Some potential underlying threshold concepts in engineering dynamics

Dianne C Hesterman
The University of Western Australia, Perth, Australia
dianne.hesterman@uwa.edu.au

Sally A Male
The University of Western Australia, Perth, Australia
sally.male@uwa.edu.au

Caroline A Baillie
The University of Western Australia, Perth, Australia
caroline.baillie@uwa.edu.au

Abstract: *Engineering academics have a responsibility to continuously improve the educational experience of their students. One approach is to identify the critical thresholds that students need to pass through. As part of an international project, we are using threshold concept theory to improve engineering education. Threshold concepts are transformative in nature and open up pathways to future knowing, but they are potentially troublesome for students to master. By first identifying and investigating the first and second year engineering threshold concepts, we are designing our curriculum to optimise the transformative experiences that will help our students become engineers. This is the first global study of first and second year thresholds across all engineering disciplines. In this paper we discuss the process we have developed to identify threshold concepts using some examples. The process involved a Divergent Phase in which many potential threshold concepts were identified and an Integrating Phase in which underlying threshold concepts were identified. Underlying potential threshold concepts discussed are: conservation principle, vectors and vector calculus, system identification and definition, and temporal and spatial frames of reference. These are required for dynamics and also more generally in engineering. The findings support the significance of spatial visualisation and modelling. The inventory of threshold concepts continues to evolve as the concepts are negotiated across disciplines and universities.*

Introduction

Engineering educators have a responsibility to continuously improve the educational experience of their students. Godfrey and King (2011, pp. 64-66) recognised "killer" engineering subjects that act like gateways to students. Threshold concept theory recognises that many courses have concepts that are transformative for students, in that they open up new ways of thinking and understanding, and often troublesome for students (Meyer & Land, 2003). The theory therefore provides a framework to identify and investigate concepts that are the barriers within "killer" subjects. We can thereby develop curricula that focus on transformative and troublesome concepts and enhance the learning experience of engineering students, improving their understanding and possibly student retention.

At the University of Western Australia we are undertaking the first ever identification and investigation of threshold concepts across the first and second years of all engineering disciplines (Male & Baillie, 2011a). We are using the outcomes to help develop a new engineering course and a guide on engineering curriculum development. The term "curriculum' is used here to include the whole learning experience of students, including teaching, learning, assessment, learning spaces, faculty and university cultures, and off-campus learning experiences.

In this paper we discuss the development of some underlying threshold concepts which have arisen in our study. The paper begins with an introduction to the theory, methodology, and analysis, and the two main phases of the concept identification process: the Diverging Phase and the Integrating Phase. We then present four examples to demonstrate the process.

Theoretical Framework, Methodology, and Analysis

Threshold concept theory has been found to be useful for curriculum development (Cousin, 2010). The theory describes features of threshold concepts (Meyer & Land, 2003). They are transformative because they open up new ways of thinking and understanding required for students to progress in a course. They are also usually troublesome. For example, they can be *inert*, *ritualistic*, *conceptually difficult*, or *alien* (Perkins, 1999, pp.8-10), *tacit* or *using troublesome language* (Meyer & Land, 2003, pp.8-9), or troublesome due to *fear of uncertainty* (Baillie & Johnson, 2008, pp. 137-138). Threshold concept theory also describes other common features. For example, many threshold concepts are irreversible - understanding is not reversed, and integrative - connecting other concepts.

We have established a methodology to identify and investigate threshold concepts by focusing on their transformative and troublesome characteristics (Male & Baillie, 2011b). It uses threshold capability theory (Baillie, Bowden, & Meyer, forthcoming) which combines threshold concept theory with capability theory, a theory which recommends students develop knowledge capabilities for unknown futures (Bowden, 2004). This has broadened the focus from threshold concepts that are strictly concepts, to threshold capabilities which might be tools rather than concepts. As the other common characteristics of threshold concepts are common but not compulsory, we did not use these as criteria for identification of potential thresholds concepts.

