Troublesome knowledge in engineering design courses

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Abstract

Design is a central activity in engineering, and project-based design courses are increasingly common in engineering programs. Their open-ended nature presents challenges in evaluating and assessing their effectiveness. Identifying the troublesome knowledge encountered in these courses could provide a means of understanding and improving student learning. This paper describes an exploratory study aimed at finding troublesome knowledge in project-based mechanical engineering design courses. An ethnographic approach was used to determine the troublesome knowledge encountered by students in two design courses, one with a focus on universal design and the other on medical device design. Five categories of troublesome knowledge were identified: engineering science, project management, tacit skills, domain knowledge and tools and equipment. The results will be used to redesign course elements, and to inform further investigation of threshold concepts in engineering design.

Introduction

This paper describes an exploratory study aimed at identifying troublesome knowledge in project-based engineering design courses. Such courses are becoming increasingly common in response to a large body of engineering education research which has demonstrated the shortcomings of the traditional, lecture-based education model (Crawley *et al.* 2007, Spinks *et al.* 2006).

Design involves open-ended, unstructured problem solving, and is the central element of engineering. It is an integrative activity, in which students must select from a mixed toolset of techniques and theories, by evaluating and synthesizing what they have learnt in a range of courses covering fundamental science and mathematics, applied science topics and project management. Ideally students are working at the upper end of Bloom's Taxonomy – analysing, synthesizing and evaluating their learning (Bloom *et al.* 1956). In terms of threshold concepts, this could represent a move from liminality to understanding.

However, the open-ended, integrative nature of design courses also presents some difficulties in understanding and evaluating the learning taking place. Much of the knowledge that students are interacting with and applying cannot be identified from the course lectures or syllabus, and most of the learning activity takes place outside of class time. Due to the open-ended nature of the projects undertaken, each student may follow a completely different path and require different conceptual tools and skills. While students *may* be integrating a range of fundamental concepts, it is also possible that the majority of their time is spent acquiring facts specific to the problem being solved or learning how to use required virtual and physical tools. This type of activity is the equivalent of rote learning in traditional lecture-based courses, in that it results in very little meaningful, transferrable knowledge being acquired. As such, educators in this area require tools to identify the learning taking place, so that they can assess student learning and improve their courses. Dym *et al.* (2005) propose a set of open research questions in the area of engineering design education which include questions on how best to evaluate learning in design courses.

The theory of threshold concepts (Meyer and Land 2003) may provide a useful framework for investigating learning in open-ended, project-based courses. Focusing on core concepts that are troublesome, transformative, etc. would allow educators to look beyond the range of activities undertaken by students and assess the underlying pedagogical

content of their courses. Much work has been done on developing methods for identifying threshold concepts. Quantitative approaches include using Likert-scale questions (Holloway *et al.* 2010) and multiple-choice questions (Gray and Yavash 2007) to determine the more troublesome and transformative concepts in a subject area. Qualitative approaches include curriculum mapping (Quinnell and Thompson 2010), concept maps (Hay 2007), focus groups (Galligan *et al.* 2010), think-alouds (Miller-Young 2010) and analysis of students coursework (LeBard and Quinnell 2008). These techniques seem useful in situations where a list of candidate concepts or a well-bounded curriculum is available. In engineering design courses however, as explained above, this is often not the case. In this study, therefore, an exploratory approach was taken to identify candidate threshold concepts by focusing on the troublesome knowledge encountered by students.

Methods

A mixed-methods research design was used in the collection, analysis and interpretation of data. Engineering design courses at Harvard University and Trinity College Dublin (TCD) were selected as the sites for the study. The main research was carried out in a medical device design course in Harvard. The class of 16 was made up of a mixture of undergraduate and postgraduate students. During the course, four teams of students worked with surgeons to identify a medical need, design a solution to it and have a prototype manufactured by an outside vendor. The TCD course in mechanical engineering design was taken by 81 third-year undergraduate students, who worked with elderly people to develop universally designed solutions to common needs. The TCD course was used to expand the results from the Harvard research.

Ethnographic methods were used to study the students and teaching staff throughout the 15-week medical device design course. The difficulties they faced, as well as the skills and knowledge they used to overcome these difficulties, were studied. Data was gathered through participant observation and unstructured informal interviews by a teaching assistant, supplemented by online questionnaires completed by the students and reflection sheets completed by other members of the teaching staff. The observations and interviews were conducted during the weekly meetings that teaching staff held with each team, the weekly laboratory sessions, and the student team meetings outside of class time. The observations and informal interviews were detailed in handwritten fieldwork notes, which were later transcribed on a computer.[1] Students in the universal design course completed the same open-ended online questionnaires.

The resulting dataset consisted of dozens of text files composed of units, short paragraphs describing individual events or statements. In the first round of analysis, those units which described students' difficulties or misunderstandings were identified and comments describing the relevant concepts and skills were made. These comments were then clustered around similar themes, which were used to create basic codes. This process of clustering and coding continued until higher-level codes emerged. These higher-level codes describe the broad types of concepts and skills that were troublesome for students. Table 1 shows an example of a text unit and the associated comments and codes.

Results & Discussion

The analysis resulted in a list of skills and concepts that proved troublesome for students on the course, organised under the five broad categories described in Table 2. This section contains examples of the difficulties faced by the students for each category.

