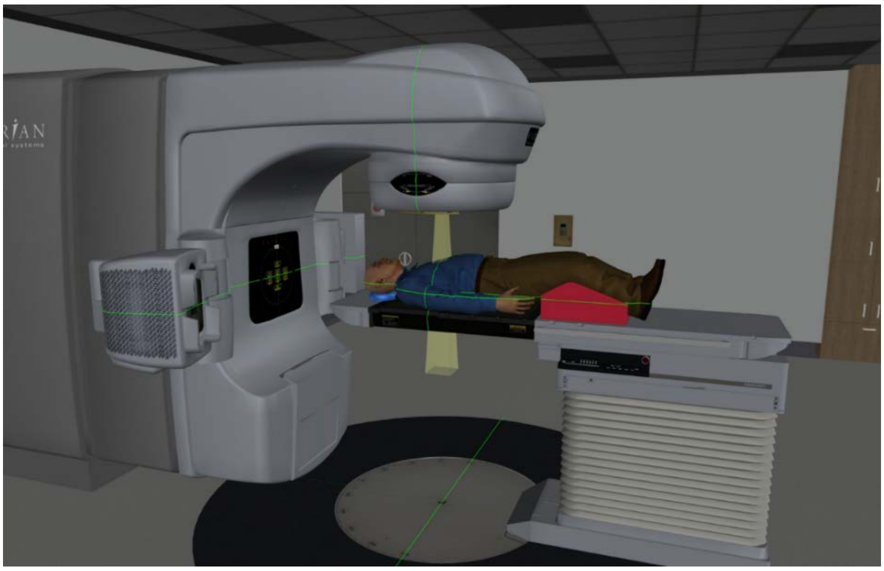


Figure 6.11 Strengthening the epistemic semantic gravity of the isocentre

The fact that one ‘sees’ the beam does not reduce the level of challenge; but it does means that the semantic density increase is scaffolded (the separate elements are more clearly visible and can be sequenced with less of a steep learning curve). As one of the first year students explained

> …you know the steps to follow, like you know, okay, you have to go to midline and you have to then go to referencing marks. You don’t just stand there and be like, oh, I have no clue where I should even start now (Y1_L4_2018); and

It should be noted that preparing students for the clinical environment does not mean that what they have learned is less semantically dense or has lower epistemic semantic gravity. This was confirmed by first year students who commented that:

> Actually working with the machine, being able to use the controls and also position the patient, actually seeing the patient on the – so in a way it’s like realistic but you just not at the hospital. So you also get the feel of what the radiographers are doing (Y1_L10_2018).

In addition to pacing the tasks needed to locate the isocentre, the virtual treatment bed also built students’ confidence for their first clinical practicals:

> for me, when I first saw the VERT, I was like, okay, this can actually you know, help me prepare myself for what to expect in the clinical department … and like not being like totally stressed out when you go into the room for the first time (Y2_L3_2018).

The students did not discount the importance of the ‘real’ clinical environment for learning, as the following first year point out:

> …when you’re at Clinicals, you just always learn more. But VERT has, with the immobilisation devices, with positioning, it helped us all with that, with what we saw at Clinicals. It’s just you will always learn more at Clinicals, the practical work and everything (Y1_L10_2018).

Lecturers reported that while the virtual learning environment was a good initiative, it had disadvantages. Technology is often seen as a barrier to teaching and learning abstract concepts. In this regard it is important to note that the software was not designed with the intention to visualise complex and complicated concepts, but rather '…very simple concepts' (Beavis et al., 2006; Bridge et al., 2007). Lecturers and clinical educators were of the opinion that technology could hide important principles. Students are subsequently not exposed to the entire process and lose out on fundamental concepts:

> And sometimes the basics get lost in the technology …the interface or the software sort of hides the equations and the concept behind everything … what is happening behind then the technological side of it sort of hides it. (Lecturer 2).

This was confirmed by a clinical educator who commented on how the use of computerised systems in the clinical setting has replaced many of the manual processed done in the past:

> It's because of systems like [Oncology Information Management System] that the students have lost out that part of things completely. Even here they don't see from when the doctor approves the field. That's why they lose that trying to see what it is on the machine because they don't see that information being put on and checked and calculated (A_Plan_2).

Lecturer 2 explained that students were also tested with 'pencil and paper' to make sure they were not over-reliant on VERT:

> For our last radioactive exercise, they can't use Excel or a programme to draw the graph, they have to draw it with pencil and paper (Lecturer 2).

The senior student participants mentioned that the virtual clinical platform is not used optimally and students spend limited time exploring VERT:

> So, I feel that it [VERT] can be a very helpful learning tool. It's just, it's not being used sufficiently (Y3_L6_2018).

Some of the clinical educators did not know what VERT was, but was keen to learn more about the virtual platform:

> … explain to [us] this VERT, what do they actually do? What do they physically do with the machines? How does it work? (A_Plan_1).

The clinical educators held that a virtual clinical environment would never replace learning in the clinical setting:

> You see, we're still living in a very tangible world. If that is what we only did, VERT and we treated our patients like that but we're not doing it. We come into a solid world on this side .. and you're teaching them something that's a techno-thing. They're being taught a techno-procedure or set up, whatever and now they have to translate into a real life patient here. That's your acid test. Do they actually know how they will be able to do it? That is what the problem is here (A_Plan_1).

6.3.5 Teaching and Learning the Inverse Square Law

The Radiation Physics lecturers had different approaches to teaching the Inverse Square Law. Lecturer 2 understood the Inverse Square Law as an abstract concept, but one that could be taught by analogy, using a can of spray paint to demonstrate the distribution of ionising radiation:

> If you spray the spray, if you spray close by then it becomes a dense block. If you spray it further away then it spreads out, and then that shows the distribution doesn't go flat nearer then it spreads out, not even in a hyperbolic manner… (Lecturer 2).

The analogy of the spray paint has the effect of strengthening the semantic gravity (SG4) with a familiar object, a can of spray paint. It also reduces the semantic density to level of basic or common sense understanding (SD1). This is illustrated in Figure 6.12. Lecturer 2 supported the idea of visual representation of the concept:

> You have to relate it visually. Even if it's visually with a graph because if you show the spread of radiation from the centre of a ball, it's the same picture almost as the spread of the spray from the spray can if that was at the centre of the ball. So, you relate the pictures (Lecturer 3).

By introducing visual representation by means of a graph, Lecturer 3 reduces the semantic gravity (SG3) by introducing a more disciplinary and scientific procedure. In the extract below, Lecturer 3 introduces the experimental approach, another more scientific way of studying the results of the spray paint experiment:

> With the spray can they could see because we put the blobs on the board and then we asked them to say which one looked more intense. You know, the same amount of spray that came out of the can and then they could see, okay, the one on the left looked more intense, it's smaller and more intense. While when you stepped further away was less intense but spread out (Lecturer 3).

Lecturer 3 thus recommends weakening the semantic gravity further (SG2) and strengthening the semantic density (SD3). Lecturer 2 went on to explain that the analogy of the spray needed to be extended and further developed to build an accurate understanding:

> Another typical example is the X-ray tube because you have the electrons hitting the target, and the target produces radiation in all directions and then you collimate it, So, that you get [direct beam] and then…that's where these analogies come from, you know, they are practical in fact because you see as you can visualise from, as the X-ray comes out of the collimation they sort of spread out. That now is an example of the inverse-square law of radiation and everything (Lecturer 2).

Lecturer 2 explains the need to further weaken semantic gravity (SG1) and strengthen semantic density (SG4), thus creating a typical semantic wave (Figure 6.12). Lecturer 3 felt that the application of the Inverse Square Law to Radiation Therapy practice was a key pedagogy that enabled students to learn the concept in context:

> Well, I think it's the visualisation because when you talk Radiation, it's something abstract and when you have to now make it practical, then that's where the problem comes in. The students have to visualise for example the inverse-square law. It's not something so obvious that you can say okay there is the inverse-square law for exponential attenuation and materials. You don't expect that when you learn the word radiation. It's just an X-ray, blah, blah, blah, and when it comes to now implementing it or applying it that's where the problem comes in (Lecturer 3).

Lecturer 3, who is radiation therapist, begins to bring in the radiation therapy context, thus starting the process of strengthening the epistemic semantic gravity (SG2). This is show in the rise of epistemic semantic gravity (Figure 6.10).

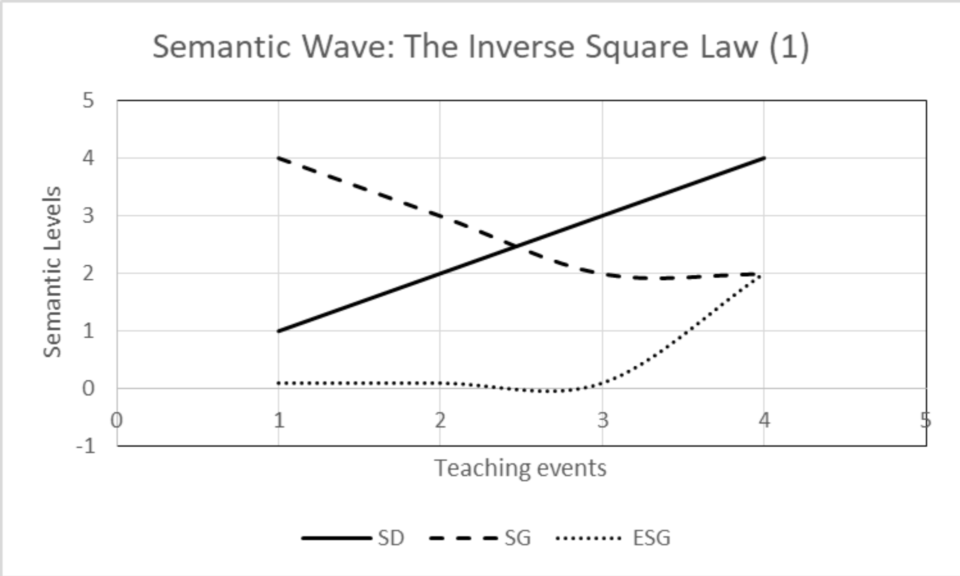


Figure 6.12: Lecturer 2 and 3's semantic wave for teaching the Inverse Square Law (1)

In contrast to Lecturers 2 and 3, Lecturer 1 took the idea of teaching the concept in context further, proposing a pedagogy of practice that required the logic of practice for teaching. Lecturer 1's explanation is quoted in full below, and a semantic profile of the proposed pedagogy is illustrated in Figure 6.13.

> I teach in a way that I learnt how to set up in the department. So it's not necessarily an academic way of teaching but it's the way we – when you come into whether it's the simulator or the CT or the treatment room, it's the way in which you would sequence an order of things that you do. 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 I'm trying to teach so I've taught them understanding your patient first because your patient care comes first. So first, how do we greet our patient? All of those things which is almost pre-clinical but is very practical and every day and it's a basis of what we need to do. So that's the first thing because that's the start of every set up. What do we do with our patient? How do we understand what must happen for our patient? Getting to know our patient by reading the information related to the patient, the treatment sheet, the notes from the doctor all of those things; understanding what your patient is there for and once you have that information then you can start looking at the room. So now in the room, which immobilisation devices do I need? Why do I need those devices? How am I going to set them up to make this patient most comfortable, most stable for the set up? Now that I've got my immobilisation devices, I need to put my patient and my immobilisation devices together. How am I going to do that? What am I

going to do? Do I need to change? And then once that is done, now I need to decide what am I going to do? What's the first thing? What is most important when we set the patient up? 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 three-point 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 where one thing leads into the other and it's the process that you would walk every day in the department or should walk every day in the department (Lecturer 1).

