Best practice

Surpassing Threshold Concepts within Engineering Mechanics Interactive Computer Aided Learning (CAL) to support the learning process

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Abstract

This paper is based on a scientific literature review and interviews with teachers and researchers active in the area of Engineering Mechanics in Swedish higher education. The paper aims to identify and highlight troublesome knowledge and threshold concepts within the field of Engineering Mechanics. Moreover, the ambition is to present ideas of how to overcome these identified threshold concepts.

Recent scientific research acknowledges many benefits of introducing digital and interactive tools, denominated Computer Aided Learning (CAL), at an early stage. Digital and interactive tools can help engineering students overcome threshold concepts. A selection of these digital tools is discussed in this paper. The study concludes that e-learning is an efficient way to enhance and complement the learning process. It also makes teaching material available from anywhere, at any time. Hence, students can individually adjust their learning pace. The interviews with teachers contributed to a clearer view of how digital tools can be utilized and transform learning in mechanical engineering.

Master students in mechanical engineering are expected to create, operate, and understand advanced digital tools. However, on the B.Sc. level, the implementation of digital tools seems to be scarce. Instead, textbooks, exercises with pen and paper, and traditional teaching are the preferred tools for learning. Implementing digital and interactive

computer tools already on a basic teaching level (B.Sc.) can assist students to understand complex theories and overcome threshold concepts.

Introduction

Students are constantly challenged at all levels of education, ranging from Kindergarten to research studies at University. Nowadays, many different learning and teaching methods exist, (cf. Biggs et al., 2011), aiding the students towards learning goals. An important objective is also to stimulate deep learning among students. Deep learning means that students reach a deep and thorough understanding of the specific topic where they really can put the knowledge into context and use it to synthesize new knowledge (cf. Ramdsen, 2003). The opposite to deep learning is surface, or shallow, learning. Surface learning can of course be of great value when learning topics such as the alphabet or memorizing multiplication. But the knowledge could be just mimicry of what the students are supposed to learn, and the risk is evident that the students will run into trouble when the knowledge shall be applied in real life situations. Moreover, a lot of the fundamental knowledge and skills learned in mathematics and physic is at a later stage further combined and utilized in advanced courses. Therefore, a deep understanding within the different disciplines is very important (cf. Quinlan et al., 2012).

The authors of this paper, looking back at their own time as students within mechanical engineering, recognize several times that they encountered troublesome and challenging threshold concepts, similar to the ones found in the literature (cf. for instance Meyer & Land, 2003). Engineering students must understand the physics behind the real-world phenomenon they are studying (cf. Quinlan et al., 2012), but it is of equal importance to master mathematical equations describing the physical phenomenon. Often, students only cross over learning thresholds when they really can visualize and understand the physics at hand. This deeper understanding is often achieved by interacting with a mathematical model, physical experiments, or computer model.

The first aim of this paper is *to identify common threshold concepts within the field of Engineering Mechanics*. This information will be extracted from a scientific literature study and interviews with teachers active in Swedish higher education. Common ways of overcoming threshold concepts will also be discussed.

Digital and interactive tools are widely used for children and teenagers to introduce and advance skills in problem-solving, mathematics, physics, and mechanics. Young students can learn and practice online, teachers can follow the progress of their students and identify troublesome areas where to support the students (cf. Croft, 2001). Often gamification, like the famous physics-based game Angry Birds, is used as a digital tool to inspire, motivate and improve the learning process of children.

Students are also familiar with using digital and interactive tools at the other end of their journey through the education system. Mechanical engineering students at the level of M.Sc. and Ph.D. are skilled and experienced enough to implement their own software to visualize and play around with physics and mathematics. The authors of this paper recognize that utilizing digital tools can have a profound impact on the understanding of problems within Engineering Mechanics. These tools also help a lot when communicating results to other students and professionals that aren´t experts in the field themselves.

The second aim of this research paper is to *discuss the implementation and benefits of digital and interactive tools in teaching and learning Engineering Mechanics*.

We would like to investigate and discuss interactive tools that can be used early in the learning process. We believe that this will enable students to understand what they are supposed to learn much earlier and increase the amount of deep learning for. We will investigate this topic within Engineering Mechanics which is our own subject where we have experience as practicing engineers with close professional connections to Swedish university education.