Based on the theoretical framework, threshold concepts were identified and investigated through interviews, focus groups and workshops, focusing on troublesome and transformative concepts and capabilities as experienced by students. Students, academics, and tutors were identified as groups of participants with awareness of students' experiences. Twelve engineering academics were interviewed. Two postgraduate students who had tutored a first year unit were interviewed. Focus groups were held with seven chemical engineering students, and with five senior undergraduate students who had tutored first year dynamics. Workshops included: discussions in meetings of the Foundation Teaching Team – a team of 19 academics planning the new first and second year engineering units; a student workshop with 13 students and a student-staff workshop with seven students and eight academics at our university; workshops in the UK at Oxford and Birmingham Universities, in Sweden at Lund University, and in New Zealand at Auckland University; and workshops in Perth, Adelaide and Melbourne, Australia with engineering teachers from multiple universities. Details about the protocols and questions are presented separately (Male & Baillie, 2011a, 2011b). Academics and tutors are aware of students' experiences through observations, students' questions, and assessments. The interviews, focus groups and workshops collected data from a diverse sample of participants spanning a range of perspectives and hence provided an insight into the range of students' experiences.

The interviews and focus groups in individual disciplines formed a Diverging Phase in which many specific and some higher level potential threshold concepts were identified. The later workshops formed an Integrating Phase in which participants from multiple disciplines and universities negotiated potential threshold concepts.

In the Diverging Phase participants' comments were analysed for examples of concepts being transformative and troublesome. During the process an inventory of potential threshold concepts was developed iteratively, with participants having the opportunity to comment on relevant concepts identified in earlier stages. Many of the potential threshold concepts identified by participants in the Diverging Phase were highly specific troublesome aspects experienced by students, for example, the difference between acceleration and rate of change of speed in curvilinear motion.

Examples of potential threshold concepts identified in the Diverging Phase were grouped under underlying potential threshold concepts in the Integrating Phase in order to refine and structure the inventory. This was achieved by workshop participants and by the researchers.

Underlying threshold concepts were identified and refined in the workshops, through broad and robust discussion among diverse participants. For example, Vectors, which is discussed later, was identified in a workshop as a threshold underlying many others. Participants realised that vectors are one of the foundation tools used in the analysis of force and motion. Until students understand vector math and can interpret the results of this math in a physical context, many motion concepts and analysis techniques remain obscured or out of reach. Troublesome aspects relate to modelling real world behaviour using a mathematical construct and transitioning between the two. Some specific examples of troublesome aspects are:

1. Representing (replacing) an arrow in space with a mathematical symbol, e.g. $\boldsymbol{R}$ or $\underline{R}$ or $\vec{R}$, and then manipulating this symbol to determine changes in the arrow's length and direction
2. Why does the Right Hand Rule work when analysing the real world?
3. Representing angular motion as a vector using the axis of rotation
4. Physical interpretation of dot and cross products, e.g. what does $\vec{v} = \vec{\omega} \otimes \vec{r}$ actually mean?
5. Differentiation of vectors (changes in the properties of a vector with time), e.g. why does a particle moving in a circle at constant speed (scalar) have a non-constant velocity (vector)?

Similarly, the researchers analysed participants' comments to identify related thresholds described by different participants in different contexts. They identified parallel concepts and confirmed these as the same as concepts noted by participants in their different contexts. For example, dynamics tutors noticed that students frequently drew friction in the wrong direction in free body diagrams. This was raised in the interview with a statics lecturer. He noted that friction is troublesome because students fail to identify the isolated body. This was identified as System identification. Similarly, a hydraulics lecturer identified defining the control volumes and an electrical engineering lecturer identified equivalent circuits. The example, System identification, was also highlighted by workshop participants as underlying several previously identified more specific potential threshold concepts.

Inventory items continue to be regarded as *potential* threshold concepts requiring confirmation through negotiation. We invite further negotiation of these during and after the conference.

