Engineering Threshold Concepts

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ABSTRACT

Threshold concept theory is one of the most important recent developments in discipline-based Higher Education research. However, relatively little work has been carried out to date on thresholds to learning of engineering students. This is the first comprehensive study to investigate threshold concepts across first and second year engineering courses. The outcomes will help engineering academics develop curricula. The idea of *threshold concepts* was developed by Jan Meyer, Ray Land and others, who realised that there were certain concepts that opened up required systems and ways of thinking and yet were troublesome for students. Potential threshold concepts have been identified using interviews, focus groups and workshops with students, tutors, and academics. This paper reports initial thresholds, in Materials as an example, identified in this growing international study, thereby leading the path towards improved negotiation through these tricky areas of learning. We propose that the method could be used more generally.

Keywords

threshold concepts, engineering education, curriculum

1. INTRODUCTION

Threshold concept theory can be used to focus a curriculum, including teaching, learning, and assessment, on the concepts that are most transformative and troublesome for students.

This paper introduces the project, theory and methodology, and some of the initial potential threshold concepts identified in Materials as an example.

1.1 The Engineering Thresholds Project

At The University of Western Australia (UWA) we have a unique opportunity to work with threshold concept theory as the basis of a complete curriculum renewal. The University is moving to a model of '3+2'. Students in engineering will do a BSc or BDes followed by a specialisation and a Masters in a discipline of engineering. We are designing an Engineering Major, which will form part of the BSc, by first exploring the thresholds that students need to know, are potentially transformative and yet that they find troublesome. We are starting with the first and second year courses that all disciplines of engineering would require.

UWA is leading a collaboration with academics in the United Kingdom. Erik Meyer at Durham University is a consultant. Artemis Stamboulis at Birmingham University, through UKSTEM, and Chris Trevitt and Kathleen Quinlan at Oxford University, are collaborating - applying our techniques and comparing findings.

Our research will identify and investigate thresholds to learning at the first and second year level across all disciplines of engineering. This will help to focus all aspects of the curriculum including the syllabus, teaching, learning and assessment. The approach will be piloted at UWA and a guide for engineering educators will be developed.

1.2 Threshold Concept Theory

The idea of *threshold concepts* was developed in the UK. Jan Meyer, Ray Land, and others realised that there were certain concepts, central to a discipline, that would open up required systems and ways of thinking and practicing, yet were troublesome for many students [15]. Meyer and Land identified several common features of threshold concepts [15, pp. 4-5]. All threshold concepts are *transformative*, meaning that they change the way students understand parts of a subject and possibly even students' identities, and *troublesome* in any manner such as discussed below. They are usually *irreversible*, and *integrative* meaning that they connect concepts in ways students did not previously understand. Many threshold concepts also enhance students' use of language in their discipline.

Perkins [17, pp.8-10] described four types of troublesome knowledge, which have been adopted by Meyer and Land as ways that threshold concepts can be troublesome. *Inert* or abstract knowledge is learnt without context. *Ritual* knowledge is learnt without understanding. *Conceptually difficult knowledge* is confusing because it is not intuitive and is easily confused by common misunderstanding. *Foreign* or *alien* knowledge comes from a perspective that is new to the student. Meyer and Land [15, pp.8-9] added two additional types of troublesome knowledge. *Tacit* knowledge is not explicitly identified, taught or learnt. This was also identified in design engineering by Schön [18]. Knowledge with *troublesome language* uses new language or language that is used with a meaning that is inconsistent with common usage. Baillie and Johnson [1, pp. 137-138] identified an additional form of troublesome knowledge. They recognised indicators of *fear of uncertainty* in students' responses to a unit in which students were asked to think rather than being given knowledge.

1st WORLD ENGINEERING EDUCATION FLASH WEEK LISBON 2011
WEE2011, September 27-30, 2011, Lisbon, Portugal.
Editors: Jorge Bernardino and José Carlos Quadrado.

It has been discovered that, not only can threshold concept theory help in focusing students' and teachers' attention, it can also be a curriculum development tool where there is a strong tendency to overcrowd the curriculum [6, 10, 16].