A further goal with the paper is to inspire research and development of Computer Aided Learning (CAL), present areas where tools can be further developed, and a higher degree of motivation through a better understanding of real-world physics (compared to just solving abstract equations).

Methods

This paper contains a literature study of common obstacles and threshold concepts within the area of Engineering Mechanics. Digital and interactive tools that can be used while teaching and learning Engineering Mechanics are presented in the second half of the literature study.

As a complement to the literature study, interviews were carried out with teachers active in Swedish higher education. This is throughout the paper combined and discussed in conjunction with observations from our own learning and teaching experience. Another goal of the interviews was to see if we could gain new insights into our questions and to get fresh answers from currently active teachers. We see this as important due to the rapid development of digital tools and distance-based learning and teaching, further accelerated by the covid-19 transformation from 2019 onwards.

A questionnaire was prepared and utilized during the open interviews of 5 academic teachers within the field of Engineering Mechanics at higher education in Sweden.

Interview Questions:

1. Give examples of "threshold concepts"/terminology or challenging topics for students?
2. What methods or tools exist for helping students to pass threshold concepts or troublesome learning?
3. Are you utilizing everyday situations in the learning process/education? Examples?
4. What are the common threshold concepts really about? What is the cause?
    - The concept/tool is too "abstract"?
    - Mathematical skills are not sufficient?
    - Applying and combining the knowledge from mathematics, physics, etc.?
    - Something else?
5. What type of digital and interactive tools are you using, or are aware of, within Mechanical Engineering that facilitates teaching and learning to aid threshold concepts? Examples: Mohr´s circle, stress/strain tensor, engineering vs. true stress/strain.

Threshold concepts in mechanical engineering from the literature

The scientific literature supports that it is beneficial to introduce software that students can interact with already at the B.Sc. level. Often, a good understanding of engineering topics is reached by interacting with digital tools in the final stages of the learning process, far into the learning process when students can implement something themselves. Then the students have already passed or are very far on their way of crossing threshold concepts, i.e., they have moved from preliminal space to post-liminal space as shown in Figure 1 (cf. Land, Meyer, et al., 2010). The authors' own experience as practitioners in mechanical engineering in the industry working a lot with CAD, CAE, CAM has also taught them the importance of interactive and graphical tools when visualizing objects and the possibility to render the results realistically.

If you are not familiar with the terminology of threshold concepts and want an introduction to the subject, the interested reader is referred to (Flanagan, 2021) who defines the topic in an informative fashion. Threshold concepts, introduced by (Meyer & Land, 2003), are characterized by being, the quote from (Elmgren & Henriksson, 2018):

> *“**Transformative**, in that, once understood, their potential effect on student learning and behavior is to occasion a significant shift in the perception of the subject.*
> *Probably **irreversible**, in that the change of perspective occasioned by the acquisition of a threshold concept is unlikely to be forgotten.*
> ***Integrative**; that is, they expose the previously hidden interrelatedness of something.*
> *Possibly often (though not necessarily always) **bounded**, in that any conceptual space will have terminal frontiers, bordering with thresholds into new conceptual areas,*
> *Potentially (and possibly inherently) **troublesome** in those cases where students have difficulty understanding the concepts and end up in a state of learning limbo where knowledge takes on a form of ritual knowledge. Understanding is not genuine.”*

Students can have a hard time passing the initially very large hurdle in the learning curve for mathematics in the first year at the university studying Engineering. Moreover, for instance (cf. Kabo, 2010) noticed that problem solving is a central activity to the engineering discipline. A combination of difficult and troublesome knowledge and a lack of experience solving and formulating problems may get students stuck in the liminal space presented in Figure 1. These large bumps that engineering students must pass are not always fully in conjunction with the above definitions of threshold concepts. In this paper, we have chosen to focus on threshold concepts. But often the bump that needs to be passed can also contain more shallow learning like algorithmic repetition while learning mathematics, this can also be very challenging even if it doesn´t fully match the definition of a threshold concept.

