

# Investigating the Conceptual Understanding of Engineering Students

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## Abstract

This paper summarizes recent work conducted by a variety of engineering educators at several universities to probe engineering students' conceptual knowledge of important engineering topics. Three methods are discussed: the creation of concept inventories, the use of Delphi studies to gather information from faculty about the difficulty and importance of some engineering concepts, and the use of focus groups and interviews to directly probe conceptual understanding. Preliminary results suggest that engineering students, even those who can correctly solve homework problems, may have poor conceptual understanding of important engineering topics. Results are tied to theories of conceptual change.

## Introduction and conceptual framework

Anecdotal evidence suggests that many engineering students may have the computational skill to correctly solve homework problems but may still not correctly understand the fundamental concepts underlying the models presented in their course work. Although conceptual understanding of important concepts has been extensively studied in science fields (Pfundt & Duit, 1994) until recently no systematic studies of engineering students' conceptual understanding of fundamental engineering concepts had been conducted and published. In the past few years, new projects have been started by engineering faculty (sometimes in collaboration with learning scientists) to probe and

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measure students' conceptual understanding of important engineering concepts. The purpose of this paper is to summarize recent work that has begun in this field.

Why do engineering students have difficulty understanding fundamental engineering concepts? Evidence in the literature, supported by the work discussed in this paper, suggest that students do not conceptually understand fundamental molecular-level and atomic-level phenomena including heat, light, diffusion, chemical reactions, and electricity because of fundamental misunderstandings about the way these molecular-scale processes differ from observable, macroscopic causal behavior that we experience in our daily lives (Reiner, et al., 2000; Chi & Roscoe, 2002). Thus, students often still believe that "heat flows from hot objects to cold objects" or that "molecular processes stop when they reach equilibrium." While these kinds of analogies ("heat flows") can be useful, they may also interfere with deep understanding of these processes.

In an effort to grasp what concepts engineering students do not understand, and the underlying reasons for the lack of understanding, engineering educators have recently begun to more systematically probe students' conceptual understanding. This work has occurred at various sites throughout the US and has not been fully summarized before. This paper is an effort to begin to synthesize current work in this area.

### Methods for probing conceptual understanding and results

Several methods have recently been used to probe engineering students' conceptual understanding of important topics. Three methods will be discussed here: (1) the creation of concept inventories in engineering fields to assess students' conceptual understanding (2) the use of Delphi studies to gather information about engineering faculty's perception of the difficult concepts students face, and (3) direct probing of students' conceptual understanding via interviews and focus groups.

#### *Concept inventories*

Concept inventories are instruments used to assess students' conceptual understanding of a topic. They are usually constructed in a multi-choice format, with the distracters identifying common areas of student misunderstanding. The most widely used

of these assessments is the Force Concept Inventory (FCI), which consists of 29 multiple-choice questions designed to assess students' conceptual framework of Newtonian and non-Newtonian mechanics (Hestenes, Wells, & Swackhamer, 1992). The FCI is constructed so that correct answers to short problems will be obtained only by using the correct conceptual framework.

The FCI has demonstrated that simple instruments can be developed to help faculty identify how well instruction has changed how students think about the concepts of the mechanics parts of commonly taught physics courses. The instrument does not take much class time, it is easy to administer and easy to grade, its questions address concepts that essentially all instructors emphasize in their instruction, and it has a well-established history of development and results. Using the FCI in a "continuous improvement mode," instructors can then their pedagogy and classroom management techniques and gauge their effectiveness by comparing gains on the FCI from semester to semester.

In an effort to drive change in engineering education in the way that the Force Concept Inventory has driven change in physics instruction, the Foundation Coalition (a coalition of engineering schools funded by the National Science Foundation [NSF grant #EEC-9802942] has been the catalyst for the development of Concept Inventories in 14 subjects found in most engineering curricula: electromagnetics, strength of materials, systems and signals, thermodynamics, circuits, fluid mechanics, engineering materials, thermosciences (or transport processes), statistics, chemistry, computer engineering, dynamics, electronics and heat transfer (Evans, 2002). In addition, other Concept Inventories are being developed with direct NSF support (Olds, et al., 2004). (See acknowledgements)

These Concept Inventories are in various stages of development, but some will soon be available to engineering faculty. It is hoped that the Concept Inventories will become assessment tools that can be used to evaluate continuous improvements in the engineering curriculum and will assist faculty in determining the level of conceptual knowledge held by their students.

*Delphi studies to query faculty about students' difficulties*

The first step in creating an engineering-based Concept Inventory is to begin to get a sense of what engineering concepts students find difficult. With NSF support, a Delphi study was used to identify important concepts in thermal and transport sciences (fluid mechanics, heat transfer, and thermodynamics). The participants, 30 well-respected engineering faculty experts and prominent engineering textbook authors, were asked to identify important concepts in these disciplines that are consistently difficult for students to understand. The purpose of the Delphi study was to provide input for a Concept Inventory for the thermal and transport sciences.

