Exploring engineering thresholds at level 4: what happens in the Oxford tutorial?

Dr. Kathleen M. Quinlan (with Prof. David J. Edwards, Dr. Susannah Speller, Dr. Alex Lubansky, Prof. Caroline Baillie, Dr. Chris Trevitt, Dr. Artemis Stamboulis, Mr. Johnny Fill)

University of Oxford

Abstract

Educational experts partnered with engineering experts to identify thresholds in learning in level 4 engineering and materials classes at Oxford. Threshold concepts is a term used by educationalists to describe particular ideas within disciplines that open up new ways of thinking, allowing students to progress in that discipline. Threshold concepts are transformative for students insofar as they change the way that students perceive the field. Often thresholds are particularly troublesome or tricky for students. 14 tutors and eight students were interviewed to: a) identify perceived thresholds, b) explore why and how proposed thresholds were troublesome, transformative and integrative, and 3) discuss their experience of teaching or learning them. The integrative function of Oxford’s tutorials gave tutors insight into the integrative and transformative dimensions of potential thresholds. They emphasised discipline-specific thinking processes that evolve over time, including connecting maths and the physical world, modelling problems, estimating and approximating and balancing convergent and divergent thinking. Tutors perceived these common thinking processes as underlying student difficulties with a variety of specific disparate topics. Thus, the tutorial serves an integrative role that helps students to make connections across the curriculum and probe their own understandings. Based on students’ experiences of what helps and hinders their learning in the Oxford tutorial system, this case study explored some implications for setting up learning environments anywhere in the sector.

Keywords: Threshold concepts, engineering thresholds, troublesome knowledge, teaching strategies

Background

Research participants included Oxford academics who tutor level 4 university students in either the materials science or engineering science undergraduate degree programmes. Tutors are experienced, full academic staff members who have a long term relationship with a small cohort of between four and six students in their college, often interviewing them for admission and then tutoring them over several years across a wide range of curricular topics. Participants also included students who had recently completed level 4 of their university studies in one of those two programmes.

Students in the programmes typically come to university with three A* science grades at A-level and have been interviewed by a college tutor to determine whether they are likely to succeed in an environment that demands considerable independent study and critical thinking.

In both the materials science and engineering science courses of study, curricula are framed by a lecture series. The curriculum is agreed by the university department and the lecturer establishes the problem sets that all students undertake each week. Laboratories are also organised by the departments. In addition, students have a weekly tutorial with their college tutor in groups of one to four, although pairs are most common. Tutorials provide an opportunity to review problem sets and
clarify students’ understanding. Compared to many undergraduate degrees in these subjects, students spend a considerable amount of their time engaged in independent study, including long (six-week) vacation periods between three short (eight-week) terms.

Students take a significant exam at the end of level 4 which integrates topics covered throughout the year and determines whether or not they can progress in their degree programme. The attrition rate is extremely low in both programmes.

**Rationale**

Locally, our goal was to engage engineering tutors at Oxford in enhancing student learning. Our hope was, in part, to support the construction of a community of practice related to teaching and learning in engineering and materials science. The language of educational research and educational development (i.e. talking about teaching and learning generically or removed from the context of particular disciplines) is often insufficient to capture the interest of scholars whose primary interest is in their discipline. Contextualising discussions of teaching within a department and a discipline are more likely to lead to positive pedagogical developments (Quinlan, 1996). Our hope was to engage teachers in those STEM subjects in what Shulman (1989, p. 10) has called a ‘pedagogy of substance’, one which is ‘rooted in the subject matter itself as well as in a connection with the lives and culture [of the students and teachers]’. Shulman’s work on subject-specific aspects of teaching (Shulman, 1986, 1989, 1993, 2005; Shulman and Quinlan, 1996) has helped spawn the scholarship of teaching movement, first in US higher education, but increasingly in an international arena (e.g. Huber and Morreale, 2002).

Separately in the UK, Meyer and colleagues introduced and developed the idea of *threshold concepts* in the early 2000s (Meyer and Land, 2003a; Land, Cousin, Meyer and Davies, 2005; Land and Meyer, 2010; Land et al., 2010). Thresholds are said to open up required ways of thinking in a discipline, yet are troublesome for students. Students may experience a threshold as troublesome (Perkins, 2006), transformative (fundamentally changing how a student views the field and/or themselves), integrative (connecting previously un-integrated ideas), irreversible (once a student “gets it”, they won’t unlearn it), bounded (referring to a subset of a discipline), involving a passage or journey characterised by liminality (in which students may feel confused, lost or stuck) and leading to the use of a new discourse (Meyer and Land, 2003a, 2003b, 2005, 2006).