Threshold concept theory has been widely used in Higher Education. Three seminal books and many papers have been published about threshold concept theory, many providing examples of its use in curriculum enhancement [7, 10-12]. Studies in engineering have considered specific units or disciplines. Scott *et al*. [19], for example, considered introductory electronics. However, this is the first comprehensive study to identify and investigate the threshold concepts experienced by students in first and second year engineering courses.

2. METHODOLOGY FOR IDENTIFYING THRESHOLD CONCEPTS

Research to identify threshold concepts has used a variety of methods. Threshold concepts are defined by their features as experienced by students. It is therefore appropriate to collect data from students or from people whose experiences give them awareness of students' experiences. Interviews are frequently employed because they provide the opportunity to probe deeply and to tailor questions to follow specific experiences of individuals. Various approaches to analysis have been used, with adapted phenomenographic approaches often suitable because these focus on common learning experiences and can therefore help to understand students' levels of understanding or progress towards understanding.

To study threshold concepts experienced by first year engineering students in a professional skills course, Baillie and Johnson [1] analysed student interview transcripts, as one of a variety of data sources, by focusing on indicators of different dimensions of troublesome knowledge, such as ritual, tacit and alien. Taking a different approach to analysis, Kabo and Baillie [9] interviewed students and analysed transcripts using an adapted phenomenographic approach focusing on students' stages of progress towards understanding a threshold concept within a unit on social justice and engineering.

Phenomenographic analysis, content analysis, and other approaches were combined in a large project that investigated threshold concepts in computer science [3]. As part of the project, Zander *et al*. [21] interviewed students , without describing threshold concept theory to the students, by instead asking questions that focused on the features of threshold concepts. They analysed the transcripts by focusing on indicators of the recognised common features of threshold concepts.

Other methods have been employed to identify threshold concepts in engineering. Holloway *et al*. [8] developed a mixed method, including quantitative surveys, in the fields of computer science and vibration. In electronic engineering, Scott *et al*. [19], combined laboratory observations with interviews of students and also suggested that a bimodal distribution among grades could indicate the presence of a threshold concept. Similarly, Carstensen and Bernard [5] observed in laboratories that students struggled to relate Laplace Transforms and the real world.

In our study, semi-structured interviews, focus groups, and workshops were conducted. As in other studies, these methods have allowed us to delve into the insights of the people with experiences that give them understanding of students' understanding. These are students and their teachers. The primary purpose was to identify, and refine identifications, of potential threshold concepts. This required that we also collected perceptions of why participants thought these were threshold concepts, and in some cases, how participants thought we could help students overcome these thresholds.

Our interest is students' experiences of concepts, particularly the concepts they find transformative and troublesome. However, different study participants are able to provide different perspectives and must therefore be asked different questions in order to glean the insight they can offer. Students are able to identify troublesome concepts, and students in their later years are able to identify transformative concepts from their earlier years. Teachers are able to identify concepts in which students have not demonstrated understanding, or have demonstrated misunderstanding, and concepts that academics consider transformative for students because these concepts are critical to later parts of a course or to engineering practice.

At every stage, we report findings to participants. This is an established tool to confirm interpretations of participants' comments in qualitative research [14]. We also expect this to help to gain the trust of participants because it reveals their comments are being used in the manner promised, the value in their participation, and that their contributions are appreciated.

Interviews, focus groups and workshops have been audio recorded with permission of the participants. Occasional participants did not give consent and their comments were not recorded, except as written notes.

All interviews, focus groups, and workshops have been led by the authors who both have qualifications and teaching experience in engineering, and qualifications and experience in engineering education research.