Delphi studies have been used extensively in business and other fields (Adler & Ziglio, 1996; Clayton, 1997; Dalkey & Helmer, 1963; Fish & Busby, 1996; Linstone & Turoff, 1975; Sackman, 1975 ), but its introduction to engineering education has been recent. In its most common form, Delphi studies use iterative surveys to gather information from a group of experts about a topic. In this case, the Delphi study was used to query faculty and authors about students' understanding of topics. During a generative round, faculty suggested areas that were important but difficult for their students. The researchers clustered these responses to form 28 items that were the focus of the survey. Delphi participants were then asked to rate the items from 0 to 10 on two scales:

- (1) What proportion of your students understand this topic?  
(0 = no one understands, 10 = everyone understands)
- (2) How important is this topic?  
(0 = no importance, 10 = extremely important).

After three rounds of the survey, 12 of the 28 topics (see Table 1) were identified as having low understanding by students (median rating of 6.5 or below) but high importance (median rating of 9 or above). (For more details about this Delphi study see Streveler, Olds, Miller & Nelson, 2003). These topics are now being used to begin a concept inventory in the thermal and transport sciences (Olds, et al., 2004).

Table 1.

Results of Delphi Study, topics with low understanding and high importance ratings

Bernoulli equation  
Conservation of linear momentum  
Differential vs. Integral Analysis  
Entropy and the 2<sup>nd</sup> Law of Thermodynamics  
Heat vs. energy  
Heat vs. temperature  
Internal energy vs. enthalpy  
Reversible vs. irreversible process  
Steady-state vs. equilibrium  
System vs. control volume  
Thermal radiation  
Viscous Momentum Flux

Although more investigation needs to be done, several of these difficult concepts (for example: heat vs. energy vs. temperature; internal energy vs. enthalpy; steady-state vs. equilibrium; viscous momentum flux) do seem to have emergent qualities and therefore may support Chi's theory that concepts with emergent properties are the most difficult to understand (Chi & Roscoe, 2002).

*Direct probing of students understanding through interviews and focus groups*

This methodology involved groups of engineering students and a faculty team from two Big Ten universities. Students, working both individually and as a team, identified conceptual problems with course material, explained why the particular concepts were difficult, and developed conceptual questions. Faculty participated in the team discussions and aided in the development of the questions. In addition, the faculty developed a set of conceptual questions and a concept inventory that encompass the conceptual difficulties identified by the students and the concepts deemed important by

the faculty. While observing the students solve problems, faculty found that students seemed to have a lot of unconnected information about the material, and had difficulty making connections between the different things that they knew.

A fluid mechanics Concept Inventory (developed by Martin, Mitchell, Jacobi and Newell) was given to groups of students at two Big Ten universities. Students who had not had taken a fluid mechanics course had an average of about 30 % knowledge of the concepts, while those who had taken the course had about 50 % knowledge. The gain from taking the course was relatively small and many important concepts were not understood (Jacobi, Martin, Mitchell & Newell, 2003; Martin, Mitchell, & Newell, 2003).

Upon learning the results of this inventory, engineering faculty were very surprised at students' low level of understanding of the basic concepts. The faculty did not anticipate many of the conceptual difficulties that students experienced, and had assumed that the concepts were readily understood. In general, faculty spend little time discussing the basic concepts underlying the subject and this probably contributes to students' poor grasp concepts (Mazur, 1992).

The draft Fluid Mechanics Concept Inventory was given to two classes as a post-test in the Fall, 2003, and as a pretest in Spring, 2004, to approximately 100 (different) students. The pre-test level of understanding was 37 % and the post-test level was 52 % - a modest gain in comprehension.

The *Cronbach's alpha* for the draft Fluid Mechanics Concept Inventory was low and a question-by-question analysis of the concept inventory is underway. The results of this analysis will be used to modify concept inventory questions and increase reliability.

Even though the concept inventory is still under development, the results that have been obtained thus have led professors at these two Universities to development a concept-based method of instruction in fluid mechanics. The goal of this instruction is to increase students' understanding of important concepts.

### Implications and conclusions

The three methods discussed in this paper are helping engineering faculty to begin to build a picture of students' conceptual understanding of engineering concepts. Although

that picture is still very cloudy, the work done by engineering faculty at a several of universities is helping engineering educators to answer several important questions.

- What are the fundamental concepts in engineering?
- Which of these concepts do engineering students find most difficult to learn?
- Why are these concepts difficult?
- Do students' fundamental misconceptions about these concepts contribute to their difficulty?
- How can we create instruments that measure students understanding of these concepts?
- How can we create instruction that helps students learn these concepts?

Although work on these issues is just in its infancy, the creation of concept inventories, and using Delphi studies, focus groups and interviews to gather input for the concept inventories is already providing insights into these questions.

Although results are very preliminary, both the results of the Delphi study and the results of student interviews suggest that the most difficult concepts for students to understand may have emergent qualities, supporting Chi's theory of conceptual change (Chi & Roscoe, 2002). This connection to conceptual change theory may help inform educators as they design instruction to help students learn these difficult concepts.

Although the results of this early work are promising, there is still much to be done. The reliability and validity of the concept inventories is currently being established (Olds, et al., 2004). Information learned in these studies needs to be fed back into instructional practices and into new programs that emphasize concept-based learning. And the discussion among the engineering education community (with more infusion from learning scientists) must continue. It is our hope that this discussion will drive engineering curriculum and pedagogy in a positive direction.

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