Threshold concept theory was chosen to frame the conversation because it has effectively engaged academics in discussions about teaching in their disciplines. Other disciplines, including economics, computer science and biology, have already applied this idea to educational enhancement (J. H. F. Meyer, February 2011, personal communication), although when the project began little was known about engineering students’ thresholds to learning. Thus, the project was also designed to contribute to a better understanding of threshold concepts, how to research them and how to use such research to enhance the teaching and learning of engineering and materials science generally.

To that end, we collaborated with separately funded parallel projects at the University of Western Australia and the University of Birmingham which offered the opportunity to both learn from and contribute to an international project focused on exploring threshold concepts and using them to enhance curriculum development and teaching and learning. Threshold concepts are useful in focusing students' and teachers' attention and prioritising teaching time in overcrowded curricula (Cousin, 2006; Land et al., 2005; Meyer et al., 2006). By comparing and contrasting findings between the individual projects, each with distinctly different teaching contexts, we could learn more about the nature of thresholds (the extent to which they are endemic to a field or specific to particular teaching contexts), as well as refining educational research methods and educational development processes based on threshold concepts which could be applied subsequently to other STEM subjects. Oxford’s small group tutorials offered a unique setting in which to consider the nature of threshold concepts and the teaching and learning approaches that facilitate students’ progress through them. Partners from Birmingham and UWA (separately funded) shared methods and results from parallel studies.
The methodology

We individually interviewed 14 Oxford academics who tutor level 4 students in either the materials science or engineering science undergraduate degree programme (there were seven academics from each discipline). Tutors were invited to participate if they taught level 4 students and were either recommended by project partners in each division (or another interviewee) or had won an award for teaching. In most cases, interviewees were first approached informally by a colleague (a project partner in their department, i.e. Susannah Speller for Materials and Alex Lubansky for Engineering). Potential interviewees were then approached by email by a Learning Institute staff member (Kathleen Quinlan or Chris Trevitt), referring to the colleague (typically a project partner) who had recommended them or to their teaching award. Most academics who were invited gave their consent and participated in an approximately one-hour interview, typically in their own office. Before the interview, tutors were sent a confirmation of the interview time and an information sheet and short introductory note which included the following advice:

> Give some thought in advance to what “threshold concepts” you might like to discuss during the interview. “Threshold concepts” is a term used by educationalists to describe particular ideas within disciplines that open up new ways of thinking and that allow students to progress in that discipline. Threshold concepts are transformative for students insofar as they change the way that students perceive the field. Often thresholds are particularly troublesome or tricky for students. In fact, some academics find it easier to start by thinking about where students get “stuck”.

They were referred to Cousin’s *An introduction to threshold concepts* (2006) for further description. Some read the article beforehand. All had given thought to the idea and were prepared to discuss something they thought was an important threshold at level 4 of engineering or materials degree programmes.

At the interview, following a brief introduction to the key features of thresholds, each tutor was asked to suggest a threshold that students typically experience during their studies at level 4. The interviewers used a semi-structured interview protocol based on the key features of threshold concepts, though the precise wording and sequence of the prompts varied depending upon the flow of the conversation. Thus interviews asked tutors to focus on one or two possible thresholds that are part of the level 4 course, addressing:

1. Outline the concept and where it occurs at level 4? In which other parts of the course is it significant?
2. What makes it transformative for students? (i.e. How do students think or act differently before and after they understand it? Does the threshold expand or change how students use the language of the discipline?)
3. Does the threshold link a number of key ideas together? (Which ones? How? Where do student blocks generally occur?)
4. What makes this concept troublesome for students? (Giving examples and explaining barriers and why it is troublesome for some students and not others)
5. What helps students master this concept?
6. What is (or might be) the role of the tutorial in uncovering or addressing threshold concepts?

Tutor interviews were conducted from May to July 2011. They were digitally recorded and transcribed *verbatim*. Each interview was conducted independently (i.e. we did not tell participants what their colleagues had proposed or seek reactions to colleagues’ suggestions at this stage).