2.1 Method

2.1.1 Interviews

Ten interviews were conducted with individual engineering academics and in one case two engineering academics together. Additionally, an interview was conducted with two postgraduate students who had tutored a first year unit called Introduction to Professional Engineering which relied more heavily on tutorials than did other units. Participants were recommended either by their Heads of School, a member of the Engineering Science Working Party, or a previous participant, as people with experience teaching relevant topics in engineering. Academics teaching the second, third and fourth years of engineering courses in which foundation concepts are required, were particularly valuable. For example, to identify threshold concepts in Materials, academics teaching solid mechanics in the second and third years of civil engineering, a mechanical engineering design unit in third year, and a second year physical electronics unit, provided invaluable insights. Academics are busy and persistence was required to arrange some of the interviews.

Most interview participants were aware of the project before the interview but had not had any experience applying threshold concept theory. They had been sent an introductory paper by Cousin [6] and most had read this before they were interviewed. There had been confusion about threshold concepts within Schools leading up to some of the interviews. Comments during the interviews and afterwards from a Head of School, were that the interviews helped to relieve some concerns that had been brewing.

The duration of each interview was one hour, and in one case 30 minutes. Participants were asked about their experience in a specific unit. The flexible plan was as follows.

1. Interviewer to explain threshold concepts without jargon.
2. Discuss the unit concept briefly.
3. *Can you think of any possible thresholds in this or similar previous units?*
4. For concepts identified, *can you describe the particular transformative way of thinking that students have trouble with? (How do you know? What do students do?)*
5. *Can you identify causes of the thresholds identified?*
6. *Are there ways you have found useful to help students understand each identified concept?*

2.1.2 Focus Groups

Two focus groups were conducted, both with students. In both cases a disciplinary co-facilitator also attended. This was an academic who was familiar to the participants and expert in the discipline of engineering discussed.

Participants in the first focus group were seven chemical engineering students. Chemical engineering students are particularly strong academically among students in the faculty, and hence their perspectives were sought.

The students were recruited through a call for participants sent to the chemical and process engineering students by email. An office bearing student in the Chemical and Process Engineers' Club, kindly contacted members. The students were mainly male students in third and fourth year, with one female student in first year. Lunch was provided.

The focus group was also attended by an academic in chemical engineering, who took the role of disciplinary co-facilitator. With his disciplinary expertise, and knowledge of the course structure, he was able to provide useful probing questions, and also responded to some course-related concerns raised by the students. We believe this made the experience more credible and worthwhile for the students, which is important for continued support for the research from students. This focus group was 45 minutes in duration, fitting into the students' lunch break. The facilitator introduced the project and threshold concept theory and asked students to identify and discuss potential threshold concepts.

Participants in the second focus group were five senior engineering students (two female) who had tutored a first year unit and recently helped grade the examination scripts for the unit. These participants therefore had three sources of experience: their recent experience as students in the course, their hands-on experience as approachable tutors, and the opportunity to check conclusions formed in tutorials when they marked the examination scripts.

This focus group was also attended by a disciplinary co-facilitator, a professor who has lectured and co-ordinated the unit for many years. She was able to ask probing questions using her extensive experience in the unit and explain background related to the unit. The focus group duration was 105 minutes. The focus group questions were similar to those in the interviews with academics.

2.1.3 Workshops

Workshops have included: discussions in meetings of the Foundation Teaching Team – a team of academics planning the engineering units in the first two years of the Engineering Science major; a student workshop held at UWA; a student-staff workshop held at UWA; workshops at Oxford, Birmingham, Lund, and Auckland Universities; and workshops with engineering teachers around Australia.

Members of the Teaching Team spent considerable time developing and refining potential threshold concepts, Team-members were academics in senior positions or with strong interest in teaching and learning. Many of these people had previously attended a workshop on threshold concept theory facilitated at UWA by Erik Meyer and Caroline Baillie. This process was also part of the curriculum development process and is discussed below in section 5. Curriculum Development.

Thirteen students (seven female), from across the engineering disciplines, mostly from senior years, attended the student workshop [13]. Participants were recruited using broadcast emails and the University Engineers' Club executive members supported the research by helping to promote the workshop. The workshop was 90 minutes in duration, with lunch provided. After initial individual time and collection of ideas within groups, participants focused in groups on several threshold concepts, answering the following questions for each.

