# Research on student understanding as a guide for the development of instructional materials in introductory engineering courses

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**Abstract:** At Hamburg University of Technology, we are engaged in (1) investigating student understanding of fundamental concepts in electrical and mechanical engineering and (2) using the results from this study to guide the development of instructional materials. In this paper, we present methodology and illustrate the process of research and curriculum development with an example from an introductory Engineering Mechanics course. Our analysis suggests that when combined with active learning techniques, instructional materials developed on the basis of research on student understanding can improve student learning.

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## 1. INTRODUCTION

While the challenges for society in the 21st century require future engineers to obtain a broad set of skills, a thorough understanding of basic science and engineering concepts will remain one of the core objectives of engineering education. It is widely known that for many students, typical introductory courses are not successful in achieving this goal. Changes in the instructional settings, such as incorporating more active learning formats, seem to have a chance at enhancing learning outcomes, but effective instruction in introductory science and engineering may require more than the mere adoption of a different learning format. Educational research based in these disciplines has identified specific conceptual and reasoning difficulties that often prevent students from developing a functional understanding of many of the topics taught in these courses. There is evidence that instructional materials that foster active learning and take into account such difficulties are more likely to improve student learning. At Hamburg University of Technology (TUHH), we are engaged in (1) investigating student understanding of fundamental concepts in electrical and mechanical engineering and (2) using the results from this study to guide the development of instructional materials.

A new development in Engineering Education in Europe is to deal with students' subject-specific misconceptions and misunderstandings. This development follows similar approaches which are increasingly used in physics education. About five years ago we began a program at TUHH to adapt the approach to engineering education in Germany. Our focus has been on the three introductory courses in mechanics, electric circuits and thermodynamics. The present article is concerned with our discoveries of student difficulties with statics concepts in mechanics which we obtained through analysis of assessment tests and interviews with students.

Our program consists of roughly three broader steps: First identifying the difficulties, addressing the difficulties through interventions and lastly evaluating the success of the intervention. To identify student difficulties we begin by analyzing students' written responses in homework assignments or examinations, including results from assessment tests. Subsequent to this analysis we invite students for an interview in which we ask them to analyze or solve problems involving concepts that our analysis flags as potentially problematic. In this article we will show how this two-step procedure identified a student misconception related to the static equivalence between forces and moments that appears to have been overlooked by previous research. Based on a deeper understanding of student difficulties we currently develop *worksheets* that address the identified difficulties. These worksheets are designed to be used in weekly collaborative-group tutorials. The success of the intervention is evaluated in a twofold manner: first through standard assessment tests; second through an assessment of student performance on exam questions which have been specially designed in light of the identified misconception.

The remainder of this article is as follows: In section 2 we provide additional details regarding our local environment and our specific methodology. In section 3 we describe particular misconceptions regarding static equivalence, in particular between forces and moments, and detail how they came to be identified. A description of the intervention is given in section 4, and the results of our assessment are provided in section 5. We conclude with a summary in section 6.

## 2. CONTEXT AND METHODS

Hamburg University of Technology (TUHH) was established in 1978 and currently has a student body of about 5000. Although it draws students mostly from the greater Hamburg area, and the primary language of instruction is German, it is internationally oriented with an increasing number of English language programs. TUHH is primarily an engineering school offering undergraduate and graduate degrees in civil, electrical, mechanical and chemical engineering among others. Students admitted to the TUHH usually have the *Zeugnis der Allgemeinen Hochschulreife* which is roughly equivalent to the *International Baccalaureate* or the English *A-Levels*. Some students will additionally have completed a three-year apprenticeship.

Our research group was established six years ago within the Institute of Mechanics and Ocean Sciences. Our focus in the project described here is on students pursuing a degree in mechanical engineering or students from other fields who require the four-semester *Mechanics* sequence. The first semester of the *Mechanics* sequence covers Statics. It is the Statics portion of the Mechanics sequence that we address in our study. Since 2005 the *Force Concept Inventory* by Hestenes et al. (1992) has been given as a pre-test prior to the start of instruction. At the end of the first semester the *Statics Concept Inventory* by Steif (2005) has been given as a post-test. To date slightly over 1200 students have taken these exams at TUHH as part of our study. Since the summer of 2009 we have also been interviewing students to identify conceptual shortcomings.

Based on an analysis of results from the Statics Concept Inventory (SCI) we identified topics which students appear to struggle with. The persistently most difficult concept covered by the test is that of *static equivalence*, as measured by a subset of three (of 27) test items. To further explore this apparent conceptual shortcoming we conducted interviews with students from the mechanics course in the summer semester of 2009. The interview procedure and questions were designed based on assessment questions and the content of course lectures. Interviewees were self selecting – during the course of the semester students were asked if they were willing to be interviewed. Of the roughly 400 students who took the course, ten students indicated a willingness to participate in our interviews, and eight eventually came to the interviews. The interviews were conducted after the semester was over, but before the final exam was given. One incentive for students to participate in the interview was the potential for it to help with their exam preparations. All of the participating students agreed to provide us with their student IDs. This information enabled us to gauge their relative standing in the class based on the already given pre-test (FCI) and post-test (SCI). The eight students were among the more highly achieving students of the class, all but one were in the upper half of their class, four of these were in or above the 90th percentile as measured by the SCI. Because we were not involved in writing or grading the course examination, we could be free (*i.e.*, unbiased) in how we posed our questions, and the students could also answer somewhat more freely as misconceptions would not be held against them. All interviews were recorded with a digital video recorder.