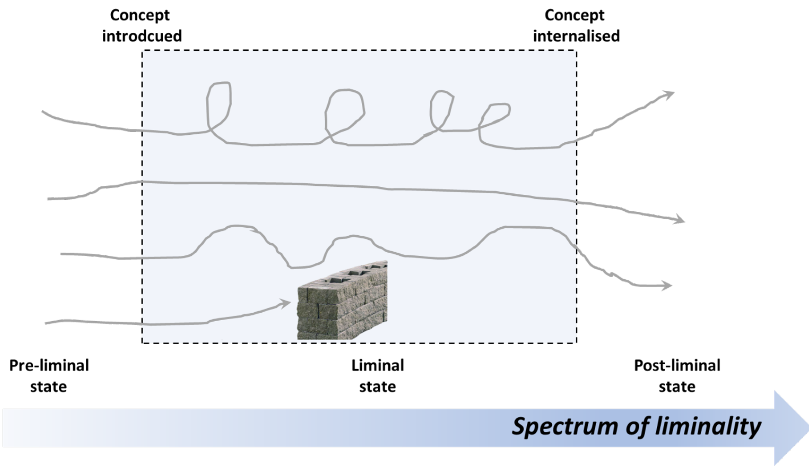

Figure 1. How different learners might navigate through a liminal space, cf. (Kabo, 2010).

Stress and strain are two common examples of terminologies and concepts that are profound to understand within the area of Engineering Mechanics (cf. Ottosen & Ristinmaa, 2005). These are also confirmed in this literature study and the following interviews. These concepts are utilized to express internal forces and deformations i.e., how much a material, a component, or a product is exposed to when an external mechanical load and/or deformation is applied. This knowledge is used to dimension materials, designs, and technical concepts during the development and construction of products. For instance, how much force is distributed in a metal wire in a bridge or how much a concrete slab can withstand? Embedded in the learning process of these difficult concepts is a combination of previously acquired knowledge from material science, math, mechanics, and physics. Moreover, stress and strain can be expressed in different formats where two common ones are engineering and true measures. Structures also move and rotate within space, to describe this mathematically and really understand what is happening is something students also tend to struggle with. Acquisition and a thorough understanding of such concepts (force, stress, strain, vector, tensor, etc.) are fundamental for grasping how a mechanical engineer thinks and practices this knowledge.

Prusty and Russell (2011) have compiled a list of threshold concepts in Engineering Mechanics which is overlapping with the conclusions from the following interviews and the authors´ experience:

- “resultant of forces, moments and couples
- 3-D force systems
- trusses
- friction in machines
- first and second moment of area
- internal forces in a beam
- shear force and bending moment
- stress and strain
- combined loading
- Generalised Hooke´s Law
- Mohr’s Circle for stresses in 3D
- Mohr’s Circle for strain in 3D.”

Digital and interactive tools in teaching and learning mechanical engineering

Digital and interactive tools are nowadays used quite extensively in teaching and learning of children and teenagers up to high school. At the university level (B.Sc.) these kinds of tools are not as widely adopted in the education teaching methods, this is confirmed by the interviews conducted in relation to this paper, the authors own experience, and the studied scientific literature, (cf. Prusty & Russell; Abad et al., 2020).

Abad et al. (2020) presents the success of implementing digital interactive teaching applications in the field of Engineering Mechanics. The tools consist of interactive tests, problem-solving step by step, and theory explained by videos and animations. This research group find a notable increase in approved students and student satisfaction compared to the reference group using traditional methods. The students can identify their knowledge gaps and focus more on difficult areas. Additionally, these methods were very appreciated by the students during the Covid-19 Pandemic.

Croft and Ward (2001) find similar results when implementing a digital learning environment for teaching mathematics to engineering students. Moreover, the authors note that it is not the digital tools themselves that are the most important part, but that it brings flexibility and a more holistic view into the teaching process that helps the students in their learning process. Engineering students can often lack motivation for the very important mathematics courses, in favor of engineering modules in their education. The flexibility and own tempo setting in mathematics can increase the motivation and learning experience for the students.

Ebner and Holzinger (2007) studied game-based learning, i.e., gamification. One important result from their study is that learning must be fun and inspiring to motivate students. Starting with digital tools instead of classical lectures and exercises often seems interesting and fun to students. However, motivation soon starts to drop, the students discover that it´s still hard to learn even though the material now is digital. The solution here could be to turn the digital learning experience into a motivating rewarding game: the students want to learn without feeling that they are learning. This paper also states that games and digital learning are recognized as good learning tools in elementary and secondary school, there is little evidence of use in higher education.