1. *What is the engineering threshold concept?*
2. *How is the threshold concept transformative? (e.g. What is the change in thinking or perceiving that occurs as a student gains understanding of the threshold concept? Perhaps you can identify levels of understanding that a student undergoes while gaining understanding of the threshold concept.)*
3. *What makes the threshold concept difficult? (e.g. misconceptions, features of the concept and features of opportunities for developing understanding of the concept within the engineering course)*
4. *How could we reduce/remove barriers to help students understand the threshold concept?*

Seven students (four female) and eight academics (three female), from across the Faculty, attended the student-staff workshop following the student workshop. In this workshop students and staff members in small groups discussed potential threshold concepts identified in the student workshops. This workshop was also 90 minutes in duration, with lunch provided.

Potential threshold concepts were also collected in three workshops conducted at Oxford University, two at Birmingham University in England and two workshops at Lund University in Sweden. Workshops in Oxford were attended by postgraduate students, academics and researchers. Workshops in Birmingham and Lund were attended by academics and researchers. At these workshops participants were introduced to threshold concept theory and identified potential threshold concepts and why they considered these to be threshold concepts, using a standard hand-out for all workshops.

Identified threshold concepts are being further investigated in regional workshops around Australia, so far Perth and Adelaide, and in Auckland, New Zealand. Academics who have taught foundation courses work in disciplinary and inter-disciplinary groups, each with a provocateur, to negotiate the identified threshold concepts and investigate their transformative, troublesome and other features, consistent with threshold concept theory. These workshops allow further identification of potential threshold concepts, and importantly allow negotiation among a large number of participants around specific concepts during a relatively short time. Facilitation keeps the conversations focused and probing questions from the facilitators ensure depth. The duration of these workshops is four hours and lunch is provided.

3. ANALYIS

Interviews, focus groups, and workshops were recorded and transcribed with consent from the participants. Three interviewees did not give consent to be recorded. Notes were also taken. Responses written by participants on workshop hand-outs were collected. Analysis of the notes, responses on hand-outs and the transcribed recordings was content based, focusing on references to transformative and troublesome aspects of concepts. The inventory of threshold concepts was iteratively developed, by identifying threshold concepts underlying related concepts that participants reported as transformative and troublesome.

4. FINDINGS

4.1 Identified Potential Threshold Concepts

We now describe the development of threshold concepts within the one area of Materials as an example of the iterative process that we are undertaking across the whole first and second year engineering course.

Potential threshold concepts identified in Materials by the Teaching Team members were as follows.

1. There is a relationship between atomic structure - microstructure – material properties – processes. Engineers can manipulate this relationship in design.
2. All systems, and their parts, tend to equilibrium. Engineers can manipulate this tendency in design.
3. Material properties depend on atomic and microscale characteristics.
4. Material behaviour depends on the interaction between material properties, forcing and boundary conditions
5. Macroscale structural behaviour depends on both the material behaviour and the structural design (dimensions, geometry, etc)

More specific potential threshold concepts listed below were identified in interviews with academics teaching solid mechanics, mechanical design, fluid mechanics, and physical electronics, and the workshops undertaken in the UK.

6. Definition and understanding of stress and strain relationships
   - *The significance of the orientation of the plane for which stress is calculated*
   - *Stress transformation and principle stresses*
   - *Cause and effect*
7. Moment equilibrium
   Used in statically determinate systems
8. Unique solution to a statically indeterminate structure
   To solve an indeterminate structure, three sets of conditions are solved simultaneously: constitutive conditions relating stresses and strains, compatibility conditions relating strains and displacements, and equilibrium conditions relating forces and stresses.
9. Effects of compatibility conditions and boundary conditions
   The displacements/deformation of all parts of a structure must be compatible with each other and boundary conditions. These conditions are required to solve the partial differential equations.
10. Material failure models/theories
    How to analyse the structural integrity of a component under multidirectional loading
11. Properties of fluids
    - *Properties of gases depend not only on temperature but also on pressure.*
    - *Properties for liquids usually depend on temperature only (except at very high pressure).*
    - *Composition of a vapour coming from a liquid*
    - *Temperature of a vapour coming from a liquid*
12. Surfactants
13. Quantum mechanics
14. Semi-conductors
    (This could be beyond foundation level.)
    - *Band Theory*
    - *Particles as waves*
    - *Separated charge implies an electric field and gradient in potential energy*
    - *Populations in semi-conductors*
    - *Fermi-level*
    - *Band diagrams: Understanding probability of occupancies of states and what will happen when equilibrium is disturbed.*