Findings and Discussion

Four examples of underlying potential threshold concepts for particle and rigid body dynamics are proposed and discussed below. Troublesome aspects of these potential thresholds were identified in individual and group discussions during the Diverging Phase. These aspects were then grouped under common or recurring themes by participants in the Integrating Phase, supported by analysis of responses from the Diverging Phase, and used to identify the underlying potential threshold concepts in the Integrating Phase. Identified types of troublesome knowledge are noted in italics.

System identification and definition

An important step in any engineering analysis is the development of a suitable mathematical model of the physical system of interest. The process involves identifying the physical system to be modelled and then defining it in sufficient detail that the model represents the important attributes and behaviours of the real system. Troublesome aspects identified with this process included defining the system and replacing everything else, e.g. constructing free body diagrams (*conceptually difficult)*; recognising different types of force and moment interactions and their effect on system behaviour (*conceptually difficult)*; understanding action and reaction which can be counter-intuitive; interpreting common terminology such as "load", "stable", and "reaction" (*troublesome language)*; making reasonable assumptions about system behaviour, which becomes *tacit* with experience; and realising that many systems change in time and space, i.e. a free body diagram may only be valid for a particular position or instant in time (*conceptually difficult)*.

It is possible that educational experiences reinforce barriers to students' understanding. It was noted by some academics that certain misunderstandings begin at school and that it is important to encourage students to question the limitations of generalisations used in high school physics (*ritualistic)*. It was also observed that we often give the students a representative model rather than the physical system to analyse, hence presenting the knowledge as *inert* and neglecting required *tacit* knowledge. For example, we provide sketches or diagrams of a system and all the necessary information to solve a particular problem. In doing this, we inadvertently remove important and necessary steps in the modelling process that our students need to master.

Temporal and spatial frames of reference

Frames of reference and coordinate systems are mathematical constructs used to measure and monitor the motion of objects in time and space. Troublesome aspects identified with using these included understanding that absolute motion is independent of the coordinate system used to measure it; understanding the difference between absolute and relative motion; analysing motion in a rotating reference frame; and understanding that an object's velocity and acceleration can change with position and time.

We note that these are *conceptually difficult*, requiring spatial visualisation skills, which are known to develop with practice, and that these concepts depend on specific potential mathematical threshold concepts, that are frequently taught without context and hence as *inert* knowledge.

Vectors and vector calculus

In particle and rigid body dynamics, vectors are used to describe the magnitude and direction of quantities such as force, position, velocity, and acceleration. Troublesome aspects identified with regards to vectors and their use included understanding the difference between scalar and vector quantities, e.g. speed is not the same as velocity, rate of change of speed is not the same as acceleration (*conceptually difficult*); representing angular motion as a vector using the axis of rotation *(alien)*, understanding the physical interpretation of dot and cross products (*alien*); understanding the difference between velocity and acceleration, e.g. velocity is always tangential to the path and denotes the direction of motion, acceleration is the result of an unbalanced force and affects the velocity vector (*conceptually difficult*); and understanding that a vector with constant magnitude can have a non-zero derivative, e.g. rotating unit vectors or the acceleration of a particle moving in a circle at constant speed (*alien*).

Regarding reinforced barriers to students' learning, vectors represent an elegant means to include magnitude and direction in a single expression, but many students struggle with their application in engineering dynamics. This may be in part due to the various ways in which academics represent vectors. A vector quantity may be represented as an arrow in space, a mathematical symbol denoted with an underscore or overscore or some other mark, or in component form (*troublesome language, alien*). Academics often move back and forwards between these representations when solving a problem. There is also a link missing between the *inert* mathematics and the physical behaviour for some students. This again raises the issue of modelling physical systems and translating between construct and real world, which was identified as a troublesome aspect of system identification and definition.

Conservation principle

The conservation laws (or accounting principles (Cornwell & Fine, 2000)) state that nothing is lost. Students often find it difficult to apply these laws because they are unsure how to account for the particular property being conserved, e.g. energy can have many forms. Another troublesome aspect identified was that Newton's 1st Law seems counter-intuitive: the Law states that a body keeps moving at constant velocity unless a force is applied, yet we never observe this in our everyday experience. There is always energy loss in real systems, but academics often design simplified problems that include the words "ignoring friction" or "assuming no energy loss". This shifts the problem from real world observation to something artificial that students cannot easily check or confirm from their experience.