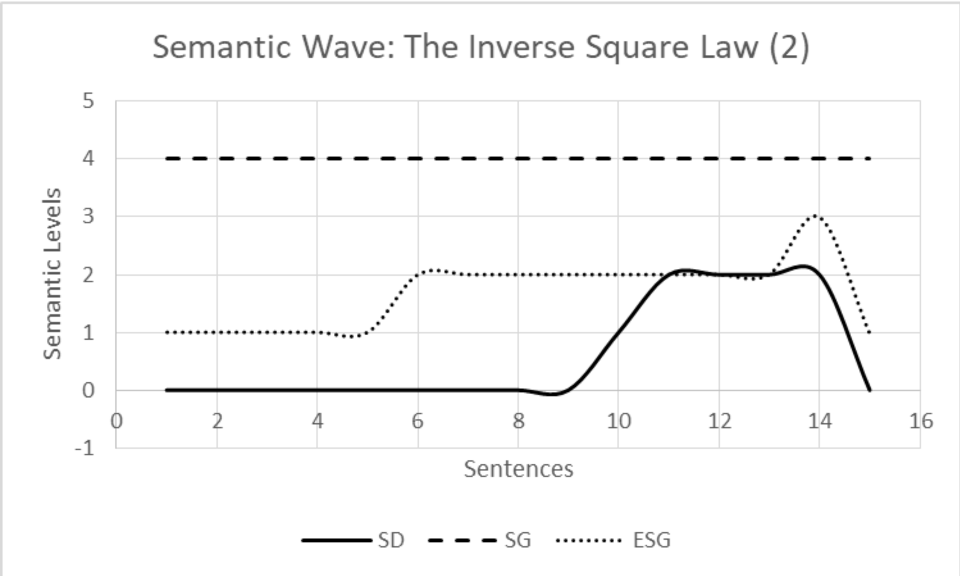


Figure 6.13: Lecturer 1's semantic wave for teaching the Inverse Square Law

Lecturer 1's fifteen sentences were studied and the semantic density, semantic gravity and epistemic semantic gravity were plotted in Figure 6.13. Although describing one of the most challenging concepts in radiation physics, Lecturer 1's description is not semantically dense (SD0). There is an increase in semantic density (SD2) towards the end of the extract in which she names the x, y and z axes and the isocentre. Her description of how she teaches foregrounds the everyday, moving from A to B and greeting the patient appropriately. This accounts for the high flat line of semantic gravity (SG4) which is disconnected from the semantic density. The semantic profile does not produce a classic semantic wave that supports cumulative learning. The clinical environment is present in the form of patient care (ESG1). The epistemic semantic gravity increases as more specialised forms of practice (ESG2), such as establishing the isocentre are mentioned, but without the detail, that is, without building the concept of the Inverse Square Law or the calculations associated with it.

Using the logic of practice to guide pedagogy in radiation physics could be meaningful if the semantic gravity was reduced and the semantic density and the epistemic semantic gravity were increased. The semantic profile created by the high semantic gravity (SG4) does not enable cumulative knowledge building, and may give students the false impression that they understanding the Inverse Square Law, when in fact they have not grasped the concept.

6.4 Conclusion

In summarising the findings of the specific pedagogies that radiation physics lecturers used to teach threshold concepts, the first trend that emerged is how the semantic density was initially weakened as lecturers applied a variety of techniques to reduce the level of difficulty (e.g., visual support, scaffolding and analogies). The lecturers then introduced more abstract representations of the concepts (e.g., graphs and scientific diagrams and scientific terms), and over a period of time, and with repetition of the concept, re-strengthened the semantic density. This trend is shown in Figure 6.14. Also evident in Figure 6.14 is the rise and fall of semantic gravity, and in this case showing an inverse relationship with semantic density. The dotted line represents the clinical environment in the inevitable rise in the epistemic semantic gravity as radiation physics is applied to the practice of radiation therapy.

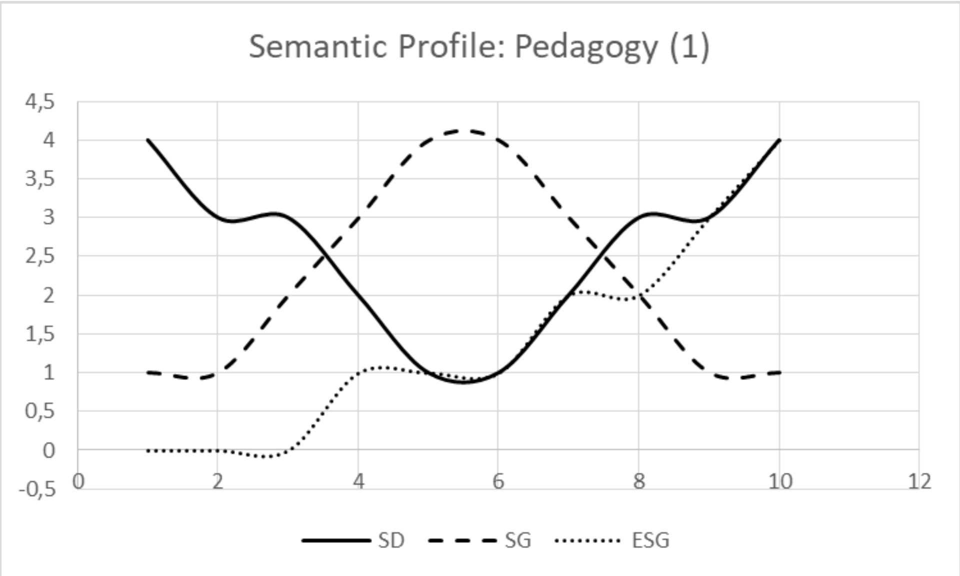


Figure 6.14: The semantic profile of Pedagogy 1.

A second trend that emerged from the data, demonstrated in Figure 6.15, was that the pedagogies used made reference to the clinical context. In particular, the use of VERT and the logic of practice. VERT, the virtual clinical environment and treatment platform, was increasingly drawn on to explain and demonstrate concepts that were particularly critical for radiation therapy practice.

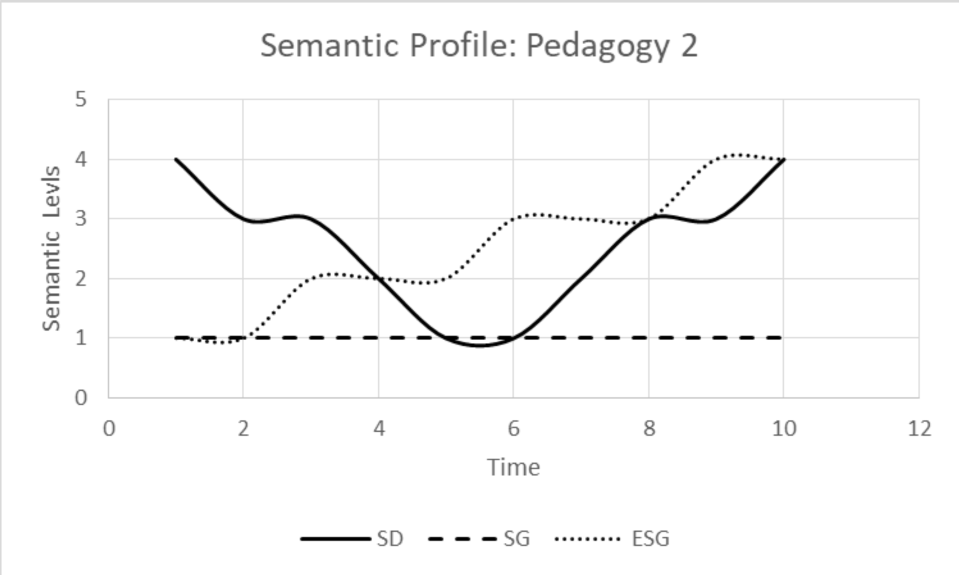


Figure 6.15: The semantic profile of Pedagogy 2.

In Figure 6.15, the epistemic semantic gravity rises, making visible the invisible, but does not fall to enable semantically dense representations. The introduction of a specialised context can initially simplify the semantic density, as the focus changes from concepts to context. However, the semantic density rises as concepts are applied in practice. The semantic gravity maintains a low flat line, which is necessary for extracting principles and engaging in theorising.

The standard state of radiation physics is stronger semantic density and weaker semantic gravity, with varieties of stronger and weaker forms of epistemic semantic gravity. The effect of the pedagogy, in particular the use of clinical examples and immersion in a virtual clinical environment, had the effect of strengthening the semantic density over time. Through pedagogy, the standard state of radiation physics was recontextualised to underpin radiation therapy practice. The details of the upward and downwards shifts in the semantic profile are summarised in Table 6.1.

Table 6.1 Pedagogies for Threshold Concepts in First Year Radiation Physics

Threshold Concept	Semantic Codes	Pedagogy	Pedagogical effect on the semantic codes	Examples from the data
Classification of Radiation	SD3/4, SG1, ESG0	**Scaffolding**: The lecturers used a variety of visual aids to teach the classification of radiation; initially very simple diagrams reduced the SD, but this was re-strengthened through scaffolding. The visual aids increased the SG initially.	SD3/4 ↔ SD2/3 SG1↔ SD4 ESG0	*We start scaffolding that before we get to that. That we started in bits and pieces, like putting the pieces together long before they got to that point. So, when they got to that point, they could understand certain things* (Lecturer 3).
Properties of Radiation	SD3/4, SG1, ESG1	**Analogy:** The lecturers used analogies (such as Coke experiment to illustrate radiation decay) to reduce the SD with regard to the properties of radiation; the SG was strengthened through the use of familiar objects for the analogy.	SD3/4 ↔ SD2/3 SG1→ SD4 ESG0 → ESG1	*You can use a glass of Coke to explain radioactive decay* (Lecturer 2).
Ionisation	SD3/4, SG1, ESG2	**Repetition:** Complex concepts take time to consolidate. The virtual clinical environment supported students' learning over time and strengthened epistemic semantic gravity, while repetition in more abstract contexts strengthened SD.	SD3/4 ↔ SD2/3 SG1 ESG0 → ESG2/3	*And then we use VERT to demonstrate those same principles. So then I will refresh what we have done and practice those concepts over and over and over by repeating it to make sure that they get it using VERT* (Lecturer 1).
Isocentre	SD3/4, SG1, ESG0	**The virtual clinical environment:** Using VERT to teach the isocentre initially reduced SD because it made visible the normally invisible concept. The change to the virtual clinical context and the presence of a virtual patient strengthened the ESG.	SD3/4 → SD2/3 SG1 ESG0 → ESG3/4	*Seeing for example the referencing and the Isocentre, a bit more how – actually understanding what they're doing and being able to maybe even try it yourself* (Y1_L1_2018)
Inverse Square Law	SD3/4, SG1, ESG0	**The logic of practice**: Teaching the Inverse Square Law with through practice brought radiation physics into the clinical environment; it weakened SD initially, but strengthened it over time. The ESG was strengthened.	SD3/4 ↔ SD2/3 SG1 ESG0 → ESG3/4	*But you just feel more confident after working on the VERT and then you come in real life and you also have to all these things. It just makes it easier. You're not so scared.* (Y1_L9_2018)

This chapter studied the pedagogies used to teach and learn the five threshold concepts identified in Chapter 5. The pedagogies to teach these concepts ranged from analogies used to demonstrate properties of radiation, to teaching the Inverse Square Law through the logic of practice. Using the external language of description demonstrated the pedagogical approaches where the semantic density was stronger, and where the epistemic semantic gravity was strengthened as the complexity of the context of clinical practice was introduced in virtual form.

In the next chapter the findings from this study are synthesised and the contributions to knowledge are discussed.

CHAPTER SEVEN

CONCLUSION

7.1 What the thesis set out to achieve

This research study intended to contribute to an understanding of threshold concepts in the first year radiation physics curriculum and to propose pedagogical approaches that supported students' understanding of radiation physics for the purpose of better preparation for competent and safe clinical practice. The main research question guiding the study was: What is the relationship between threshold concepts in the radiation physics curriculum and radiation therapy practice? This research question was focused through the following research sub-questions:

1. What were the main threshold concepts in the radiation physics curriculum?
2. How did first year radiation physics lecturers and clinical educators teach these concepts?
3. How did first year students learn these concepts?
4. How were the acquired threshold concepts transferred and applied in radiation therapy practice?

In the following sections, the research sub-questions are addressed.

7.1.1 What were the main threshold concepts in the radiation physics curriculum?

In order to address this research question, a study of curriculum documents and first year students' formative and summative assessments were undertaken. No threshold concepts were identified in the general physics module of Physical Sciences 1, but five threshold concepts were identified in the radiation physics module:

1. The classification of radiation;
2. The properties of radiation;
3. Ionisation;
4. The isocentre;
5. The Inverse Square Law.

The classification of radiation was identified as a threshold concept, as the classification signals that the student is entering a new discipline with new terms and clusters of new concepts (e.g., α-particles, β-particles, x-rays and γ-rays). The rise in semantic density (SD3) is shown by the specialised disciplinary content.

The properties of radiation was identified as a threshold concept due to its reconstitutive nature. The properties of radiation were initially understood as abstract concepts, this entailed a rise in semantic density (SD3). The concept of the properties of radiation was later found to be reconstituted in practical application; it therefore comprised both 'an epistemological and an ontological shift' (Meyer, Land & Bailie, 2010). Land explains that grasping a concept is never only cognitive, it also involves a repositioning of self in relation to the subject (Land, 2011), which implies that the concept itself is able to be 'repositioned' as either theory or practice. The properties of radiation can be reconstituted as theoretical concepts, or as concepts that underpin practice.