Eight (two engineering; six materials) students were also interviewed, individually or in pairs. The aim was to interview the students of interviewed tutors (who facilitated introductions in ways they thought were most appropriate). This was the case with all but one of the students. However, when this method of recruitment did not yield a sufficient number of volunteers, we advertised focus groups and interviews to all students in the cohort by mass emailing, posters, distributing flyers outside lecture theatres and issuing an invitation to a focus group at a lecture. Students were offered pizza at scheduled focus groups (which were scheduled in the buildings where they attend their lectures and labs and at a time that did not clash with the teaching schedule) and participants’
names were added to a draw for a £10 voucher for a local bookstore. The student interviews followed a similar protocol to the tutor interviews, with similar materials sent out in advance, asking students to identify thresholds and following up on the same features on which tutors were probed. However, more attention was paid in the student interviews to their learning strategies, resources and perceptions of the tutorial process. Interviews were arranged and conducted by a research assistant who was a DPhil student in materials science (Johnny Fill) who was thus both familiar with the content matter discussed and closer to the age and experience of the students. Recruiting students proved to be one of the biggest challenges of the project, even with incentives and repeated requests through a variety of methods and messages.

Although we attempted to recruit student participants in June, level 4 students were preparing for end-of-year exams and we only interviewed one student at that time. Most of the student interviews were conducted early in level 5, asking them to reflect on their learning during level 4. Thus, they had completed their level 4 examinations and all of the study and consolidation of understanding associated with that. No effort was made to distinguish high or low achieving students in the interview pool. Again, interviews were digitally recorded and transcribed verbatim. As the student interviews took place after initial analysis of tutor interviews, we were able to seek students’ input on the thresholds proposed by tutors. This was done only after students had an opportunity to reflect on and propose their own thresholds without prompting.

Tutor and student interviews were analysed by carefully reading each transcript and identifying segments of text (a single word or phrase, sentence or larger block of text) that roughly corresponded to different features of threshold concepts which we coded (e.g. “concepts”, “blocks/barriers” (for troublesomeness), “transformation” and “teaching”) to enable easy comparison of sections of transcripts addressing similar ideas. This enabled the identification of common themes among and across tutors and students. Sub-codes were developed for most of the main codes. This approach can be thought of as a “horizontal” approach to data analysis, in that through the codes we were able to pull out text across any interview that dealt with particular aspects of threshold concepts. This allowed exploration of particular features of threshold concepts (e.g. transformation and evidence of transformation or teaching and learning strategies to address them). Concepts mentioned in the interviews were extracted and described in a short phrase and then, with the help of disciplinary experts, clustered conceptually into a one-page diagram.

However, this “horizontal” approach did not sufficiently capture the integrative nature of the ideas discussed in the interviews. We experimented with concept mapping (Novak, 1990) to better represent the connections between ideas. Concept maps array a set of ideas hierarchically and provide linking words to show the relationships between different nodes on a map. Thus we took key phrases or words from the coded transcripts and visually explored the relationships between them by linking them with arrows and “linking phrases”. This approach can be thought of as a “vertical” one insofar as it digs beneath a simple phrase (e.g. a named, perceived threshold) to better understand where the difficulties lie, how it transforms students or how the concept is related to other concepts (integrative). An example of a concept map can be found in Figure 1. Further examples of this research process can be found in two papers to be presented by members of the team at upcoming conferences (see Further reading/bibliography).

We invited all tutors in the two departments (via standard departmental listservs) to attend a half-day workshop in January 2012 to review and interpret preliminary results. In addition, individual invitations were issued to each tutor interviewed and to tutors in those and closely related STEM subjects (e.g. physics) who had completed Oxford’s Postgraduate Diploma in Learning and Teaching in Higher Education.

Fifteen people attended, including project partners, several tutors who had been interviewed previously, some Oxford tutors who had not been interviewed previously and two engineering academics from other universities who were interested in the project and offered an external perspective.

After an introductory talk given by the project partners, the workshop was divided into two parts. In part one, the thresholds suggested by participants (tutors vs. students) were presented to the workshop participants who were then asked to engage in group discussion about their
interpretations of the findings. Participants in the workshop were organised into two groups based on their discipline: a “materials” group and an “engineering” group. The materials group also contained two physics tutors. Each group worked at a separate table, facilitated by a project partner. Each group then reported their discussions to the other group. In part two, the Principal Investigator presented findings related to teaching and learning threshold concepts, with particular emphasis on what students found most useful. Participants then discussed those findings at their tables with an emphasis on teaching strategies for progressing over thresholds. Part two was followed by a “reporting back” session. Group discussions were also digitally recorded and transcribed verbatim, providing another round of iterative data to verify, clarify and elaborate on the findings.