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[1] Approval for this work was granted by the Harvard Committee on the Use of Human Subjects in Research

Table 1 Analysis of a unit of text

Text unit	Comments	Basic codes	Higher-level codes
	Interpreting the results of analysis		
Students have calculated the power requirements of the motor from the force measured on the Instron multiplied by the displacement. Lecturer thinks the value sounds way too small. After looking up motor specs in a catalog, they calculate that the gear reduction required would be >10,000:1 (impractical)	Using manufacturer specs to guide design	Modelling & Analysis	
	Difference between idealized models and real systems	Mechanics	Engineering Science
		Testing	
	Motor selection		Project Management
	Gear ratios	Actuation & Control	
	Power calculations	Working with Vendors	
	Relationship between force and torque		

Table 2 Description of categories

Skill/concept categories	Description
Engineering science	Modelling, analysis, testing, evaluation
Project management	Planning, budgeting, communicating
Tacit skills and knowledge	Interpersonal skills, creativity, decision making
Domain-specific knowledge	Knowledge related to the specific problem which the students are attempting to solve, e.g. a surgical procedure
Tools and equipment	The knowledge and skills required to operate machines, use software applications and select off-the-shelf parts

Engineering science

Fundamental engineering activities such as modelling, analysis and testing proved troublesome for many students throughout the course. Foley (2010) describes modelling as a threshold function in engineering. Modelling requires students to make assumptions and simplify a problem, while analysis involves selecting and applying a mathematical technique or scientific theory to solve a problem.

> "We don't know enough about material selection, manufacturing processes, and other aspects that are also incredibly important in the design."

> "Unclear on what sort of analysis would be needed..."

These responses are surprising as they describe concepts and skills that the students have covered in previous courses. The difficulties reported here are examples of Perkins' (1999) inert knowledge; engineering students know how to do the required modelling and analysis, or have the conceptual tools required to find out, but without specific prompts to trigger that knowledge they feel lost. Similarly, despite having knowledge of manufacturing science the students had difficulty reconciling their ideal designs with the realities of manufacturing processes.

> "after spending many long days on looking for vendors, we basically changed many design ideas (and even discarded some of the functions) to adjust our models to the vendor capabilities"

Project management

The main management issues faced by students related to decision-making and communication. In working with users to define needs and deciding on possible solutions, the students often found it difficult to adapt their plans to changing circumstances.

> "Having to scrap ideas that you'd worked on for hours. Knowing when to scrap these ideas and that it was essential to progress in the design process"

> "the priority of our design goals keeps on changing. how flexible should that really be?"

Engineering students are used to being provided with all the information required to solve well-defined problems that have unique correct answers. However in project-based courses decisions must be made when the information available is incomplete or ambiguous. Handling this ambiguity was one of the most commonly reported problems.

> "It is extremely difficult to take decision under uncertainty. It is really difficult to evaluate each possible design before going into extremely detailed designs. At the end of the day we choose strategies/concepts guided by hunches or by the positions of the stars that night."

Osmond (2010) proposes 'the toleration of design uncertainty' as a threshold concept. After having spent some time working through this issue with others, and receiving guidance from the teaching staff, one would hope that the students learnt that uncertainty is an unavoidable part of project management and the design process. However, when asked towards the end of the course what would have helped them to deal with uncertainty, many still felt that there was supplemental information that they didn't have access to.

> "Just talking with more experts that have straight answers"

Tacit skills and knowledge

Much of the knowledge required for engineering practice is not taught explicitly. When working on a team project, interpersonal skills are of course an issue.

> "…the team […] is small, and conflicts become harder to resolve because we don't have enough people to survey more opinions and ideas…"

Working within time constraints was frequently mentioned as a difficulty; however there was very little discussion of what was consuming students' time. From the observation data it is clear that a contributing factor to students' time management problems was spatial reasoning. During the first half of the course, the majority of team meetings were spent trying to describe and interpret descriptions of three-dimensional systems. Often an apparent agreement had to be revisited because team members had each interpreted a mechanism or process in a different way. Miller-Young (2010) identified visualizing and describing three-dimensional forces as a troublesome activity for engineering students.

Domain knowledge

In order to understand a problem and design a solution to it, the students had to acquire a lot of information related to the problem area. The students designing medical devices, for example, needed to learn about elements of surgical practice, physiology, anatomy, and so on. The observation data contained many examples of students making incorrect assumptions about the problem being investigated. The troublesome knowledge encountered here was how to approach problem-solving in a new field. Engineers often design technology to be used in a domain in which they are not experts, so the ability to quickly assimilate knowledge and navigate a new field is essential.

Tools and equipment

Throughout their projects the students made use of a large number of software applications, machine tools, testing equipment and off-the-shelf parts. A common problem was underestimating the planning and evaluation required in using these tools. For example, patent search engines and literature searches were conducted to understand the prior art in each problem area. This required skills such as compiling a search strategy and evaluating the resulting information. Yorke-Barber *et al.* (2008) have mentioned these as possible threshold concepts in the field of information research. Some student teams struggled to find enough information and discovered relevant prior art towards the end of the process, while other teams were overwhelmed by too many search results which resulted in them feeling that it would be difficult to contribute to the area.

> "We need to be really clever considering the large number of patents on this problem"

Similarly, the use of engineering and mathematical analysis software required students to carefully design input data and evaluate results. There was a tendency among students to accept the results of software tools uncritically.

Conclusions and future work

This study has identified a range of troublesome knowledge encountered by students in mechanical engineering design courses. These results will be used to improve the courses investigated, for example by redesigning laboratory sessions to better address the problems and misconceptions of students. Many of the examples presented here have been proposed as threshold concepts by others, which indicates that they are worthy of further study. Having identified a range of problems faced by students, the next step is to design a more focused set of data-collection instruments. For topics such as modelling and analysis, concept questionnaires will be designed and used to test for changes in understanding throughout the course. For skills that are less easily measured, such as tolerating design uncertainty, concept mapping and self-explanation exercises will be used.

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