Arras (2014) describes a strategy called Computer Aided Learning Module (CALM) for digital and remote labs in a material science course. This approach gives the students the flexibility they enjoy, the possibility to set their own tempo, and can also be very important in times where campuses aren't accessible for several different reasons. It can be distance education, sick students, or the current Covid-19 Pandemic. Access to University premises and especially laboratories have been a huge concern, and a problem, due to the Covid-19 Pandemic. Therefore, digital and virtual tools can in the format of a Virtual Test Laboratory be a great complement to the ordinary experimental labs, both in respect of accessibility and also due to safety, preparation work before normal lab events, and for students to try and test different combinations and loading conditions that often is hard to fit in the time constraint given at the lab occasion.

Access to University premises and especially laboratories have been a huge concern and a problem due to the Pandemic 2019 onwards. Therefore, digital and virtual tools can in the format of a Virtual Test Laboratory, (cf. Brophy et al., 2013), be a great complement to the ordinary experimental labs. Another article describing the benefits with the extension of the Physical Laboratories exercises with a Virtual Laboratory is summarized in Soner (2013) with the following associated gains:

"As a result, the use of computer in education, contributes a lot to learn. The contributions listed as follows;

- The students go into an active mode by computer while learning.
- The student has the chance to control the problem over and over.
- Learning is faster thanks to computers, time-gain is provided.
- Learning can be made more enjoyable and attractive.
- There are opportunities to learn both individually and as a group.
- While the students work individually, they can set the speed of learning.
- By saving feature, the studies in the past can be displayed."

Results

In this Result chapter and the following Discussion and Conclusion chapter, we present and discuss results from interviews and the literature survey. The two major goals of this paper are to:

1. Identify common threshold concepts within the field of Engineering Mechanics
2. Discuss the implementation and benefits of digital and interactive tools in teaching and learning Engineering Mechanics.

Summary of interviews with teachers in higher education

Threshold Concepts

All the interviewees mentioned very similar threshold concepts within Engineering Mechanics. Both themselves and their students had through the years struggled with stress and strain theory as mentioned earlier from the literature study, tools like Mohr´s circle that are useful but abstract and hard to grasp, mathematical derivations, mathematical transformations and translations of stresses and strains, coordinate transformations. Different courses and books tend to use different notations and definitions to describe the same quantities which were also highlighted as a troublesome issue. These non stringent ways of defining the same quantity in various ways can be very confusing, even for experienced teachers and engineers. All interviewed academic teachers seemed to commonly agree that it´s very important to start with very simple illustrative examples and build on that foundation to reach a good understanding and at the same time practice and apply the theoretical understanding.

Digital and Interactive Tools

The interviews showed that digitalization and pre-recorded teaching and learning are now widely used standards across universities in Sweden. Mainly it consists of live web sessions and/or recorded lectures. Many teachers had already adopted parts of this technology years ago, but a large portion of different courses was also forced into web lectures because of the coronavirus pandemic that started at the end of 2019.

Most teachers in the interviews didn´t know about any digital interactive tools used in B.Sc. level of Engineering Mechanics, or they had heard or seen some examples but weren´t using or looking for such tools themselves. It was suggested that very experienced teachers sometimes crossed the threshold a very long time ago, and therefore can have a hard time seeing the need to make it simple for the students due to their vast insight into the topic themself.

Threshold concepts in the area of Engineering Mechanics

The literature, together with the interviews and the authors´ own experience paints a picture of Engineering Mechanics students struggling with several common threshold concepts during the initial years of their education. Classical teaching and learning like lectures, exercises, and practical experiments are widely adopted teaching methods in Engineering Mechanics. When students progress through their education, and later on a professional career, they will gain the skill to use and implement their digital tools and other available software. The following list compiled by Prusty and Russell (2011) contains common threshold concepts in Mechanical Engineering. The conducted interviews and the authors´ own experience confirm and support these thresholds:

- “resultant of forces, moments and couples
- 3-D force systems
- Trusses
- friction in machines
- first and second moment of area
- internal forces in a beam
- shear force and bending moment
- stress and strain
- combined loading
- Generalised Hooke´s Law
- Mohr’s Circle for stresses in 3D
- Mohr’s Circle for strain in 3D.”