This list and others were negotiated by the participants, mainly engineering, mathematics, and physics academics from three universities, at a workshop at UWA. One of the comments was that items 6 to 13 were mostly specific examples of items 1 to 5, suggesting that it might be possible to reduce the list. It was suggested that moment equilibrium is not a threshold concept because it is not transformative.

4.2 Why We Consider These to be Threshold Concepts

Concepts identified in interviews were discussed in depth. Academics largely drew on mistakes and misconceptions demonstrated by students in quizzes, examination scripts, and assignment solutions, and questions and comments from students. Students spoke about their own experiences as engineering students.

Stress and strain were considered to be essential for all future units in mechanical and civil engineering. They are difficult to visualise and particularly difficult parts were considered to be tangential stress and the significance of the orientation of the plane over which stress is calculated. This also caused difficulty when transforming stresses. The material failure models could be troublesome because students are struggling to transform stresses and strains. One of the students in the student workshop described how stress and strain were transformational for him. He had ‘played’ with pieces of paper, thinking about the stresses and strains. Once he understood them he saw buildings and objects as combinations of stresses and strains.

Some of the concepts are troublesome because students forget to apply parts of them. For example, they forget some of the properties of fluids such as properties of gases depending not only on temperature but also on pressure, and they forget to apply boundary conditions. Perhaps these are examples of concepts that are learnt as ritual knowledge and require application before they are transformative. Some of the properties of fluids are also conceptually difficult.

The concepts required to understand semiconductors are conceptually difficult and those related to understanding quantum mechanics are counter-intuitive or alien. Workshop participants reported that the properties of fluids are sometimes counter-intuitive, identifying supersonic gas flows as an example.

Many of the concepts rely on understanding of concepts from mathematics and physics, for example, probability, vectors, and solutions to differential equations. Without sound understanding of these, the concepts are troublesome for students. The mechanical design lecturer had realised that students retained assumptions from physics learnt at secondary school, without realising that these were for specific cases and could not be generalised. For example, students had learnt to draw forces assuming that beams were “simply supported”. When given a beam attached to a wall, they drew forces from non-existent supports. They must have learnt rituals, without understanding. to solve the problems they were given in secondary school. A concept that has been learnt as a ritual but is not yet applied reliably by students will need to be experienced by students before it is transformational.

4.3 Under Which Circumstances These are Threshold Concepts

Concepts can be troublesome due to features of a student, a subject, or the way a subject is taught. Future investigation will consider the possibility that different student cohorts find different concepts to be transformative and troublesome.

5. CURRICULUM RENEWAL

In this section we introduce the particular approach to combining threshold concept research with curriculum renewal in engineering, developed in our project at UWA. The first stage was performed by the whole Faculty, led by the Foundation Team. This Team was established to develop the four engineering units that, along with complementary science units, will form the first two years of the Engineering Science Major within the Bachelor of Science in 2012. The Team consisted of 19 academics across the Faculty of Engineering, Computing and Mathematics.

Roger Hadgraft and Carl Reidsema consulted to the Faculty to support the initial curriculum development process. Roger Hadgraft guided the Team into identifying three big ideas for the curriculum. The Foundation Team members consulted about these within their Schools between meetings of the Team. This effectively involved approximately 150 academics in the decision. Learning outcomes for each main idea, one of which was Materials, were identified in a similar manner. For each of the three main ideas, potential threshold concepts important to the learning outcomes were then identified by members of the Teaching Team. This was achieved, along with other parts of the curriculum development, during weekly meetings over ten months with preparation between meetings.