Lessons learned

We summarise our findings here by each of the main research questions:

1) **What are the perceived thresholds in level 4 engineering and materials at Oxford? How much overlap is there between students and tutors?**

There were more than 40 specific possible threshold concepts mentioned in interviews, including specific ideas within applications of calculus, estimation/approximation and problem-solving, crystallography, thermodynamics and electricity, use of terminology and visualisation. There was reasonable consensus between tutors and students on the topics and concepts mentioned. However, in probing the ideas further in the interviews and in the interpretation workshop, many of the thresholds were traced back to difficulties students had in four tightly connected areas (see Figure 1) which were common to both materials and engineering science:

a) Connecting maths and the physical world. Here the problem was generally not in doing mathematics itself, but rather in “translating abstract ideas into mathematics” or “mathematical representation of the physical world”. This was one of the most commonly mentioned thresholds.

b) Approximation and estimation, also described as “back-of-the-envelope calculation” and an “automatic checking system”, was one of the most commonly mentioned thresholds. Students who understand how maths and the physical world are related will be able to, according to one tutor, ‘appreciate the appropriate approximations which we all have to do to actually produce a new engineering solution. [They will] have the confidence to chuck away those terms [in the] approximation process […] the larger skill is translating physical problems in a meaningful way into a mathematical representation.’

c) Modelling a problem. Many of the tutors (and several of the students – see responses to question 2 below) say that students need to learn the ‘set up of the problem […] we call that modelling - actually modelling a problem […] And one thing we hope is, by doing courses together, they will see those links. They’re quite bad at that actually - the links between, say, electricity and fluids, electricity and mechanics […] they’re not very good at that, again, because they compartmentalise by examples.’

d) Convergent vs. divergent problem solving. Students come into university accustomed to questions that converge on a single right answer. In engineering, real world problems are open-ended; choices need to be made about how the problem will be modelled and the goal is a “good” answer that meets the needs of the situation at hand. Creativity in modelling a problem is valued as a feature of engineering design, therefore students must become more comfortable with uncertainty.
2) **Why and how are proposed thresholds troublesome, transformative, integrative?**

Tutors’ interviews provided information mainly about how the processes in a - d above were transformative and integrative. The thresholds are integrative insofar as they underlie all of “thinking like an engineer”. Many of the technically difficult ideas mentioned in the interviews were offered as examples: for instance, one tutor gave numerous examples of situations in which modelling problems is required, including Kirchoff’s laws, Newton’s laws of motion, Thevenin’s theorem, Ohm’s law and phasors. It is the thinking process of reducing complex systems that provides links between these disparate technical areas and between different topic areas, including electricity, fluids and mechanics. Thus, the elements highlighted above are highly integrative. They also seem to be transformative to students. Student interviews both confirmed and elaborated tutors’ perceptions as they pertained to troublesomeness. Students tended to refer to the specific topic areas although, by level 5, several of them were also able to reflect on the general processes that are common to many of the topics.

Students, however, reported more specific blocks/barriers to their understanding of thresholds, which can help identify teaching practices that may help teachers achieve their high level goals:

a) Not explaining why answers were correct or incorrect or skipping steps in a worked solution

b) Getting lost in a lecture

c) Abstractions/over-reliance on visualisation (e.g. tensors)

d) Changing notation (e.g. complex numbers in electrical circuits)

e) Understanding the physics of a situation

f) Sequencing (e.g. thermodynamics being taught before partial differentiation)

g) “Pattern-matching” approach to learning

h) Separating analogies from reality

i) Difficulty understanding textbooks.

Their comments indicated that lectures can be problematic because the lecturer may not pace their explanations in a way that students can benefit from them. Instead, some of the students reported the value of the lecture notes themselves, which were comprehensive, tailored to what is expected at Oxford and useful as stand-alone study resources. Textbook
explanations may be inadequate to address the challenging underlying concepts with which students struggle.

3) **What teaching methods and learning strategies support students in passing over these thresholds? What is the role of the tutorial in the learning process?**

Ten key themes emerged in students’ reports of what was helpful to them in passing through thresholds:

a) Working in groups with peers  
b) Being able to visualise a process  
c) Suspending disbelief/accepting assumptions/trusting the maths  
d) Going through worked solutions  
e) Revision/reducing a topic to its “essentials”/integrating across subjects  
f) Focusing on approaching/setting up the problem  
g) Helpful structure of the curriculum  
h) Independent reading of notes and texts  
i) Multiple ways of explaining or representing an idea  
j) Tutorials.