While the interviews did not adequately sample the class, this was not their purpose. Rather, our goal was to use the interviews to identify misconceptions that students appeared to have. Our hypothesis was that a misconception that emerges consistently in interviews with even a few students is likely to be more widely shared. Put another way, one may ask what is the probability that among eight - admittedly self-selected - students a misconception emerges that is otherwise absent from the wider student body. Given that the students we interviewed ended up being relatively high achievers, it would seem even more likely that the misconceptions which they held would be reflected more broadly. But even to the extent that the misconceptions we identify turn out to be isolated, many of our points address methodological issues and hence remain germane to the larger questions in engineering education to which our study addresses itself.

**Figure 1: At the conclusion of the interview students were given the opportunity to hold the imagined slider-and-beam to test their understanding of the concepts explored in the thought-experiment part of the interview.**

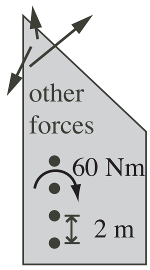
Each interview consisted of two parts. The first part involved having the students participate in a thought experiment. They were shown an object consisting of a moveable $\Gamma$-shaped object (slider) mounted on a beam that was assumed to be weightless (Figure 1). The slider could be mounted in one of two ways: with the overhanging branch directed along the beam away from, or toward, the person. We will refer to this object as *slider-and-beam*. The students were asked to imagine holding the end of the beam in their hand and to predict whether they would feel a difference in their hand while holding the slider-and-beam as a function of the orientation of the slider. They were then asked to explain their prediction using concepts developed in the mechanics course.

In the second part of the interview the students were asked to answer one question from the SCI and another question similar to the SCI question, but with an answer (tailored to probe what we anticipated to be a major misconception) added (Figure 2). In both parts of the interview we asked the students to think 'out loud' as much as possible so that we could gain insight into the root of any misunderstandings.

A 60 Nm couple acting clockwise keeps the member in equilibrium while it is subjected to other forces acting in the plane shown schematically at the top. The four dots denote vertically aligned, equally spaced points along the member.

Assuming the other forces stay the same, what load(s) could replace the 60 Nm couple and maintain equilibrium?

Mark all possible answers.



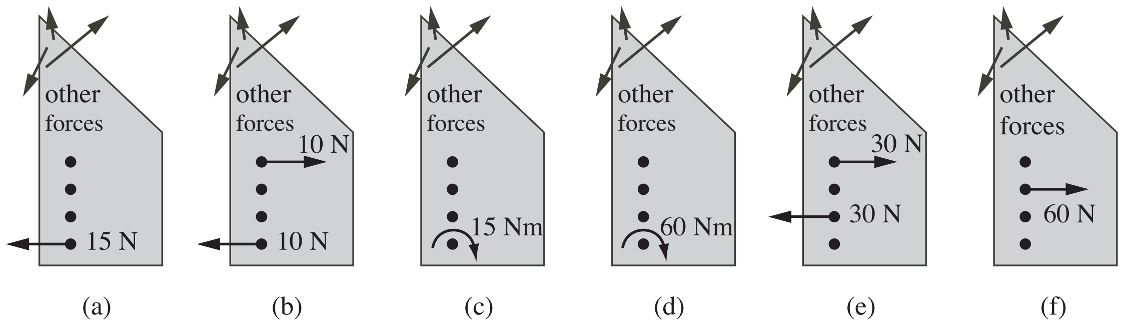




**Figure 2: Example of an SCI-like interview question designed to explore the student misunderstanding that forces and moments are interchangeable.**

## 3. MISCONCEPTIONS IN ENGINEERING STATICS

The answers and explanations received from the interviewees in relation to the first task, the slider-and-beam thought experiment, revealed various difficulties associated with identifying a specific system to be analyzed and recognizing the implications of a specific choice of system. Students generally were able to answer correctly that the beam with outward-directed slider would 'feel heavier' than the inward-directed case. They also could explain this in terms of the change in the center of mass of the system consisting of the beam and the slider. We then asked the students to consider their answer if the beam alone were chosen as the system to be analyzed, as this was the object that communicated the change in the orientation of the slider to their hand. From this point of view, or choice of system, the students had difficulty in identifying a reason as to why the situation should depend on the orientation of the slider. Some students, who realized that their answer should not depend on the choice of the system, then changed their initially correct answer and said that the orientation of the extension would not be felt by the person holding the beam.

Through our analysis of student responses in both parts of the interview we identified the following misconceptions:

- belief that forces and moments are interchangeable;
- failure to recognize that forces as well as moments are interactions between two bodies;
- belief that the point where a couple is applied will be a fixed point in an ensuing rotation caused by the couple;

The first point has been discussed by Newcomer and Steif (2008), and (in a somewhat different context) by Ortiz et al. (2005), the second by McDermott et al. (1994). To our knowledge the third point has not previously been identified.