Regarding reinforced barriers, as one participant at the Perth workshop noted "This principle has many applications across engineering and can be very useful in modelling real world complex systems".

However, if educators do not apply it to real world problems and use oversimplified examples, then the concept seems *alien* because it is inconsistent with students' experiences of the physical world.

Discussion

Vectors, system identification and definition, and temporal and spatial frames of reference are tools that open up new ways of representing, understanding and analysing. However they are frequently overlooked as *tacit* knowledge used to solve problems without sufficient development. They are also frequently taught as abstract or *inert* knowledge in mathematics.

We have found that there are multiple levels of inter-related threshold concepts. Vectors, system identification and definition, and temporal and spatial frames of reference could be part of an overarching potential threshold concept: modelling. This concept is required to identify and represent critical features of a system in order to analyse it and predict future performance based on past experience. Understanding the relationships between physical systems and models was a recurring theme among the potential threshold concepts.

Conversely, we expect that vectors, system identification and definition, and frames of reference all require spatial visualisation skills, which could be a more specific threshold along with other mathematical thresholds required for the potential threshold concepts identified in this study.

Conclusions and Future Work

Using interviews, focus groups, and workshops, with students, tutors, and academics, we have identified potential threshold concepts. This paper demonstrates the evolution of one set of the potential threshold concepts related to dynamics of participles and rigid body systems: Conservation principle, vectors and vector calculus, system identification and definition, and temporal and spatial frames of reference. These threshold concepts also apply to other topics and disciplines of engineering.

Thoughts on teaching using thresholds

This paper has focussed on the approach to defining and managing threshold concepts information which may be used to design curricula, using specific examples related to dynamics. It is also possible to develop pedagogies, which support students in learning these concepts. This area will not be discussed further here but a few thoughts are worth considering.

It has been noted by lecturers who have found these concepts troublesome to teach that increased use of videos, simulations and practical experiences could help students understand vectors, system definition, and temporal and spatial reference frames. Additionally spatial visualisation skills have been found to correlate with success in engineering courses (Sorby & Baartmans, 2000). The threshold nature of these tools could help to explain the benefits to engineering students of helping them develop spatial visualisation skills.

The findings indicate modelling as an overarching threshold concept. We recommend that engineering educators clarify the relationships between models and physical systems. Similarly, one way to help students with otherwise *inert* concepts is to teach within contexts. As recognised by student participants in our workshops, and by others, students appreciate examples demonstrating the application of otherwise abstract concepts when they are introduced (Wandel, 2010).

All four of the potential underlying threshold concepts proposed in this paper, and spatial visualisation and modelling will be better understood by students with increased practical and laboratory learning experiences, and problem based learning using drawings and physical and analytical models.

Reflections on process

Participants' responses complemented each other in the various modes of data collection. Students and tutors raised specific difficulties experienced by students. Academics raised some of these and also potential threshold concepts from which the specific difficulties could arise. Inconsistent with Carstensen and Bernhard's (2008, p. 150) experience of teachers: "they perceive a whole conglomerate of disparate concepts to be troublesome, instead of seeing a single integrated concept as the threshold concept", we found that academics recognised underlying thresholds among concepts.

The Integrating Phase of interdisciplinary discussions was particularly effective. The workshop in Perth, where Vectors was identified, was an example.

Future work

We are concurrently developing a research and curriculum design process, with emerging curriculum content focussed on thresholds. Our methods are being adopted and trialled by collaborators at Oxford and Birmingham Universities in the UK. The thresholds inventory will be refined based on further research and analysis.

Using the threshold concepts approach we have identified transformative and troublesome concepts that have formerly appeared in courses without sufficient attention and clarification. Curricula will now be explicitly developed for students to focus on these critical and transformative concepts.

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