Tutorials were reported to be helpful because they i) offer deeper conceptual explanations that respond to students’ concerns and problems, ii) make connections between topics studied at different points during the course, iii) encourage or teach other ways of learning (e.g. drawing or using other tools), iv) compare methods of approaching a problem, v) test students’ understanding and provide targeted feedback, vi) offer students opportunities to explain how they solved a problem and how they understand things, which clarifies and consolidates their understanding, vii) push students to explain why something works as it does, and viii) allow students to hear different explanations of the same concepts. The students’ experiences of tutorials suggest that the emphasis in those dialogues is on ensuring that students have a deep understanding of the concepts underlying the problem sets and the tools to apply those understandings to problems.

By early in level 5, students are aware of the same key issue raised by the tutors: the underlying difficulty in understanding the physics of the situation (and connecting that to the maths) and the need to change from a “pattern-matching” approach to learning’, as one student and some tutors put it, to focusing on learning how to set up and approach problems (“model” problems) in more sophisticated ways.

**Evaluation**

By working with both the University of Birmingham HE STEM project team (Artemis Stamboulis) and the University of Western Australia curriculum development team (Caroline Baillie), we were able to compare research methods and findings throughout the study. These team members served as “critical friends” to the Oxford process, providing peer evaluation and prompts to self-evaluation. In addition to regular meetings and phone conferences across the three sites, we undertook an exercise in which a small core set of transcripts (from Oxford and UWA interviews) that addressed a particular topic (Mohr’s Circle) were analysed by each of the three teams using their own analysis methods. This activity enabled not only a critical discussion of the content related to the particular topic, but also a grounded discussion of differences in analytic approach. Thus, through this exercise, we could probe the methods (including the pros and cons of each) that each team was using.

In terms of local engagement, participants at the January workshop completed feedback forms. All participants either agreed or strongly agreed that the workshop: a) met its goals, b) was useful, c) gave them an expanded understanding of or a new perspective on the topic, and d) that the findings were useful/relevant to their own teaching. In open-ended comments, most participants found either the opportunity for discussion with colleagues or the notion of threshold concepts itself to be the most useful aspect of the workshop. The workshop was useful to the research team in
clarifying that the participants recognised the broader thresholds (as described in the findings above) as being more “fundamental”. Several participants expressed reservations about the cluster diagrams with some 40 different discrete topics.

Finally, conference papers have been accepted through a peer review process for three conferences in the overlapping domains addressed by this research (one on materials education, one on engineering education and one on threshold concepts). These will be presented between April and July 2012. The success of these proposals in a peer review process is an indication of the quality of the work and its perceived utility to each of these fields. The larger project (with UWA and the University of Birmingham) has attracted interest from a number of other universities that have expressed interest in future collaborations to extend the project.

**Discussion, summary**

The research illuminated the key connections between a variety of difficult topics in engineering. It emphasises the thinking processes that students must master on the way to becoming engineers: connecting maths and the physical world, modelling problems, estimating and approximating and balancing convergent and divergent thinking. These generic engineering thinking processes are encountered and illustrated in a variety of topic areas that students may experience as troublesome, but it is often this deeper conceptual understanding itself that causes students’ difficulties. These connections can best be spotted and taught by tutors (experienced academics) who are involved across a wide range of the curriculum. Thus, the tutorial serves a unique integrative role that helps students to probe their own understandings deeply and make connections across the curriculum. While weekly tutorials of such small groups are not feasible for most of the higher education sector, students’ experiences of what helps and hinders their learning have significant implications for how to set up learning environments anywhere in the sector. For instance, students might be formed into small, self-regulated peer groups in which they must explain their thinking to other students. They might be taught how to ask each other probing “why” questions. Once this group work has taken place, students might be able to take unanswered questions to an expert question/answer session. Finally, assessment exercises might focus on seeking integration across disparate topics in an otherwise modular curriculum.

**Further development**

At Oxford, the results will be used to inform educational development sessions related to tutorial teaching. In 2013, we anticipate launching a new Teaching Fellowship Preparation Programme in the Sciences (3.5 days of seminars, some written assignments, culminating in Fellowship of the Higher Education Academy, in line with Descriptor 2 of the UK Professional Standards Framework). We will prepare materials from this project for use in that new course. Discussions about further dissemination within Oxford and in other conferences and journals are ongoing with the project partners.

**References**


Further reading / bibliography


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