## 4. INTERVENTION

Starting in the Fall of 2009 we developed weekly worksheets modeled after the *Tutorials in Introductory Physics* by McDermott et al. (1998), which are now widely used in Physics instruction. These worksheets included problems and exercises, some of which were designed to address specific difficulties that our research had previously uncovered. The other major difference between these worksheets and traditional exercises given in engineering courses is the emphasis on qualitative understanding rather than quantitative problems often mastered through having memorized algorithms.

Hannes: *"System* II *is equivalent to system* I. *Remember,* $\vec{M} = \vec{d} \times \vec{F}$. *Hence, a moment of* $12\,\mathrm{Nm}$ *with respect to* $P$ *can be replaced by a* $3\,\mathrm{N}$ *force,* $4\,\mathrm{m}$ *to the right of* $P$."

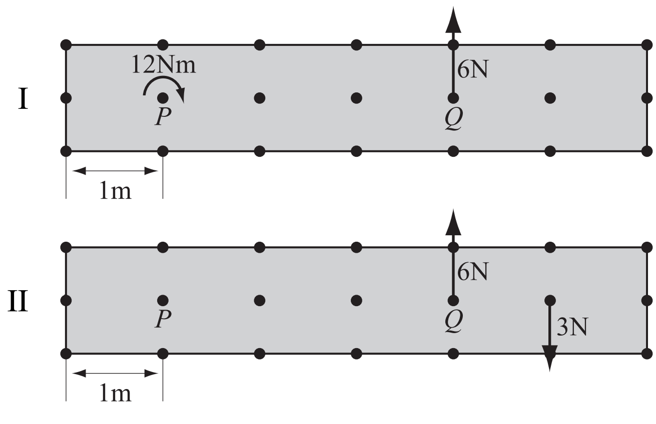



**Figure 3: An example of material for a qualitative question designed to address misunderstandings of interchangeability of forces and moments**

An example of this type of question is provided by the situation shown in Figure 3. Students, organized in small groups, are then asked to answer three questions.

a. Do you agree with Hannes? Justify your answer.

b. Compare the resulting forces in systems I and II.

c. Compare the resulting moments relative to point $Q$ for both systems.

## 5. ASSESSMENT

We attempted to measure the effectiveness of interventions by comparing pre- and post-test data for the past five years. Only one of these years, the last, incorporated the intervention described above. Of the five years, the year 2009-2010, which had the benefit of the intervention, scored the highest on the SCI (see Table 1). This year also had a relatively lower pre-test (FCI) score, indicating that higher achievement was not likely attributable to initial conditions.

Because the instructional sections on static equivalence (included as parts of three subsequent worksheets) were most directly affected by the outcomes of the interviews, we specifically looked at the average post-test results of the three test items comprising the static-equivalence subsection (stat-eq) of the SCI (see last column in Table 1). In contrast to the overall post-test results, student achievement on the subsection was by far the highest in the 2009-2010 cohort, even if compared to the relatively strong result of 2005-2006.

| Year | Instructor | FCI (pre) [%] | SCI (post) [%] | stat-eq [%] |
|---|---|---|---|---|
| 2005-2006 | A | 50 | 42 | 17 |
| 2006-2007 | B | 45 | 36 | 12 |
| 2007-2008 | A | 51 | 30 | 11 |
| 2008-2009 | B | 49 | 29 | 13 |
| 2009-2010 | B | 47 | 43 | 27 |

**Table 1: Summary of FCI pre and SCI post-test results over the last five years, as well as post-test results of static equivalence subsection of SCI.**

While these results are encouraging, there are at least two additional factors which could explain the relatively good performance 2009-2010 semester students. First, in 2009-2010 the curriculum was slightly changed, with the net effect that student contact hours with a teaching assistant effectively doubled. Second, instructor B (Table 1) who taught the course in 2009-2010 followed a format that was introduced by instructor A in 2007-2008 to incorporate active learning, and which instructor B had followed for the first time in 2008-2009. Hence additional contact with teaching assistants and improvement in the basic instruction, including a mastery of active learning techniques, could provide alternative explanations for the remarkable gains in 2009-2010. We believe all of the above likely played a role.

## 6. SUMMARY AND CONCLUSIONS

A three step program has been implemented to advance engineering education at the TUHH. The steps consist of identifying student difficulties or misconceptions, designing interventions to address these misconceptions, and developing methods to explore the effectiveness of such interventions. In this paper we focus on a description of this program as applied to a first semester mechanics course taken by incoming engineering students. Interviews identified the following issues:

- belief that forces and moments are interchangeable;
- failure to recognize that forces as well as moments are interactions between two bodies;
- belief that the point where a couple is applied will be a fixed point in an ensuing rotation caused by the couple;

While the first two points are generally well recognized, the third has to our knowledge not previously been identified. The use of new learning material, specifically designed to address these student issues, and its implementation in an active learning environment show signs of significantly improving student outcomes.

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