The list can, based on the interviews, be extended with the following threshold concepts:

- Mathematical derivations
- Mathematical transformations
- Coordinate transformations
- Notations and definitions
- Purpose and applicability of methods and knowledge
- Eigenvalues

These identified threshold concepts in Engineering Mechanics often circle abstract and difficult terminologies and theories, for instance, stresses and strains, and their related equations and physical meaning. These abstract and complicated concepts, like stress and strain, are often not fixed i.e., constant in time and space, and they are changing and transforming depending on position and time. Therefore, there is a need to visualize and interact with them both in time and space during experiments, either physical or virtual.

Digital and interactive tools

Right now, the transition to online teaching and e-learning is very rapid, the Covid-19 Pandemic has boosted the transition to online lectures and pre-recorded online lectures. These efforts have made course content accessible and available from anywhere at any time.

There is an apparent gap found in the literature (cf. Prusty & Russell; Abad et al., 2020) and during the interviews of using digital and interactive tools around bachelor level in Engineering Mechanics education methods. Digitalization and pre-recorded teaching and learning are now widely used standards across Universities in Sweden. Mainly it consists of live web sessions and/or recorded lectures. All teachers had already adopted parts of this technology years ago, but a large portion of different courses was also forced into web lectures because of the coronavirus pandemic that started at the end of 2019.

The literature and interviews confirm that "Learning by doing" is very important in Mechanical Engineering. The interviewed teachers are stating that theory and practice need to be connected, both for understanding and motivation.

Virtual experimenting and interactive models are not yet widely adopted as teaching tools. Previous literature however points to many benefits of adopting computer aided learning tools.

Most teachers in the interviews didn´t know about any digital interactive tools used in the B.Sc. level of Engineering Mechanics, or they had heard or seen some examples but weren´t using or looking for such tools themselves.

Discussion and conclusion

Already today many digital and/or interactive tools are available within the area of mathematics and physics ranging from the very simple ones like apps and games to more advanced tools utilized in later stages of Higher Education. A few examples of common digital and interactive tools found in the literature and during the interviews are summarized and presented as Digital Tools in Figure 2.

The identified gap of using digital teaching tools is around the B.Sc. level in Engineering Mechanics. There exist digital tools that seem suitable for the purpose. But they are not yet developed and customized towards Mechanical Engineering and/or widely adopted in higher education.

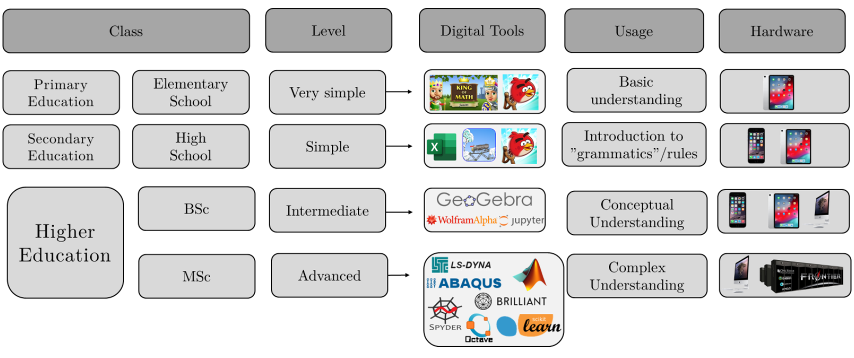

Figure 2. Digital and interactive tools in math, physics, and mechanics that are utilized at different ages and education levels.

Subjects that are particularly abstract and difficult can be supported with practical work in the form of experiments. The hands-on work in laboratories often helps students to a more thorough understanding of physical events and mechanisms. “Touch, feel, and see” is very useful for increased understanding of the concepts like stress and strain.

Experimental observations and hands-on experience can help students to embrace abstract and troublesome knowledge, referring to a quote by Confucius:

“I hear and I forget. I see and I remember. I do and I understand”

Şeker (2013) summarize the benefits of combining the theoretical knowledge with experiments:

"the theoretical knowledge´s are supported with the laboratory studies. That is because they are to implement the theoretical knowledge; theory and practice are required to follow each other. This is an important condition in terms of engineering students to gain the ability to apply.”