Ionisation was identified as a threshold concept due to its integrative characteristics and calculations which strengthened semantic density (SD4). Ionisation was initially introduced as a non-threshold concept, for example, to distinguish between ionising and non-ionising forms of radiation. Later in the curriculum ionisation was introduced in its full complexity as the ionising radiation dose that radiation therapists administer to patients. Understanding and using concepts such as the International System of Units (SI) and Common Unit Terminology (e.g., for radioactivity, absorbed dose, dose equivalent, exposure) vertically integrates prior concepts, including the prior threshold concepts of the classification of radiation and the properties of radiation. The threshold concept of ionisation also horizontally integrates with practice, and a deep understanding of ionisation underpins the safe administration of radiation therapy related prescriptions, radiation dose measurement, radiation protection, and radiation energy uniformity (Noh et al., 2014). The particular scope of the radiation therapists' practice is the administration of ionising radiation to patients, which makes their full grasp of ionisation crucial to competent and safe professional practice. While a radiation oncologist will prescribe the ionising dose, radiation therapists have the legal authority to plan, calculate and administer the ionisation dose:

> The Radiation Therapist is involved in the planning and/or dose calculation and accurate administration of various forms of ionising radiation for the treatment and care of patients with malignant and benign neoplasms, according to a prescription of a Radiation Oncologist (SAQA, 2018).

Ionisation is integrative in the way that the concept subsumes concepts such as the classification of radiation and the properties of radiation, but it is also deeply integrated with radiation therapy practice.

A central threshold concept in radiation physics is that of the ‘isocentre’, the point in space through which the central rays of the radiation beams pass. The complexity of the concept and its calculations increased the semantic density (SD4). Fundamental to understanding the isocentre is the axis of rotation of a rigid body which is determined ‘using the trajectory of any point on a plane that intersects the rigid body’ (Zhang, Zhou & Qu, 2015). An essential mathematical tool which the isocentre as a threshold concept subsumes is three-dimensional coordinate transformation. Understanding the rotation isocentres of treatment machines is complex, involving high levels of semantic density and epistemic semantic gravity. The isocentre is therefore a radiation physics threshold concept that is central to practice.

The Inverse Square Law states that if you double your distance from a source of ionising radiation you will reduce your exposure by 4 – thus if you triple your distance from the source, the exposure will reduce to 1/9 of the original value. While many students understand the Inverse Square Law, its mathematical representations and calculations cause confusion. Thus understanding the Inverse Square Law mathematically (SD4) and applying it in practice (ESG4) pose high levels of challenge. Beam divergence, the concept that ‘the width of the radiation beam increases linearly with distance from the isocentre’ (Tyler & Hanna, 2015) was not found to be a threshold concept.

The threshold concepts are the cornerstones of radiation protection and strongly linked to radiation therapy practice. These threshold concepts were characterised by a rise in semantic density. This rise represents required an understanding of scientific principles and mathematical representation. As practice became more strongly present in the radiation physics curriculum, the epistemic semantic gravity rose. In particular, the last three threshold concepts turned towards the field of practice and were characterised by strong upward shifts in the epistemic semantic gravity. The study thus identified threshold concepts in the first year radiation physics curriculum and was able to offer a theoretically based explanation for what constitutes a threshold concept in radiation physics.

7.1.2 How did first year radiation physics lecturers and clinical educators teach these concepts?

Five distinct pedagogical approaches were identified comprising:

1. Scaffolding
2. Analogy
3. Repetition

4. The virtual clinical environment
5. The logic of practice.

In order to scaffold students' understanding, lecturers used a variety of visual aids to teach the classification of radiation; initially very simple diagrams increased the semantic gravity (SG4) and reduced the semantic density (SD1 - SD2) of complex concepts. The semantic density was re-strengthened through the introduction of more scientific representations, such as graphs and tables. The lecturers used analogies (such as the Coke experiment to illustrate radiation decay), initially to reduce the semantic gravity (SG4) when explaining the properties of radiation; however, the lecturers also introduced scaffolding, for example, shifting from the Coke experiment towards a more scientific experiment and mathematical representation of the exponential curve as a graph. This process re-strengthened the semantic density and reduced the semantic gravity. Complex concepts take time to consolidate and repetition is often necessary. While the virtual clinical environment supported students' learning, repetition in more abstract contexts strengthened the semantic density (SD3 – SD4). Using VERT to teach the isocentre did not reduce the semantic density but made visible the invisible which in turn made the semantic density rise less steeply. A gradual rise in the epistemic semantic gravity (ESG2 – ESG4) was demonstrated by VERT due to the virtual clinical context and the presence of a virtual patient thereby simulating advanced practice. The upward shift in epistemic semantic gravity was particularly noticeable when VERT was used for teaching and learning threshold concepts. The Inverse Square Law was taught both through the analogy of the spray can and through the logic of practice in order to bring the clinical environment into the radiation physics classroom. In the first pedagogical approach (Figure 6.14), teaching initially weakened the semantic density, but re-strengthened it as the epistemic semantic gravity increased. In the second pedagogical approach (Figure 6.15) strengthening then weakening the semantic gravity shown that both semantic density and epistemic semantic gravity strengthened.

7.1.3 How did first year students learn these concepts?

Many of the descriptors of the Threshold Concept Framework characterised students' experiences in the process of learning radiation physics threshold concepts. They experienced the liminal state as one of frustration, confusion, and a lack of certainties. This was characterised as a state in which students had not yet attained a sufficiently high level of semantic density in their understanding. Both lecturers and clinical educators recognised the liminal state – for the lecturers it was a state in which repetition and practice, explaining and re-explaining dominated classroom discourse, for the clinical educators it was a state of ‘robotic’, rather than engaged or reflective practice. The senior students, in particular the third and fourth year students, could look back on their experiences as first year students and understand that the liminal state was a ‘rite of passage’; a period of confusion before clarity and competence were attained.

7.1.4 How were the acquired threshold concepts transferred and applied in Radiation therapy practice?

The study intended to address the gap between the threshold concepts taught in the first year radiation physics curriculum and their transfer and application to radiation therapy practice. The study found that threshold concepts, when learned in isolation from practice were difficult to transfer to the clinical environment. The pedagogies used by the lecturers that included strengthening the epistemic semantic gravity were key to transferring the knowledge learned in the radiation physics classroom to the clinical workplace. The virtual clinical environment in teaching and learning threshold concepts played a key role in the transfer of threshold concepts in radiation physics to radiation therapy practice. However, the study also identified a range of other pedagogies that could also support the transfer of concepts learned in the classroom to clinical practice.

7.2 The contribution to knowledge

The contribution to knowledge that this thesis makes is a reconceptualization of the Threshold Concept Framework in a way that is theoretically consistent and that addresses the nature of threshold concepts as well as lecturers’ teaching and students’ acquisition thereof. Threshold concepts are found in different disciplines and fields, they are the building blocks of knowledge and require a knowledge based theory to understand their characteristics. Using LCT’s Semantics dimension in conjunction with the Threshold Concept Framework, the study was able to offer a coherent account of the knowledge structures of threshold concepts in radiation physics.

In revising the Threshold Concept Framework, the study found that five descriptors, comprising four descriptors from the original list (Meyer & Land, 2003) and one additional descriptor (Meyer & Land 2006) described the nature of the threshold concept itself. The other concepts described students’ struggles to understand the concept, for example, ‘liminal’ describes the student’s state of confusion; it does not describe the concept. In the revised external language of description, the revised Threshold Concept Framework comprises: bounded, reconstitutive, integrative, transformative and troublesome (Table 7.1). In addition, drawing on the explanatory power of semantic density, semantic gravity and epistemic semantic gravity enabled considerably more detail and clarity in the descriptors.

7.3 The contribution to educational practice

The contribution that the study makes to educational practice is to make the 'rules of the game' explicit (Maton, 2016), that is, the study reveals the characteristics of threshold concepts, it explains threshold concepts as curricular elements and proposes a pedagogy for teaching of threshold concepts in order to underpin professional practice. The study therefore makes a contribution to curriculum development and review; and provides curriculum developers with the tools to identify and understand the 'jewels of the curriculum'. The study proposes a range of effective pedagogies that are characterised by weakening and re-strengthening semantic density, as well as strengthening and weakening semantic gravity, and strengthening epistemic semantic gravity in cases where the threshold concept explicitly underpins practice. The study has implications for how lecturers in the applied sciences, such as radiation physics, might understand their subject area in a more 'applied' way by taking into account the crucial role of the discipline in underpinning practice. The study has implications for clinical educators (and other professional educators) in understanding and valuing the basic sciences. Clinical educators acknowledge that engaged and reflective practice is more than 'pressing the buttons'; but the study explains why threshold concepts are crucial to practice. The problem is not 'book knowledge'; the problem is applying the 'book knowledge' to the clinical context. The pedagogies proposed in the study will help lecturers who teach the basics sciences to transfer that knowledge to the site of practice.

7.4 The contribution to Radiation Therapy Practice

In addition to its knowledge contribution and contribution to the education of radiation therapists, the study also makes a contribution to radiation therapy practice. The study relates many of the inconsistencies and errors in unsafe practice to misunderstandings of the threshold concepts that underpin practice. This is clearly the case with regard to understanding the isocentre and being able to locate its position accurately for the safe and effective treatment of the patient. Similarly, understanding the Inverse Square Law is crucial to planning and calculating the dose delivered to the patient. The less obvious threshold concepts, such as ionisation and properties of radiation are also crucial to safe practice. It is worth remembering that radiation therapists have an independent practice status within their scope of practice, that is, the planning and administration of ionising radiation. Without fully understanding the nature of ionising radiation, radiation therapists will not be able to engage in competent or safe practice.

The contribution of the study is summarised in Table 7.1, which synthesises the findings with regard to the identification of threshold concepts, threshold concepts as curricular elements and proposed pedagogies for threshold concepts:

Table 7.1 Synthesis of the contribution of this study

Threshold Concept Framework	Revised external language of description	Semantic Codes	Threshold Concepts in the Curriculum	Key Pedagogies (and related semantic codes)	Threshold concepts
Bounded	The terminology introduced in the classification of radiation signals the disciplinary field (SD3) of radiation physics. The concepts are abstract (SG1) and the clinical context is not yet apparent (ESG0)	SD3, SG1, ESG0	Concepts such α-particles, β-particles, x-rays and γ-rays as are rarely taught outside of radiation physics (e.g., in general physics), and are thus key to the applied discipline of radiation physics.	Scaffolding *increase semantic gravity and decrease semantic density.*	The classification of radiation
Reconstitutive	Radiation physics subsumes prior concepts (SD3), it is abstract (SG1), it can be reconstituted in practice, or as underpinning practice (ESG2).	SD3, SG1, ESG2	Concepts in atomic structure, ionisation and excitation are the building blocks of radiation physics and are applied in practice.	Analogies *increase semantic gravity and decrease semantic density.*	The properties of radiation
Integrative	Concepts are vertically integrated and cumulative in radiation physics (SD3), but concepts can also be integrated into practice (ESG2-4). The shift occurs in mathematical representation (SD3 - SD4).	SD3-4, SG1, ESG2-4	Basic radiation protection principles integrate radiation physics knowledge into protocols for practice; ionisation integrates prior threshold concepts towards competent and ethical practice, such as 'dose limits', 'radiation protection' and 'radiation conversion'.	Repetition *increase semantic gravity and decrease semantic density.*	Ionisation
Transformative	Transformation is understood as attaining the highest level of abstract conceptual understanding (SD3 - SD4, SG1), and clinical practice (ESG4).	SD3-4, SG1, ESG4	The isocentre underpins radiation therapy practice; when it is fully understood it can transform practice.	The virtual clinical environment *increase semantic gravity and decrease semantic density.*	The isocentre
Troublesome	Semantic density strengthens as additional concepts are subsumed with mathematical representation (SG4) and increasing abstraction (SG1). Challenges are also shown by an increase in ESG 3 to ESG4.	SD4, SG1, ESG3-4	The 'Inverse Square Law' is difficult to master (it is a geometrical progression, in contrast to 'Beam Divergence' which is a linear progression); it underpins the safe administration of the ionising dose.	The logic of practice *increase semantic gravity and decrease semantic density.*	The Inverse Square Law

7.5 What is known now that was not known before this research study

The Threshold Concept Framework pointed to those aspects of the curriculum that create challenges for teaching and learning, but the descriptors used have insufficient depth, and as several studies point out, are inaccurate (Nicola-Richmond et al., 2018; Pėpin et al., 2018; Rowbottom, 2007; Walker, 2013). Describing a threshold concept as 'troublesome' is imprecise and does not assist lecturers in understanding what it is that comprises its 'troublesomeness'. This study has provided accurate and theoretically based descriptors. In place of 'troublesome', the revised external language of description proposes that threshold concepts are characterised by increases in semantic density. This sharp rise can be mitigated through scaffolding, a pedagogy that temporarily weakens semantic density and strengthens semantic gravity before re-building it over a period of time. This study further describes troublesomeness in professional learning as increases in the epistemic semantic gravity.