Other studies to identify threshold concepts have not necessarily informed participants about threshold concept theory. In contrast, we have had strong incentives to help our participants develop an understanding and trust in the theory during the research. The restructure [20] relies on the sustained good-will of staff and students across the Faculty during a time of great change.

The outcomes of this project are contributing to the design of the new curriculum. This is a completely new design, not based on the previous course, and will involve profoundly new approaches to teaching in the Faculty. The new design for the foundation years of the engineering science major is integrated across traditional engineering disciplines. The new approaches to teaching are more interactive than before, and even the learning spaces are entirely new. Dramatic changes bring the potential for cynicism and yet rely on enthusiasm. It has been critical to have a shared understanding of the theories driving the changes and to gain trust among stakeholders.

Therefore, our approach has been designed with the secondary goal of developing an understanding of threshold concept theory among the project participants. We therefore begin all of our interviews, focus groups and workshops with an outline of threshold concept theory, similar to that provided in the Introduction of this paper. We consider this to be a respectful, direct approach, appreciated by participants.

6. IMPLICATIONS AND FUTURE RESEARCH

The method described in this paper could be adapted by other universities. The features of the method that are designed to help participants develop an understanding of threshold concepts will be relevant at other universities. Even if a faculty is not in a process of dramatic change, universities are environments in which staff members value their autonomy and therefore willingness among academics is crucial to the success of any curriculum development. Better understanding, among academics, of the theory and motives behind the approach is likely to encourage more willing support.

The potential engineering threshold concepts identified in this paper continue to be negotiated. Concepts have been negotiated with engineering academics, so far in Perth and Adelaide, Australia; and Auckland, New Zealand. They will be further negotiated in Melbourne, Australia; Oxford and Birmingham, England; and likely Sweden. We also invite global negotiation, of the identified potential engineering thresholds, among engineering academics on the engineering thresholds web forum (http://www.ecm.uwa.edu.au/engineeringthresholds).

Having identified potential engineering thresholds, curricula can be enhanced to help students overcome these. This part of the research is beyond the scope of this paper and will be discussed in forthcoming publications. Opportunities abound to redesign syllabi, pedagogy, and assessment to focus on threshold concepts. Strategies can be implemented to help students understand threshold concepts. Learning theories support strategies that engage students in deep learning through genuine problems and learning opportunities that provide experience of variation for students [2, 4]. Consistent with these recommendations, Boustedt [3], for example, concluded that application of variation theory, and engaging students in programming and problem solving, would help students to understand threshold concepts required to become a successful software engineer.

UWA academics are introducing initiatives to help students overcome the perceived threshold concepts, now and especially in the new curriculum in 2012. To evaluate these, and further investigate students' experiences of the perceived thresholds, we continue to collect data. Analysis of data collected will help to build our understanding of potential thresholds until a point of consensus is reached.

7. ACKNOWLEDGMENTS

We are grateful to the UWA Engineering Foundation Teaching team, the Engineering Thresholds Project Team, the Project Reference Group, the collaborators in the UK, and the numerous participants at UWA, nationally, and internationally. We thank the UWA University Engineers Club and Chemical and Process Engineers Club for helping recruit participants. Special acknowledgement is made to Daniela Ciancio, Arcady Dyskin, Yuxia Hu, Gia Parish and Adam Wittek, and Teaching Team members who focused on Materials, Tim Sercombe, Carolyn Oldham, Hong Hao, and Jasmine Henry. Project Team and Reference Group members are listed on the Project website: http://www.ecm.uwa.edu.au/engineeringthresholds.

Support for this work has been provided by the Australian Learning and Teaching Council, an initiative of the Australian Government Department of Education, Employment and Workplace Relations. The views expressed in this publication do not necessarily reflect the views of the Australian Learning and Teaching Council.

Support for the national workshops has been provided by the Australian Council of Engineering Deans. Support for the international collaboration has been provided by a University of Western Australia Research Collaboration Award.

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