Moreover, Şeker (2013) adds the advantage to further include computer modeling to supplement the theoretical exercises and laboratory studies, and highlight the possibility to utilize the Virtual Laboratory:

"In some branches of engineering, combination of theoretical knowledge and practices don't seem favourable in terms of time, space and cost. In this case with modeling the applications on computer, the gap can be filled with lifelike visuals."

In other words, when studies are not possible to perform in real laboratories, it is often possible to create and implement a Virtual Laboratory instead, an example is shown in Figure 3.

The Virtual Laboratory can provide an environment where the student can explore, interact, and visualize the system of interest and observe the theoretical concepts described in the course. Hence fruitfully combining theory and practice enhance the possibility for the student to pass the liminal space and reach profound deep learning and physical understanding.

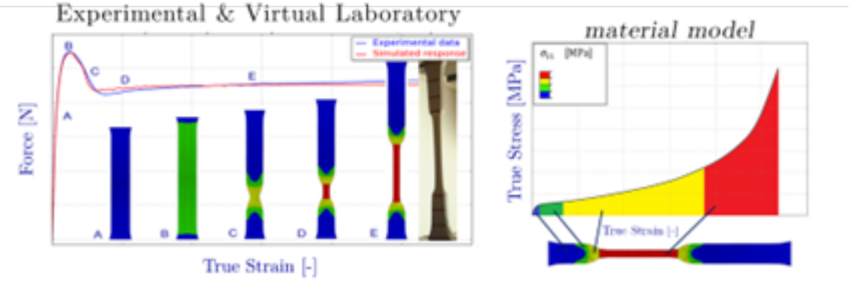

Figure 3. results combined with the results from the "Virtual Laboratory", (cf. Nordlund et al., 2014)

The findings of threshold concepts within Mechanical Engineering in this paper are made by literature, interviews, and the authors' experience from learning, supervising students, teaching, and practice within the industry. The authors had the same issues and difficulties when they studied at the university and the transition to Industry wasn´t always smooth and easy. However, working with simulation-driven development in the packaging and car industry, as shown in Figure 4, involving a lot of experimental material testing and material characterization with a wide range of experimental setups and techniques have given both the authors a fundamental understanding of the mechanics involved, and a deeper understanding of the theoretical parts taught at university.

It is very beneficial to actively work with applications utilizing many of the theories explained and studied at the University. Therefore, the authors have by experience, interacting, teaching, and supervising students learned the abstract and complex beforementioned threshold concepts and passed the learning barriers by utilizing a combination of experimental methods and techniques supplemented with a wide range of digital, visualization, and interactive computer tools.

Today simple and very advanced digital tools exist and are utilized. However, intermediate digital tools are not commonly used, nor awareness of what tools exists is common knowledge among teachers. This gap could be filled with a Virtual Laboratory setup or utilization and implementation of digital tools.

The authors of this paper recommend that educators consider utilizing digital and interactive tools applied in Engineering, referred to as Computer Aided Learning (CAL) tools, a component of engineering learning pedagogy.

The authors´ respective industries, Packaging, and Automotive stamping can be a part of a more integral CAL development. It´s probably possible to build a strong connection and develop students learning through Virtual Packaging and/or Virtual Stamping Laboratories currently discussed at the two companies (cf. Andreasson, 2019; Pilthammar, 2020).

MATLAB® or other advanced programming tools are often used in several Engineering and mathematics courses at Higher Education, however, a lot of the time and focus is spent on programming and this can be a challenge for many students. There is therefore a need for simpler tools that is putting the "Material"-mechanics topics and fundamental understanding in focus.

*Figure 4***.** Virtual Package Laboratory, (cf. Petersson, 2019) and Virtual Tryouts (cf. Pilthammar, 2020).

Nowadays, CAL is not widely adopted in Engineering Mechanics and there is a need to develop tools based on computer simulations that are interactive, easy to use, and available to non-expert users, i.e., democratizing the utilization of simulation methods and tools. Attempts have been made within this area in for instance material engineering (Magana, 2013). In this approach, students can connect to a web interface and simply perform inquiry-based simulations. Simulations are very helpful in the learning process as simulations make understanding theoretical concepts much easier. Virtual experimenting can also fill a gap where experiments are too time-consuming or expensive to carry out on a sufficiently large scale in engineering courses.

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