It has been pointed out that threshold concepts are transformative; Cousin (2010) explains that 'we are what we know' thus acquiring the new knowledge and understanding presented by threshold concepts can transform our being. This has also been described in terms of an 'ontological shift' (Meyer, Land & Bailie, 2010). In the revised external language of description, the ontological shift is characterised by the attainment of the highest levels of semantic density and epistemic semantic gravity. Transformative knowledge in applied disciplines also turns towards practice which involves attaining the highest level of epistemic semantic gravity. High level of competent professional practice are underpinned by high levels of semantic density and epistemic semantic gravity.

7.6 Implications for further research

There are more threshold concepts to be uncovered across the radiation physics curriculum. Even more complex concepts found in the second, third and fourth year curricula. The extent to which these additional concepts are higher level threshold concepts is an area for further study. Additional implications for further research include evaluation research with regard to curricular and pedagogical practices in radiation therapy education.

The new external language of description and the revision of the Threshold Concept Framework could be tested across related Health Sciences and other STEM-based professional disciplines.

Finally, the role of the virtual clinical environment needs further investigation. The world of clinical practice has become increasing complex and highly computerised. It has been pointed out that practitioners' reliance on new forms of imaging and on sophisticated machines could have negative consequences of unintentional increasing the dose to patients. This is because much of the new technologies seem to eliminate the need for the mathematical calculations that radiation therapists need to understand and engage in. The extent to which competent and safe practice should be independent of machine-based calculations is a matter that needs urgent investigation.

7.7 Final reflection

Finally, the study has also contributed to an understanding of the theory/practice divide that has plagued much professional education. The study shows that scientific knowledge, in the form of threshold concepts, constitutes powerful knowledge and that it underpins competent and safe practice – the study clearly indicates that the problem in the theory/practice divide is not the fact that the students have too much 'book knowledge' – the problem is how to unlock the 'book knowledge for practice. The proposed pedagogies for threshold concepts include pedagogies for practice. These pedagogies have the potential to unlock book knowledge for transfer to practice. This study has shown that understanding and valuing the interrelationship between radiation physics and radiation therapy practice is fundamental to professional practice that is focused on the treatment and care of the patient.

REFERENCES

Academy of Science of South Africa (ASSAf), Council on Higher Education (CHE), Department of Higher Education and Training (DHET), Department of Science and Technology (DST), National Research Foundation (NRF) & Universities of South Africa (USAf). 2019. Statement on ethical research and scholarly publishing practices. https://www.nrf.ac.za/sites/default/files/documents/STATEMENT%20ON%20ETHICAL.pdf [25 September 2019].

Airey, J. & Linder, C. 2009. A disciplinary discourse perspective on university science learning: achieving fluency in a critical constellation of modes. *Journal of Research in Science Teaching*, 46(1):27-49.

Alessi, S.M. & Trollip, S.R. 2003. *Multimedia for learning: methods for development.* 3rd ed. Boston, MA: Allyn & Bacon.

Babbie, E.R. & Mouton, J. 2001. *The practice of social research.* Cape Town: Oxford University Press Southern Africa.

Baillie, C., Bowden, J.A. & Meyer, J.H.F. 2013. Threshold capabilities: threshold concepts and knowledge capability linked through variation theory. *Higher Education*, 65(2):227-246.

Baillie, L. 2015. Promoting and evaluating scientific rigour in qualitative research. *Nursing Standard,* 29(46):36-42.

Baker, G.L. & Blackburn, J.A. 2005. *The pendulum: a case study in Physics.* Oxford: Oxford University Press.

Barradell, S. 2013. The identification of threshold concepts: a review of theoretical complexities and methodological challenges. *Higher Education*, 65(2):265-276. doi: 10.1007/s10734-012-9542-3

Baumann, M., Krause, M., Overgaard, J., Debus, J., Bentzen, S.M., Daartz, J., Richter, C., Zips, D. & Bortfeld, T. 2016. Radiation oncology in the era of precision medicine. *Nature Reviews Cancer*, 16(4):234-249.

Beavis, A. & Ward, J. 2012. WE-G-BRA-04: The development of a virtual reality dosimetry training platform for Physics training. *Medical Physics*, 39(6, Part 28):3969. doi:10.1118/1.4736199

Beavis, A.W. & Ward, J.W. 2014. The use of a virtual reality simulator to explore and understand the impact of Linac mis-calibrations. *Journal of Physics: Conference Series*. 489, Conference 1.

Beavis, A.W., Ward, J., Bridge, P., Appleyard, R. & Philips, R. 2006. MO-D-230A-02: an immersive virtual environment for training of radiotherapy students and developing clinical experience. *Medical Physics*, 33:2164.

Bernstein, B. 1977. *Class, codes and control, vol. 3: Towards a theory of educational transmissions.* 2nd ed. London: Routledge & Kegan Paul.

Bernstein, B. 1996. *Pedagogy, symbolic control and identity: theory, research, critique.* London: Taylor & Francis.

Bernstein, B. 1999. Vertical and horizontal discourse: an essay. *British Journal of Sociology* *of Education*, 20(2):157-173.

Bernstein, B. 2000. *Class, codes and control, vol. V: Pedagogy, symbolic control and identity: theory, research critique.* Revised ed. Lanham, MD: Rowan & Littlefield.

Bevis, E.O. 1989. *Curriculum building in nursing: a process.* 3rd ed. Sudbury, MA: Jones and Bartlett.

Biggs, J. 1996. Enhancing teaching through constructive alignment. *Higher Education*, 32(3):347-364.

Biggs, J.B. & Tang, C. 2011. *Teaching for quality learning at university: what the student does.* 4th ed. New York, NY: McGraw-Hill; Society for Research into Higher Education; Open University Press.

Bourdieu, P. 1993. *The field of cultural production: essays on art and literature*. Cambridge: Polity Press.

Bourland, J.D. 2016. Radiation Oncology Physics, in *Clinical Radiation Oncology*, 4th ed. Gunderson, L.L. & Tepper, J.S. (eds) Philadelphia: Elsevier, 96.

Bradbury, J. & Miller, R. 2011. A failure by any other name: the phenomenon of underpreparedness. *South African Journal of Science*, 107(3-4), Article no. 294, 8pp.

Bradley, P. 2006. The history of simulation in medical education and possible future directions. *Medical Education*, 40(3):254-262.

Bridge, P., Appleyard, R.M., Ward, J.W., Philips, R. & Beavis, A.W. 2007. The development and evaluation of a virtual radiotherapy treatment machine using an immersive visualisation environment. *Computers & Education*, 49(2):481-494.

Brink, H.I., Van der Walt, C. & Van Rensburg, G.H. 2006. *Fundamentals of research methodology for health care professionals*. 2nd ed. Cape Town: Juta.

Burch, V. 2014. Does simulation-based training have a future in Africa? *African Journal of Health Professions Education*, 6(2):117-118.

Cape Peninsula University of Technology. 2012. Research, technology innovation and partnerships: 10-year blueprint. https://www.cput.ac.za/storage/research/RTI_Blueprint_2013_WEB.pdf [17 September 2017].

Cartwright, N. 1983. *How the laws of Physics lie.* Oxford: Clarendon.

Carver, D.E., Willis, C.E., Stauduhar, P.J., Nishino, T.K., Wells, J.R. & Samei, E. 2018. Medical Physics 3.0 versus 1.0: a case study in digital radiography quality control. *Journal of Applied Clinical Medical Physics*, 19(5):694-707.

Cassidy, S. 2015. Resilience building in students: the role of academic self-efficacy. *Frontiers in Psychology*, 6, Article no. 1781, 14 pp. doi: 10.3389/fpsyg.2015.01781

CHE – *see* Council on Higher Education

Clouder, L. 2005. Caring as a ‘threshold concept’: transforming students in higher education into health (care) professionals. *Teaching in Higher Education*, 10(4):505-517.

Conana, H., Marshall, D. & Case, J.M. 2016. Exploring pedagogical possibilities for transformative approaches to academic literacies in undergraduate Physics. *Critical Studies in Teaching and Learning*, 4(2):28-44. doi: 10.14426/cristal.v4i2.73

Conana, H., Marshall, D. & Case, J.M. 2020. A Semantics analysis of first year physics teaching: Developing students' use of representations in problem-solving. In Winberg, C, McKenna, S. & Wilmot, K. *Building Knowledge in Higher Education*: *Enhancing teaching and learning with Legitimation Code Theory*. New York, NY: Routledge.

Concari, S., Giorgi, S., Cámara, C. & Giacosa, N. 2006. Didactic strategies using simulations for Physics teaching. In Méndez-Vilas, N. (ed.). *Current Developments in Technology-Assisted Education: Proceedings of 4th International Conference on Multimedia and ICTs in Education, Seville, Spain, 29 November –2 December.* Badajoz: Formatex. http://www.researchgate.net/publication/237308516 [17 September 2017].

Council on Higher Education. 2013. *A proposal for undergraduate curriculum reform in South Africa: the case for a flexible curriculum structure*. Pretoria: Council on Higher Education.

Cousin, G. 2006a. An introduction to threshold concepts. *Planet,* No.17:4-5, December. http://dx.doi.org/10.11120/plan.2006.00170004

Cousin, G. 2006b. Threshold concepts, troublesome knowledge and emotional capital: an exploration into learning about others. In Meyer, J.H.F. & Land, R. (eds). *Overcoming barriers to student understanding: threshold concepts and troublesome knowledge*. London: Routledge: 134-147.

Cousin, G. 2009. *Researching learning in higher education: an introduction to contemporary methods and approaches*. New York, NY: Routledge.

Cousin, G. 2010. Neither teacher-centred nor student-centred: threshold concepts and research partnerships. *Journal of Learning Development in Higher Education*, (2):1-9.

CPUT *see* Cape Peninsula University of Technology

Crane, G.D. & Abbott, P.V. 2016. Radiation shielding in dentistry: an update. *Australian Dental Journal,* 61(3):277-281.

Crouch, C.H., Watkins, J., Fagen, A.P. & Mazur, E. 2007. Peer instruction: engaging students one-on-one, all at once. *Research-Based Reform of University Physics*, 1(1):40-95.

Delwiche, F.A. 2013. Mapping the literature of radiation therapy. *Journal of the Medical Library Association*, 101(2) 120-127. doi: 10.3163/1536-5050.101.2.007

Denzin, N.K. & Lincoln, Y.S. 2008. Introduction: The discipline and practice of qualitative research. In Denzin, N.K. & Lincoln, Y.S. (eds). *Collecting and interpreting qualitative materials*. 3rd ed. Thousand Oaks, CA: Sage: 1-43.

Ditkofsky, N., Shekhani, H.N., Cloutier, M., Chen, Z.N., Zhang, C. & Hanna, T.N. 2016. Ionizing radiation knowledge among emergency department providers. *Journal of the American College of Radiology,* 13(9):1044-1049.

Dunn, M.J. 2019. Crossing the threshold: when transition becomes troublesome for A-level students. *Education and Health,* 37(1):24-30.

Elder-Vass, D. 2010. *The causal power of social structures: emergence, structure and agency.* Cambridge: Cambridge University Press.

Ellery, K. 2017. Framing of transitional pedagogic practices in the sciences: enabling access. *Teaching in Higher Education*, 22(8):908-924.

Ellis, J. 2006. All inclusive benchmarking. *Journal of Nursing Management*, 14(5):377-383.

Engel-Hills, P.C. 2009. Radiation therapist research in Africa: overcoming the barriers to reap the rewards. *Journal of Radiotherapy in Practice*, 8(2):93-98. doi:10.1017/S1460396908006547

Engel-Hills, P.C., Garraway, J., Jacobs, G., Volbrecht, T. & Winberg, C. 2010. Position paper on work-integrated learning in the new Higher Education Qualifications Framework. Paper presented at the NQF Research Conference, Benoni, 2–4 June.

Eriksen, J.G. et al. 2012. The updated ESTRO core curricula 2011 for clinicians, medical physicists and RTTs in radiotherapy/radiation oncology. *Radiotherapy and Oncology*, 103(1):103-108.

Flinton, D. 2013. Competency based assessment using a virtual environment for radiotherapy. *Procedia Computer Science*, 25:399-401. https://doi.org/10.1016/j.procs.2013.11.049

Flyvbjerg, B. 2006. Five misunderstandings about case-study research. *Qualitative Inquiry*, 12(2):219-245. https://doi.org/10.1177/1077800405284363

Fredholm, A., Henningsohn, L., Savin-Baden, M. & Silén, C. 2019. [In press]. The practice of thresholds: autonomy in clinical education explored through variation theory and the threshold concept framework. *Teaching in Higher Education*, 16 pp.

Frey, J.H. & Fontana, A.1991. The group interview in social research. *Social Science Journal*, 28(2):175-187.

Gaba, D.M. 2004. The future vision of simulation in health care. *Quality and Safety in Health Care,* 13(Suppl. 1):i2–i10. doi: 10.1136/qshc.2004.009878

Georgiou, H. 2016. Putting physics knowledge in the hot seat: the semantics of student understanding of thermodynamics. In Maton, K., Hood, S., & Shay, S. *Knowledge building: Educational studies in Legitimation Code Theory*. Abingdon: Routledge.

Good, M.L. 2003. Patient simulation for training basic and advanced clinical skills. *Medical Education,* 37 (Suppl. 1):14-21.

Hamid, S.A., Plusch, K., Hammond, A. & Doorey, A. 2016. Adherence to radiation safety in the cardiac catheterization laboratory. How good are we? An observational study. *Catheterization and Cardiovascular Interventions*, 87(S1):23.

Harnett, N., Bak, K., Lockhart, E., Ang, M., Zychia, L., Gutierrez, E. & Warde, P. 2018. The clinical specialist radiation therapist (CSRT): a case study exploring the effectiveness of a new advanced practice role in Canada. *Journal of Medical Radiation Sciences*, 65(2):86-96. doi: 10.1002/jmrs.281

Harnett, N., Bak, K., Zychia, L. & Lockhart, E. 2014. A roadmap for change. Charting the course of the development of a new, advanced role for radiation therapists. *Journal of Allied Health*, 43(2):110-116, Summer.

Harrison, D. & Serbanescu, R. 2017. Practice and evidence of the scholarship of teaching and learning in higher education. *Threshold Concepts in Physics*, 12(2):352-377.

Hudson, L., Engel-Hills, P. & Winberg, C. 2018. Threshold concepts in Radiation physics underpinning professional practice in radiation therapy. *International Journal of Practice-Based Learning in Health and Social Care,* 6(1):53-63.

Hyett, N., Kenny, A. & Dickson-Swift, V. 2014. Methodology or method? A critical review of qualitative case study reports. *International Journal of Qualitative Studies on Health and Well-Being,* 9:1, 23606, doi: 10.3402/qhw.v9.23606

Inhelder, B. & Piaget, J. 1958. *The growth of logical thinking from childhood to adolescence: an essay on the construction of formal operational structures*. New York, NY: Basic Books.

Jansen, J.D. 1998. Curriculum reform in South Africa: a critical analysis of outcomes-based education. *Cambridge Journal of Education*, 28(3):321-331.

Jimoyiannis, A. & Komis. V. 2001. Computer simulations in Physics teaching and learning: a case study on students' understanding of trajectory motion. *Journal of Computers & Education*, 36(2):183-204.

Johnson, A. & Hafele, A. 2010. Exploring student understanding of atoms and radiation with the Atom Builder Simulator. In Singh, C., Sabella, M. & Rebello, S. (eds). *Proceedings of the 2010 Physics Education Research Conference, Portland, Oregon, 21–22 July.* Vol. 1289, No. 1. New York, NY: American Institute of Physics: 177-180.

Katz, D.M. 2017. *Physics for scientists and engineers: foundations and connections, vol. 1.* Boston, MA: Cengage Learning.

Kerr, J.F. 1968. *Changing the curriculum.* London: University of London Press.

Khan, F.M. & Gibbons, J.P. 2014. *Khan's The Physics of radiation therapy.* 5th ed. Philadelphia, PA: Lippincott Williams & Wilkins.

Killpack, T.L. & Melón, L.C. 2016. Toward inclusive STEM classrooms: what personal role do faculty play? *CBE Life Sciences Education*, 15(3), es3, Fall, 9 pp.

Kinchin, I.M., Cabot, L.B. & Hay, D.B. 2010. Visualizing expertise: revealing the nature of a threshold concept in the development of an authentic pedagogy for clinical education. In Meyer, J.H., Land, R. & Baillie, C. (eds). *Threshold concepts and transformational learning*. Rotterdam: Sense/Brill: 303-316.

Kirby, M.C. 2015. Teaching radiotherapy Physics concepts using simulation: experience with student radiographers in Liverpool, UK. *Medical Physics International,* 3(2):87-93.

Knight, P.T. 2001. Complexity and curriculum: a process approach to curriculum-making. *Teaching in Higher Education*, 6(3):369-381.

Körhasan, N.D. & Wang, L. 2016. Students' mental models of atomic spectra. *Chemistry Education Research and Practice*, 17(4):743-755.

Land, R. & Meyer, J. 2010. Threshold concepts and troublesome knowledge (5): dynamics of assessment. In Meyer, J.H., Land, R. & Baillie, C. (eds). *Threshold concepts and transformational learning.* Rotterdam: Sense/Brill: 61-80.

Land, R. 2011. Crossing tribal boundaries: interdisciplinarity as a threshold concept. In Trowler, P., Saunders, M. & Bamber, V. (eds). *Tribes and territories in the 21st century: rethinking the significance of disciplines in higher education.* London: Routledge: 175-185.

Land, R., Cousin, G., Meyer, J. H. F. & Davies, P. 2005. Threshold concepts and troublesome knowledge (3): implications for course design and evaluation. In Rust, C. (ed.). *Improving student learning: diversity and inclusivity.* Oxford: Oxford Centre for Staff and Learning Development: 53-64.

Land, R., Meyer, J.H.F. & Baillie, C. 2010. Editors' preface. In Meyer, J.H., Land, R. & Baillie, C. (eds). *Threshold concepts and transformational learning.* Rotterdam: Sense/Brill: i-xxxv.

Legitimation Code Theory Glossary. 2019. Concept glossary. www.legitimationcodetheory.com/concept-glossary.html [12 June 2019].

Lopreiato, J.O. (ed.), Downing, D., Gammon, W., Lioce, L., Sittner, B., Slot, V., Spain, A. E. (associate eds) & the Terminology & Concepts Working Group. 2016. *Healthcare simulation dictionary*. http://www.ssih.org/dictionary [12 June 2019].

Male, S.A. & Bennett, D. 2015. Threshold concepts in undergraduate engineering: exploring engineering roles and value of learning. *Australasian Journal of Engineering Education*, 20(1):59-69.

Martin, J. 2017. Bigger than Bieber: The Second International Legitimation Code Theory Conference (summary), Sydney, Australia, 3–7 July. legitimationcodetheory.com/wp-content/uploads/2018/06/LCT2.pdf [13 June 2019].

Martin, J.R., Maton, K. & Doran, Y.J., 2019. *Accessing Academic Discourse: Systemic Functional Linguistics and Legitimation Code Theory*. Routledge.

Marton, F. 2014. *Necessary conditions of learning*. New York, NY: Routledge.

Maton, K. 2000. Languages of legitimation: the structuring significance for intellectual fields of strategic knowledge claims. *British Journal of Sociology of Education,* 21(2):147-167.

Maton, K. 2009. Cumulative and segmented learning: Exploring the role of curriculum structures in knowledge-building. *British Journal of Sociology of Education*, 30(1): 43-57.

Maton, K. 2014. *Knowledge and knowers: towards a realist sociology of education*. London: Routledge.

Maton, K. 2016a. Legitimation Code Theory: building knowledge about knowledge building. in Maton, K., Hood, S. & Shay, S. (eds). *Knowledge building: educational studies in Legitimation Code Theory.* London: Routledge: 1-24.

Maton, K. 2016b. Starting points: resources and architectural glossary. In Maton, K., Hood, S. & Shay, S. (eds). *Knowledge building: educational studies in Legitimation Code Theory.* London: Routledge: 233-243.

Maton, K. & Chen, R.T-H. 2016. LCT in qualitative research: creating a translation device for studying constructivist pedagogy. In Maton, K., Hood, S. & Shay, S. (eds). *Knowledge* *building: educational studies in Legitimation Code Theory.* London: Routledge: 27-48.

Maton, K., Hood, S. & Shay, S. (eds). 2016. *Knowledge building: educational studies in Legitimation Code Theory.* London: Routledge.

Matthews, K., Wright, C. & Osborne, C. 2014. Blending work-integrated learning with distance education in an Australian therapy advanced practice curriculum. *Radiography*, 20(3):277-282.

Meyer, J., Land, R. & Baillie, C. (eds). 2010. *Threshold concepts and transformational learning*. Rotterdam: Sense/Brill.

Meyer, J.H. & Land, R. 2005. Threshold concepts and troublesome knowledge (2): epistemological considerations and a conceptual framework for teaching and learning. *Higher Education*, 49(3):373-388.

Meyer, J.H.F. & Land, R. 2003. Threshold concepts and troublesome knowledge (1) – linkages to ways of thinking and practising. In Rust, C. (ed.). *Improving student learning and practice – ten years on. Proceedings of the 2002 10th International Symposium: Improving Student Learning.* Oxford: Oxford Centre for Staff and Learning Development: 412-424.

Meyer, J.H.F. & Timmermans, J.A. 2016. Integrated threshold concept knowledge. In Meyer, J.H., Timmermans, J.A. & Flanagan, M.T. (eds). *Threshold concepts in practice.* Rotterdam: Sense/Brill: 25-38.

Meyer, J.H.F., Land, R. & Davies, P. 2006. Implications of threshold concepts for course design and evaluation. In Meyer, J.H.F. & Land, R. (eds). *Overcoming barriers to student understanding: threshold concepts and troublesome knowledge.* London: Routledge: 195-206.

Miles, R. 2015. Complexity, representation and practice: case study as method and methodology. *Issues in Educational Research,* 25(3):309-318.

Ministry of the Environment, Government of Japan. 2016. Booklet to provide basic information regarding health effects of radiation. https://www.env.go.jp/en/chemi/rhm/basic-info/index.html [15 November 2019].

Moore, J.C. 2012. Transitional to formal operational: using authentic research experiences to get non-science students to think more like scientists. *European Journal of Physics Education*, 3(4):1-12.

Morais, A.M. 2002. Basil Bernstein at the micro level of the classroom. *British Journal of Sociology of Education*, 23(4):559-569.

Motola, I., Devine, L.A., Chung, H.S., Sullivan, J.E. & Issenberg, B.S. 2013. Simulation in healthcare education: a best evidence practical guide. AMEE Guide No. 82, *Medical Teacher*, (35)10:e1511-e1530. doi: 10.3109/0142159X.2013.818632

Mouton, J. 1996. *Understanding social research.* Pretoria: Van Schaik.

Muller, J. 2014. Every picture tells a story: epistemological access and knowledge. *Education as Change*, 18(2):255-269.

Muller, J. 2015. The future of knowledge and skills in science and technology higher education. *Higher Education*, 70(3):409-416.

Nerland, M. & Jensen, K. 2014. Learning through epistemic practices in professional work: examples from nursing and computer engineering. In Fenwick, T. & Nerland, M. (eds). *Reconceptualising professional learning: sociomaterial knowledges, practices & responsibilities.* London: Routledge: 25-37.

Neve, H., Lloyd, H. & Collett, T. 2017. Understanding students' experiences of professionalism learning: a 'threshold' approach. *Teaching in Higher Education*, 22(1):92-108.

Nicola-Richmond, K., Pépin, G., Larkin, H. & Taylor, C. 2018. Threshold concepts in higher education: a synthesis of the literature relating to measurement of threshold crossing. *Higher Education Research & Development*, 37(1):101-114.

Noble, H. & Smith, J. 2015. Issues of validity and reliability in qualitative research. *Evidence Based Nursing,* 18(2):34-35.

Noh, S.J., Lee, M.W., Jung, D.H., Lim, H.J., Kim, H., Kim, H.J. & Kang, Y.R. 2014. A study on the development of quality assurance development and dose distribution for medical linear accelerator. *Proceedings of the Spring Meeting of the Korean Nuclear Society, Jeju, South Korea, 28–30 May.* https://inis.iaea.org/search/search.aspx?orig_q=RN:46050622 [8 March 2018].

Osterhölm, L., Framholt, H. & Nordentoft, I. 2010. 3D virtual training facility. Poster presented at the 29th Meeting of the European Society for Therapeutic Radiology and Oncology (ESTRO 29), Barcelona, Spain, 12–16 September.

Park E.J. & Light G. 2009 Identifying atomic structure as a threshold concept: Student mental models and troublesomeness. *International Journal of Science Education*, 31 (2), 233–258.

Perkins, D. 1999. The many faces of constructivism. *Educational Leadership*, 57(3):6-11.

Perkins, D. 2006. Constructivism and troublesome knowledge. In Meyer, J.H.F. & Land, R. (eds). *Overcoming barriers to student learning: threshold concepts and troublesome knowledge.* London: Routledge; 33-47.

Podgorsak, E.B. (ed.). 2005. *Radiology oncology Physics: a handbook for teachers and students.* Vienna: International Atomic Energy Agency.

Ragin, C.C. 1992. "Casing" and the process of social inquiry. In Ragin, C.C & Becker, H.S. (eds). *What is a case? Exploring the foundations of social inquiry.* Cambridge: Cambridge University Press: 217-226.

Richardson, L. & St Pierre, E.A. 2005. Writing: a method of inquiry. In Denzin, N.K. & Lincoln, Y.S. (eds). *Sage handbook of qualitative research*. Thousand Oaks, CA: Sage: 959-978.

Rogers, E.M. 2011. *Physics for the inquiring mind: the methods, nature, and philosophy of physical science.* Princeton, NJ: Princeton University Press.

Rosca, F., Lorenz, F., Hacker, F.L., Chin, L.M., Ramakrishna, N. & Zygmanski, P. 2006. An MLC-based Linac QA procedure for the characterization of radiation isocentre and room lasers' position. *Medical Physics,* 33(6):1780-1787.

Rowbottom, D.P. 2007. Demystifying threshold concepts. *Journal of Philosophy of Education*, 41(2):263-270.

Rowlands, W. 2018. The basics of Physics: Massive Open Online Course. https://www.mooc-list.com/course/basic-Physics-open2study [March 2018]

Royeen, C.B., Jensen, G.M., Chapman, T.A. & Ciccone, T. 2010. Is interprofessionality a threshold concept for education and health care practice? *Journal of Allied Health*, 39(Suppl.1):251-252, Fall.

Rule, P. & John, V. 2011. *Your guide to case study research.* Pretoria: Van Schaik.

SAQA *see* South African Qualifications Authority

Savelsbergh, E.R., Prins, G.T., Rietbergen, C., Fechner, S., Vaessen, B.E., Draijer, J.M. & Bakker, A. 2016. Effects of innovative science and mathematics teaching on student attitudes and achievement: a meta-analytic study. *Educational Research Review*, 19:158-172.

Schank, P. & Kozma, R. 2002. Learning chemistry through the use of a representation-based knowledge building environment. *Journal of Computers in Mathematics and Science Teaching*, 21(3):253-279.

Scheja, M. & Pettersson, K. 2010. Transformation and contextualisation: conceptualising students' conceptual understandings of threshold concepts in calculus. *Higher Education*, 59(2):221-241.

Schneider-Kolsky, M., Wright, C. & Baird, M. 2006. Evaluation of selection criteria for graduate students in radiation therapy. *Medical Teacher,* 28(8):e214-e219. doi: 10.1080/01421590600969538

Schwandt, T.A. & Gates, E.F. 2018. Case study methodology. In Denzin, N.K. & Lincoln, Y.S. (eds). *Sage handbook of qualitative research.* 5th ed. Thousand Oaks, CA: Sage: 341-358.

Scott, I. 2018. Designing the South African higher education system for student success. *Journal of Student Affairs in Africa*, 6(1):1-17.

Serbanescu, R. 2017. Identifying threshold concepts in Physics: too many to count! *Practice and Evidence of the Scholarship of Teaching and Learning in Higher Education*, 12(2):378-396.

Shay, S., 2013. Conceptualizing curriculum differentiation in higher education: a sociology of knowledge point of view. *British Journal of Sociology of Education*, 34(4): 563-582.

Shay, S., Wolff, K.E. & Clarence-Fincham, J. 2016. Curriculum reform in South Africa: more time for what? *Critical Studies in Teaching and Learning*, 4(1):74-88.

Shumba, A., Ndofirepi, A.P. & Gwirayi, P. 2012. A critique of constructivist theory in science teaching and learning. *Journal of Social Sciences*, 31(1):11-18.

Silverman, D. 2014. *Interpreting qualitative data.* 5th ed. Los Angeles, CA: Sage.

Simons, H. 2009. *Case study research in practice.* London: Sage.

Socratic. 2019. Physics. https://socratic.org [13 November 2019].

South African Qualifications Authority (SAQA). 2018. Registered qualification: Bachelor of Radiation therapy. http://regqs.saqa.org.za/viewQualification.php?id=66951 [13 June 2019]

Taba, H. 2013. *The dynamics of education: a methodology of progressive educational thought.* London: Routledge.

Taber, K.S. 2003. Mediating mental models of metals: acknowledging the priority of the learner's prior learning. *Science Education*, 87(5):732-758.

Tan, C.P., Van der Molen, H.T. and Schmidt, H.G., 2017. A measure of professional identity development for professional education. *Studies in Higher Education*, 42(8): 1504-1519.

Tan, K.C.D., Taber, K.S., Liew, Y.Q. & Teo, K.L.A., 2019. A web-based ionisation energy diagnostic instrument: exploiting the affordances of technology. *Chemistry Education Research and Practice*, 20(2):412-427.

Tan, K.C.D., Taber, K.S., Liu, X., Coll, R.K., Lorenzo, M., Li, J., Goh, N.K. & Chia, L.S. 2008. Students' conceptions of ionisation energy: a cross-cultural study. *International Journal of Science Education,* 30(2):263-283.

Tanner, B. 2011. Threshold concepts in practice education: perceptions of practice educators. *British Journal of Occupational Therapy*, 74(9):427-434.

Thoirs, K., Giles, E. & Barber, W. 2011. Use of simulated learning environments in radiation science curricula submitted by the University of South Australia School of Health Sciences. https://www.researchgate.net/publication/264622956 [13 June 2019].

Tyler, A. & Hanna, L. 2015. Radiotherapy planning 1: Fundamentals of external beam and brachytherapy. In Hanna, L., Crosby, T. & MacBeth, F. (eds). *Practical clinical oncology*. 2nd ed. Cambridge: Cambridge University Press: 54-69.

University of Wisconsin-La Crosse. 2019. Radiation therapy program. https://www.uwlax.edu/health-professions/undergraduate-majorsminors/radiation-therapy/ [13 November 2019].

Van den Akker, J., 2004. Curriculum perspectives: an introduction. In Van den Akker, J., Kuiper, W. & Hameyer, U. (eds). *Curriculum landscapes and trends*. Dordrecht: Springer: 1-10.

Van Heerden, M., Clarence, S. & Bharuthram, S. 2017. What lies beneath: exploring the deeper purposes of feedback on student writing through considering disciplinary knowledge and knowers. *Assessment & Evaluation in Higher Education,* 42(6):967-97. doi: 10.1080/02602938.2016.1212985

Verellen, D., De Ridder, M., Linthout, N., Tournel, K., Soete, G. & Storme, G. 2007. Innovations in image-guided radiotherapy. *Nature Reviews Cancer*, 7(12):949-960. https://doi.org/10.1038/nrc2288

Walford, G. 2001. Site selection within comparative case study and ethnographic research. *Compare: A Journal of Comparative and International Education,* 31(2):151-164.

Walker, G. 2013. A cognitive approach to threshold concepts. *Higher Education*, 65(2): 247-263.

Walsh, R. & Craig, A. 2016. Radiation therapists' and diagnostic radiographers' participation in continuing professional development and knowledge of regulatory body registration. *Journal of Radiotherapy in Practice*, 15(2):150-160. doi:10.1017/S1460396916000054

Watkins, J. & Mazur, E. 2013. Retaining students in science, technology, engineering, and mathematics (STEM) majors. *Journal of College Science Teaching*, 42(5):36-41.

Weurlander, M., Scheja, M., Hult, H. & Wernerson, A. 2016. The struggle to understand: exploring medical students' experiences of learning and understanding during a basic science course. *Studies in Higher Education,* 41(3):462-477.

Wheelahan, L. 2012. *Why knowledge matters in curriculum: A social realist argument*. Abingdon: Routledge.

Wiji, W. & Mulyani, S. 2018. May. Student's mental model, misconceptions, troublesome knowledge, and threshold concept on thermochemistry with DToM-POE. *Journal of Physics: Conference Series*,1013:012098, 5pp.

Wilson, A., Åkerlind, G., Francis, P., Kirkup, L., McKenzie, J., Pearce, D. & Sharma, M.D. 2010. Measurement uncertainty as a threshold concept in Physics. In Sharma, M. (ed.). *Proceedings of the 16th UniServe Science Annual Conference: Creating Active Minds in Our Science and Mathematics Students, Sydney, Australia, 29 September – 1 October*. Sydney: UniServe Science: 98-103.
https://opus.lib.uts.edu.au/bitstream/10453/16072/1/2010001741OK.pdf [13 June 2019].

Winberg, C. 2005. Continuities and discontinuities in the journey from technikon to university of technology. *South African Journal of Higher Education*, 19(2):189-200.

Winberg, C., Winberg, S., Jacobs, C., Garraway, J. and Engel-Hills, P. 2016. 'I take engineering with me': epistemological transitions across an engineering curriculum. *Teaching in Higher Education*, 21(4): 398-414.

WMA *see* World Medical Association

Wolff, K. 2018. A language for the analysis of disciplinary boundary crossing: insights from engineering problem-solving practice. *Teaching in Higher Education*, 23(1), 104-119.

Wolff, K. & Hoffman, F. 2014. 'Knowledge and knowers' in engineering assessment. *Critical Studies in Teaching and Learning*, 2(1):74-95.

Wolfson, A.J., Rowland, S.L., Lawrie, G.A. & Wright, A.H. 2014. Student conceptions about energy transformations: progression from general chemistry to biochemistry. *Chemistry Education Research and Practice*, 15(2):168-183.

World Conference on Research Integrity. 2010. Singapore Statement on Research Integrity. [Developed as part of the 2nd World Conference on Research Integrity, Singapore, 21–24 July 2010.] https://wcrif.org/documents/327-singapore-statement-a4size/file [3 May 2019].

World Medical Association. 2013. World Medical Association Declaration of Helsinki: ethical principles for medical research involving human subjects. *Journal of the American Medical Association (JAMA)*, 310(20):2191-2194. doi:10.1001/jama.2013.281053

Wyrley-Birch, B. 2010. 'Talking technical': learning how to communicate as a health care professional. *Southern African Linguistics and Applied Language Studies*, 28(3):209-218.

Yorke, J. 2014. *Into the woods: how stories work and why we tell them*. London: Penguin.

Zhang, M.T., Zhou, S.-M. & Qu, T.X. 2015. What do we mean when we talk about the linac isocentre? *International Journal of Medical Physics, Clinical Engineering and Radiation Oncology*, 4(3):233-242. http://dx.doi.org/10.4236/ijmpcero.2015.43028

APPENDICES

Appendix 3.1: Interview guide with student participants
Appendix 3.2: Interview guide with lecturer participants
Appendix 3.3: Interview guide with clinical educator participants
Appendix 3.4: Ethical approval - academic site
Appendix 3.5: Ethical approval - clinical site
Appendix 3.6: Ethical approval - clinical site
Appendix 3.7: Call for voluntary participation
Appendix 3.8: Informed consent: Lecturer and Clinical educator participants
Appendix 3.9: Informed consent: Student participants
Appendix 3.10: Physical Science 1 section from first year learnerguide

APPENDIX 3.1

SEMI-STRUCTURED FOCUS GROUP INTERVIEW GUIDE (FIRST TO FOURTH YEAR STUDENTS)

TITLE OF STUDY: Teaching threshold Radiation physics concepts in a virtual clinical environment

DEPARTMENT: Department of Medical Imaging and Therapeutic Sciences, Cape Peninsula University of Technology

RESEARCHER: Lizel Hudson (under supervision of Associate Professor P Engel-Hills and Professor C Winberg)

DATE:

COMMENTS/NOTES:

Guiding questions:

10. Why should BSc: Radiation therapy students learn Radiation physics?
11. What is your understanding of threshold concepts in Radiation physics?
12. What is your experience of learning threshold Radiation physics concepts in VERT^{TM}?
13. Comment on the following statement: Knowing/mastering threshold concepts in physics improves clinical competence.
14. After your clinical rotation: What helped you to apply Radiation physics concepts in the clinical department? What did not help you?
15. Did the sessions in VERT^{TM} help you to apply concepts in the clinical department? What about those sessions helped/did not help?
16. What are your suggestions for teaching threshold concepts in Radiation physics?
17. Is there anything in the Radiation physics module that you found beneficial for your own learning and clinical practice? Please elaborate.
18. Is there anything else about learning Radiation physics that you would like to share with the researcher?

APPENDIX 3.2

SEMI-STRUCTURED INDIVIDUAL INTERVIEW GUIDE (LECTURERS)

TITLE OF STUDY: Teaching threshold radiation physics concepts in a virtual clinical environment

DEPARTMENT: Department of Medical Imaging and Therapeutic Sciences, Cape Peninsula University of Technology

RESEARCHER: Lizel Hudson (under supervision of Associate Professor P Engel-Hills and Professor C Winberg)

DATE:

COMMENTS/NOTES:

Guiding questions:

1) What is your understanding of threshold concepts in radiation physics?
2) How do you teach threshold concepts in radiation physics?
3) Do you use computer simulations or computer-simulated learning environments, for example, VERT™ in your teaching? Why/ Why not?
4) In your opinion, what kinds of knowledge do students acquire when learning threshold concepts in VERT™?
5) How do your teaching methods promote learning, application, and transfer of threshold concepts in radiation physics?
6) How does learning threshold concepts in VERT affect/not affect students' clinical practice as Radiation therapists?
7) What suggestions/recommendations do you have for improving teaching and learning threshold concepts in radiation physics?
8) Is there anything else you would like to share with the researcher about your teaching and students learning threshold concepts in radiation physics?

APPENDIX 3.3

SEMI-STRUCTURED FOCUS GROUP INTERVIEW

GUIDE (CLINICAL EDUCATORS)

TITLE OF STUDY: Teaching threshold Radiation physics concepts in a virtual clinical environment

DEPARTMENT: Department of Medical Imaging and Therapeutic Sciences, Cape Peninsula University of Technology

RESEARCHER: Lizel Hudson (under supervision of Associate Professor P Engel-Hills and Professor C Winberg)

DATE:

COMMENTS/NOTES:

Guiding questions:

1) What do you consider to be key/building-block concepts in Radiation physics?
2) What is your understanding of threshold concepts in Radiation physics?
3) Are threshold concepts the same for all the different levels/year groups? If not, please specify which concepts are thresholds for what year group.
4) What is the main cause of the difficulties – if any, that students are experiencing when transferring these concepts from the classroom to practice?
5) What is the effect on students' competence of learning Radiation physics concepts in a virtual clinical environment, such as VERT™?
6) What suggestions/recommendations do you have for improving teaching and learning in Radiation physics?
7) Is there anything else you would like to share with the researcher about students transferring and applying Radiation physics concepts in the clinical environment?

APPENDIX 3.4

Cape Peninsula University of Technology

HEALTH AND WELLNESS SCIENCES RESEARCH ETHICS COMMITTEE (HW-REC)
Registration Number NHREC: REC- 230408-014

P.O. Box 1906 • Bellville 7535 South Africa
Symphony Road Bellville 7535
Tel: +27 21 959 6917
Email: sethn@cput.ac.za

6 December 2018
REC Approval Reference No:
CPUT/HW-REC 2017/H40 (renewal)

Dear Ms Lizel Hudson

Re: APPLICATION TO THE HW-REC FOR ETHICS CLEARANCE

Approval was granted by the Health and Wellness Sciences-REC on 30 November 2017 to Ms Hudson for ethical clearance. This approval is for research activities related to student research in the Department of Medical Imaging and Therapeutic Sciences at this Institution.

TITLE: **Teaching threshold radiation physics concepts in a virtual clinical environment**

Supervisor: Prof P Engel-Hills and Prof C Winberg

Comment:

Approval will not extend beyond 7 December 2019. An extension should be applied for 6 weeks before this expiry date should data collection and use/analysis of data, information and/or samples for this study continue beyond this date.

The investigator(s) should understand the ethical conditions under which they are authorized to carry out this study and they should be compliant to these conditions. It is required that the investigator(s) complete an **annual progress report** that should be submitted to the HWS-REC in December of that particular year, for the HWS-REC to be kept informed of the progress and of any problems you may have encountered.

Kind Regards

Dr. Navindhra Naidoo
Chairperson – Research Ethics Committee
Faculty of Health and Wellness Sciences

APPENDICES
3.5 and 3.6

Permission letters from: Radiation Oncology department at Site B and Site A hospitals

Western Cape Government
Health

TYGERBERG HOSPITAL
REFERENCE:
Research Projects
ENQUIRIES: **Dr GG Marinus**
TELEPHONE:**021 938 5752**

Ethics Reference: **CPUT/HW-REC 2017/H40**

TITLE: Teaching threshold radiation physics concepts in a virtual clinical environment.

Dear Ms Lizel Hudson

PERMISSION TO CONDUCT YOUR RESEARCH AT TYGERBERG HOSPITAL.

1. In accordance with the Provincial Research Policy and Tygerberg Hospital Notice No 40/2009, permission is hereby granted for you to conduct the above-mentioned research here at Tygerberg Hospital.
2. Researchers, in accessing Provincial health facilities, are expressing consent to provide the Department with an electronic copy of the final feedback within six months of completion of research. This can be submitted to the Provincial Research Co-Ordinator (Health.Research@westerncape.gov.za).

DR GG MARINUS
MANAGER: MEDICAL SERVICES

CHIEF EXECUTIVE OFFICER

Administration Building, Francie van Zijl Avenue, Parow, 7500
tel: +27 21 938-6267 fax: +27 21 938-4890
Private Bag X3, Tygerberg, 7505
www.capegateway.go.v.za

Ethics Reference: **CPUT/HW-REC 2017/H40**

TITLE: Teaching threshold radiation physics concepts in a virtual clinical environment.

BY ______________________
An authorized representative of Tygerberg Hospital

NAME ______________________

Dr. P Ciapparelli
MBChB (UCT),
MBA (UCT)
MP0244546
Director

TITLE ______________________

GROOTE SCHUUR HOSPITAL
Enquiries: Dr Bernadette Eick
E-mail : Bernadette.Eick@westerncape.gov.za

E-mail: HudsonL@cput.ac.za

Dear Ms. Hudson

RESEARCH PROJECT EXTENSION: Teaching Threshold Radiation Physics Concepts in A Virtual Clinical Environment

Your recent communication to the hospital refers.

The extension of your research is approved in accordance with UCT Ethics clearance, until **7 December 2019.**

As previously mentioned:

a) Your research may not interfere with normal patient care.
b) Hospital staff may not be asked to assist with the research.
c) No hospital consumables and stationary may be used.
d) **No patient folders may be removed from the premises or be inaccessible.**
e) Please provide the research assistant/field worker with a copy of this letter as verification of approval.
f) Confidentiality must be maintained at all times.
g) Once the research is complete, please submit a copy of the publication or report.

I would like to wish you every success with the project.

Yours sincerely

DR BERNADETTE EICK
CHIEF OPERATIONAL OFFICER
Date: 24 December 2018

C.C. Mr L. Naidoo
Dr H. Aziz

G46 Management Suite, Old Main Building,
Observatory 7925

Private Bag X,
Observatory, 7935

Tel: +27 21 404 6288 fax: +27 21 404 6125

www.capegateway.go.v.za

APPENDIX 3.7

Call for voluntary participation

Office A 17
Old Education Building
Bellville Campus
CPUT
7535
September 2017

Dear Colleague/Student

Call for voluntary participation in research project

As a student registered for the qualification Doctor of Radiography (student number: 198093764), I am inviting your assistance with a research project entitled: *Teaching threshold Radiation physics concepts in a virtual clinical environment* once ethical approval is granted. I am supervised by Penelope Engel-Hills and Christine Winberg.

The main purpose of the study will be to explore how threshold concepts (those complex concepts that are underpinned by more than one key concept and that must be accurately understood in theory in order to be applied in practice) in Radiation physics are learned in a computer simulated learning environment, and transferred and applied in clinical practice – ultimately benefitting students in their academic studies and in their clinical practice.

This study has potential benefits for undergraduate BSc: Radiation therapy students as well as students in professional fields that are underpinned by Radiation physics concepts as the research will feed back into the curricular and pedagogical arrangements. Information (data) generated from this study will be disseminated at academic conferences and published in accredited, peer reviewed journals while ensuring the confidentiality of information and anonymity of participants.

On replying to this call, you will receive a consent form detailing the nature of the study and your contribution as research participant will be clarified

Please feel free to contact me should you need more information.

Yours sincerely,

Mrs. Lizel Hudson – Principal investigator
hudsonl@cput.ac.za

APPENDIX 3.8

INFORMED CONSENT

ACADEMIC AND CLINICAL STAFF PARTICIPANTS

TITLE OF STUDY: Teaching threshold Radiation physics concepts in a virtual clinical environment

DEPARTMENT: Department of Medical Imaging and Therapeutic Sciences, Cape Peninsula University of Technology

RESEARCHER: Lizel Hudson (under supervision of Associate Professor P Engel-Hills and Professor C Winberg)

I (please print name and surname)

……………………………………………………………………………………………………….

agree to participate in this study being conducted by the above researcher.

I understand that the main purpose of the study will be to explore how threshold concepts (those complex concepts that are underpinned by more than one key concept and that must be accurately understood in theory in order to be applied in practice) in Radiation physics are learned in a computer simulated learning environment, and transferred and applied in clinical practice – ultimately benefitting students in their academic studies and in their clinical practice.

In signing this consent form I agree to a short interview (30 mins) to identify how key concepts in Radiation physics are structured within the BSc: Radiation therapy curriculum in order to determine how knowledge building occur. This will assist to understand how threshold concepts in Radiation physics are learned, and if sufficient time and resources are provided. I acknowledge that information generated from this study will be presented at academic conferences and published in accredited, peer-reviewed journals and that my personal identity will not be revealed.

Confidentiality

I understand that the information provided by this study will be used to improve teaching and learning as well as for scholarly publication. All individual information will remain confidential and at no time will my personal identity be revealed.

Voluntary participation

The nature and purpose of the study have been explained to me. I understand that participation in this study is voluntary and refusal to participate will involve no penalty or victimization. I may terminate my participation at any time I choose, without penalty. I understand that I may withdraw from participation at any point in the study with no penalty.

Benefits of participation

I understand that by participating in this study, I will make a contribution to understanding key factors for student success in studying Radiation physics and in practice as a Radiation therapist. I am aware that the information gathered will not benefit me directly.

Persons to contact with questions

I understand that the principal investigator in this study is Lizel Hudson and that I may contact her at (hudsonl@cput.ac.za) if I have any additional questions. I may also contact her supervisors, Penelope Engel-Hills (engelhillsp@cput.ac.za) or Chris Winberg (winbergc@cput.ac.za) should I wish to do so.

Consent to participate

I certify that I have read all of the above and received satisfactory answers to any questions that I asked. I willingly give my consent to participate in this research study.

Participant's Name: ____

Participant's Signature: ____

Date: ______________________________

Witness Name: ____

Witness Signature: ____

Date: ______________________________

APPENDIX 3.9

Study code:

Date:

INFORMED CONSENT

STUDENT PARTICIPANTS

TITLE OF STUDY: Teaching threshold Radiation physics concepts in a virtual clinical environment

DEPARTMENT: Department of Medical Imaging and Therapeutic Sciences, Cape Peninsula University of Technology

RESEARCHER: Lizel Hudson (under supervision of Associate Professor P Engel-Hills and Professor C Winberg)

I (please print name and surname)

……………………………………………………………………………………………………..….

agree to participate in this study being conducted by the above researcher.

I understand that the main purpose of the study will be to explore how threshold concepts (those complex concepts that are underpinned by more than one key concept and that must be accurately understood in theory in order to be applied in practice) in Radiation physics are learned in a computer simulated learning environment, and transferred and applied in clinical practice – ultimately benefitting students in their academic studies and in their clinical practice.

In signing this consent form **I agree to participate in an audio recorded, semi-structured focus group interview of approximately 60 minutes**. **I give the researcher permission to study relevant academic assignments and tests that I have completed for Radiation physics. I also agree that classroom activities, clinical tutorials and practical sessions in the Virtual Environment for Radiotherapy Training (VERT^{TM}), may be observed by the researcher and supervisors.** The information will be used to identify how key concepts in Radiation physics are structured within the BSc: Radiation therapy curriculum in order to determine how knowledge building occur. This will assist to understand how threshold concepts in Radiation physics are learned, and if sufficient time and resources are provided. I acknowledge that information generated from this study will be presented at academic conferences and published in accredited, peer-reviewed journals and that my personal identity will not be revealed.

Confidentiality

I understand that the information provided by this study will be used to improve teaching and learning as well as for scholarly publication. I will receive a copy of the transcribed recording, and will also have the opportunity to delete/comment on any sections. All individual information will remain confidential and at no time will my personal identity be revealed. I will not divulge the identity of any person(s) involved in this study to a third party.

Voluntary participation

The nature and purpose of the study have been explained to me. I understand that participation in this study is voluntary and refusal to participate will involve no penalty or victimization. I may terminate my participation at any time I choose, without penalty. I understand that I may withdraw from participation at any point in the study with no penalty.

Benefits of participation

I understand that I will not directly benefit by participating in this study and that my participation will make a contribution to understanding the key factors for student success in studying Radiation physics and in practice as a Radiation therapist.

Persons to contact with questions:

I understand that the principal investigator in this study is Lizel Hudson and that I may contact her at (hudsonl@cput.ac.za) if I have any additional questions. I may also contact her supervisors, Penelope Engel-Hills (engelhillsp@cput.ac.za) or Chris Winberg (winbergc@cput.ac.za) should I wish to do so.

Consent to participate

I certify that I have read all of the above and received satisfactory answers to any questions that I asked. I willingly give my consent to participate in this research study.

Participant's Name: ____

Participant's Signature: ____

Date: ____________________________________

Witness Name: ____

Witness Signature: ____

Date: ____________________________________

APPENDIX 3.10

Subject	Credits	Subject Coordinator
Physical Sciences I **(Codes: PSC100S, PSC101S, PSC102S, PSC103S)** **(Fundamental to all disciplines)**	**20**	**M. Marais**

The Physical Sciences 1 cluster consists of the Physics 1a, Physics 1b, Chemistry 1a modules, and elements of Medical Imaging Oncology (MIO) and Radiographic Technology 1.

Introduction

Physical Sciences 1 for Radiography underpins the physical principles encountered in current and cutting-edge medical imaging, and prepares students for future imaging technologies.
The course aims to develop the necessary:

- Content knowledge,
- Conceptual and cognitive skills,
- Contextual articulation of physics (and chemistry) with radiography, and
- Problem-solving skills applied to real-world, field-of-practice situations.

Course requirements

You will be required to purchase the prescribed textbooks either in hard copy or electronically. The books on the recommended reading list are available in the library. Laptops are available on a rental basis. A scientific calculator is required. Each student is required to acquire a Gmail email address in addition to the CPUT email address.

Objectives

At the end of this course the learner should be able to:

- Articulate a clear conceptual understanding of the physical principles dealt with.
- Apply this to a variety of medical imaging situations, as well as everyday situations.
- Apply explicitly taught problem solving techniques to a variety of imaging problems.
- Interpret the principles and concepts to Imaging Physics.

Mode of delivery:

Teaching methods: Face-to-face lectures, tutorials, group work, audio-visual media, simulations, and discussion groups.

Teaching activities: Electronic media presentations, problem-based learning, Learning Management System tools (Blackboard and Google Drive), practical demonstrations, DVD's, videos, web-based tools (i.e. virtual software), Massive Online Courses (MOOCs).

Learning activities: Learning management system based activities, web-based activities, group work, oral presentations, poster design, technical writing, model building, educational visits.

Modules

Physics

1. Classical Physics I
2. Modern Physics I
3. Physics of Medical imaging I

Chemistry

Chemistry 1a

Assessments

Formative

Structured tutorial sessions form part of the course and provide learners with amongst other, opportunities for formative feedback on tutorials or worksheets.

Continuous & Summative

Assessment Type		Weighted Percentage	Submission Date
Physics 1a, b & Chemistry 1a	**Continuous Assessment**		
Short format	**Based on (online) readings/articles.**	30/75	Continuous assessment – during each two week block
Tutorial tests	**Based on the tutorials, and workshop/tutorial session discussions.**	30/75	Continuous assessment – at the end of each two week block
MOOCs		15/75	Throughout the year – certificates due **27 October 2018**
TOTAL		**75**	
Radiation	**Written test**	**10/25**	**06 June 2018**
Physics of Medical Imaging 1	**Written test**	**15/25**	**22 October 2018**
TOTAL		**25**	
IMPORTANT	**Continuous Assessment does NOT carry any end of Semester/Year Reassessment.**		

Prescribed texts:

Hewitt, P.G. 2006. *Conceptual Physics.* 10th Edition – Pearson International Edition. St Petersburg: Pearson/Addison Wesley.

In addition; free electronic media resources will be made available online.

Contact information

	Name	Building	Email	Telephone no.	Consultation hours
Lecturer	Dr M. Marais	Old Education Blg – D16	physics.cput@gmail.com	(021)9596538	By arrangement
Lecturer	Ms L Hudson	Old Education Blg – A17	hudsonl@cput.ac.za physics.cput@gmail.com	(021)9596538	By arrangement

Class times

Physics 1a, b	Mon, Wed	10.45 am to 1.00 pm	A18, Old Education Blg
Chemistry 1a	Tues	10.45 am to 1.00 pm	A18, Old Education Blg

Online encyclopedias and e-books:

- e-Encyclopedia Science: http://www.science.dke-encyc.com/
- e-Encyclopedia: http://www.dke-encyc.com/
- EncyclopediaBrittanica Academic online edition: http://www.britannica.com/
- Easton, S. (Ed) 2009 *An introduction to radiography.* https://www.dawsonera.com/abstract/9780080982496
- Powsner, RA & Powsner, ER (Eds) 2006. *Essential Nuclear Medicine Physics*. Second Edition http://onlinelibrary.wiley.com/book/10.1002/9780470752890

Useful websites:

Health professions council of South Africa: http://www.hpcsa.co.za
Society of Radiographers of South Africa: http://www.sorsa.org.za
Department of Health (South Africa): http://www.doh.gov.za World
Health Organisation: http://www.who.int
International Commission on Radiological Protection: http://www.icrp.org International
Commission on Radiation Units and Measurement: http://www.icru.org International
Atomic Energy Agency: http://www.iaea.org
International Society of Radiographers and Radiological Technologists: http://www.isrrt.org

Note on General Rules

1. Continuous Assessment does NOT carry any associated end of Semester/Year Reassessment.
2. Short form and Tutorial tests do not have make-up assessments associated with them, but individual students may be considered for make-up assessments to these, STRICTLY under the following conditions:
   2.1 An original medical certificate is presented to their Discipline Coordinator within three days of missing a test;
   2.2 A relevant and original affidavit is presented to their Discipline Coordinator within three days of missing a test.
3. Students behaving disruptively during class will be asked to leave the venue.
4. Disciplinary procedures will be instituted against disruptive students.
5. An ethos of considerate behaviour towards fellow students and instructors, and respect for all, forms part of the core philosophy of the course.
6. General rules of the department, faculty, and university apply.

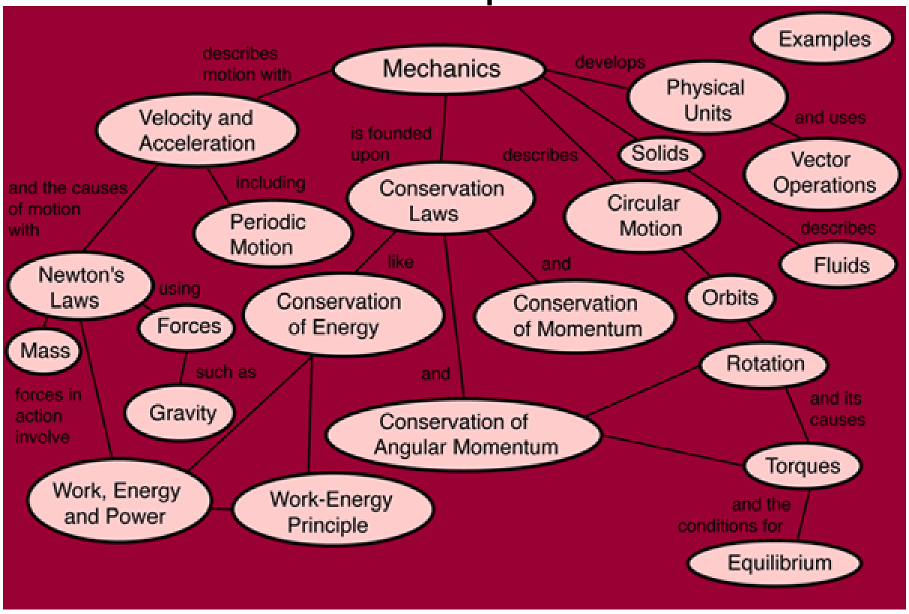
PHYSICS 1A CONTENT

PHYSICS SECTIONS	KEY CONTEXT THEMES
Tools & Skills 1 (done as part of Health Science Literacy)	Key Themes: Dimensional Analysis Basic Maths Vectors
MECHANICS	PHYSICS OF MOTION (in 1D)
Kinematics	Key Themes: Why should we care about motion? (Reading: Motion Mountain: The Adventure of Physics – Vol. 1, Edition 27.30, 1990-2015, Cristoph Schiller. www.motionmountain.net) Linear Motion How to describe motion
	PHYSICS OF FORCES
Dynamics (Forces, Newton's Laws)	Key Themes: Forces cause acceleration Resultant Forces Newton's 3 Laws of Motion Gravity

	PHYSICS OF ENERGY
Energy Work Work-Energy Power	Key Themes: Energy of a System Conservation of Energy
Linear Momentum	Key Theme: Conservation of Momentum

	PHYSICS OF ROTATIONAL MOTION
Rotation & Torque	Key Theme: Conservation of Angular Momentum

Mechanics Map



From: http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html

GEOMETRIC OPTICS	PHYSICS OF LIGHT (1)
Reflection & Refraction	**Key Themes:** Light as a Ray Concept of Reflection Concept of Refraction

ELECTRICITY & MAGNETISM	PHYSICS OF ELECTRICITY & MAGNETISM
Electro--Statics	**Key Themes:** Nature of Electrical Charge Behaviour of Electrical Charge Concept of Electric Fields
Electric Current	**Key Themes:** Flow of Charge Basic Circuits Electricity and the Body
Magnetism	**Key Theme:** Nature of Magnetism
Electromagnetic Induction	**Key Theme:** Concept and Application of Electrical Induction

PHYSICS 1B CONTENT

PHYSICS SECTIONS	KEY CONTEXT THEMES
PROPERTIES OF MATTER	PHYSICS OF MATTER
The Atomic Nature of Matter (done as part of Chemistry)	Key Theme : Atomic Nature
Solids, Liquids, Gases, Plasmas (done as part of Chemistry) (Gases done in specialised module in second year)	Key Themes : Solids Liquids Plasmas
HEAT ENERGY	PHYSICS OF HEAT
Heat & Thermodynamics	Key Theme : Temperature, Heat, and Expansion Heat Transfer Change of Phase Thermodynamics
SOUND	PHYSICS OF SOUND
Vibrations & Waves	Key Themes : Energy transmitted through a wave
Sound	Key Theme : Nature of Sound

LIGHT AS A WAVE	PHYSICS OF LIGHT (2)
Properties of Light	Key Theme : Light as Electromagnetic Waves
Colour	Key Theme : The Colour we see
Light Behaving as a Wave	Key Theme : Light as Wave: Effects
Light Emission	Key Theme : Ways in which Light is emitted

MODERN PHYSICS	
LIGHT AS QUANTA	PHYSICS OF LIGHT (3)
Quantum Nature of Light	Key Theme : Light as Quantised Photons
ATOMIC AND NUCLEAR PHYSICS	PHYSICS OF RADIATION
The Atom and the Quantum	Key Themes: Atoms Quantum Mechanics
The Atomic Nucleus and Radioactivity	Key Themes: Radioactivity Radiation
Clinical Radio-isotope Decay	Key Themes: Clinically useful Radionuclides & Radio isotopes used in Medical Imaging Decays in the Human Body
Nuclear Fission and Fusion	Key Themes: What is Fission & Fusion? Fission & Fusion Reactions

Radiation Protection Physics	**Key Themes: Introduction to Radiation Protection**
INTRODUCTION TO MEDICAL IMAGING	**PHYSICS OF MEDICAL IMAGING**
Convergence of Acquired Physics Knowledge to Imaging Applications	**Key Themes: Overview of main imaging Modalities Image production and appearance**

CHEMISTRY FOR RADIOGRAPGHY

CHEMISTRY 1A
CHEMISTRY SECTIONS
Atoms & Elements
Molecules & Compounds
Chemical Bonding
Chemical Reactions & Quantities

Massive Open Online Course (MOOC)

You will be required to complete three MOOCs for the year.

1. The MOOC Project consists of 4 parts:
   - 1.1. Familiarise yourself with start/end dates, and duration of the MOOC.
   - 1.2 Enrol for the MOOC.
   - 1.3 Participate in, and complete the MOOC.
   - 1.4 Print out your certificate of completion and hand in the hard-copy timeously.

2. Three MOOCs are required for the year, one for each of the following:
   - 1.3 Physics 1a
   - 1.4 Physics 1b
   - 1.5 Chemistry 1a.

3. The final weighting of the MOOCs towards each of the above is:
   - 1.3 Physics 1a : 12.5% towards the second semester mark.
   - 1.4 Physics 1b : 12.5% towards the second semester mark.
   - 1.5 Chemistry 1a: 25% of the overall final mark.

4. The list of MOOCs which you are required to do will be published in the first term. Procedures for submission of the certificate of completion will be published at a later date. The following general rules apply:
   - 4.1 You are expected to work independently on your MOOC.
   - 4.2 Late submissions of your certificate of completion will be penalised at 5% per day.

5. The process towards a successful MOOC Project involves the following steps:
   - 5.1 Consult with your lecturer/discipline coordinator frequently.
   - 5.2 Notify your lecturer/discipline coordinator timeously of any problems encountered.
   - 5.3 Observe timelines.

GOOD-LUCK

May the force be with you!