Using concept inventories for formative assessment of conceptual learning: A case study from engineering

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Abstract

Assessing students' conceptual understanding of key concepts within a professional discipline is an important first step in identifying robust misconceptions which must be repaired. In this paper, we describe the development and use of the Thermal and Transport Concept Inventory for assessing engineering student misconceptions in thermodynamics, fluid mechanics and heat transfer processes. Cross-tabulation and factor analysis of beta test data are reported and example misconceptions identified in data analysis are presented.

Objective and Purpose

The ability to solve problems is a critical skill that undergraduate engineering students must develop, and knowing how and when to apply that skill is vital to a successful career as an engineer. The criteria used for engineering program accreditation attests to this emphasis with four (out of eleven total) prescribed outcomes focusing on the identification and solution of engineering problems. Most students can solve problems that are identical or similar to what they have seen before (Svinicki, 2004), but when the context is different, students often fail to recognize the connections and are at a loss about how to solve the problems. This ability to see connections across related concepts and problems demands deep conceptual understanding. Without the undergirding of conceptual understanding, flexibility in using their knowledge is nearly impossible (Pellegrino, J.W., Chudowsky, N. & Glaser, R., 2001).

Students' inability to develop profound understanding of some basic concepts may be attributed to fundamental misconceptions that they hold (Chi, Slotta and deLeeuw, 1994; Chi & Roscoe, 2002). For example, some engineering students describe heat as "a substance stored in cold objects" or contend that "molecular motion stops when substances reach equilibrium." The literature suggests that often student understanding is fragile (Shepard, 2001) Their knowledge is superficial and often riddled with misconceptions (Chi & Roscoe, 2002) which prevent the kind of deep understanding that would facilitate transfer to new contexts and related disciplines.

We report here on the development of a concept inventory that <u>identifies persistent misconceptions</u> in the thermal sciences. Our primary goal in developing this instrument is to provide information to instructors that will inform their instruction and thus be used as a formative assessment tool. Other concept inventories have been developed to be used as formative and summative assessment measures (Allen, K., Stone, A., Reed-Rhodes, T., &

Murphy, T.J., 2004; Martin, J.K., Mitchell, J., & Newell T., 2003).

The objectives of this paper are to:

1) describe the theoretical framework emphasizing how concept inventories can be used as formative assessment tools

2) briefly describe how the instrument was developed and provide evidence of the validity and reliability of our instrument

3) demonstrate how the concept inventory identifies misconceptions

Theoretical Framework

Instructors often ask why some concepts are so difficult for students to learn (Olds, Streveler, Miller and Nelson, 2004). This fundamental question has received the explicit attention of a number of contemporary researchers. While several hypotheses have been offered, part of the reason seems to be that certain beliefs can become quickly and deeply entrenched and are not easily changed (Chinn & Brewster, 1993). Chi explains that when students set out to learn a new body of knowledge they face two main obstacles. First, there is the matter of simply acquiring new information. Second, students come to every new situation with some prior knowledge that forms a foundation for the new learning. When prior knowledge structures are weak or faulty, the process of acquiring new knowledge becomes more difficult.

Chi proposes that misconceptions are often embedded in flawed mental models that students produce. If students create incorrect but coherent mental models, they may cling to their explanations because those explanations provide students with a “reasonable” way to organize the facts and procedures they have learned. Because students with flawed but coherent models “are able to answer questions adequately and consistently, they may be blind to their lack of deep understanding” (Chi & Roscoe, 2002, p.7). Since the notion of heat as a substance helps students explain such things as heat transfer, they cling to this incorrect mental model. These fundamental misconceptions must be identified through good formative assessment, so that teachers can help students confront their incorrect beliefs, making it possible for students to acquire correct understandings.

Though many concept inventories have summative assessment as their primary goal (Allen, et al., 2004; Martin et al., 2003), the TTCI (Thermal and Transport Concept Inventory) was created specifically as a formative assessment tool designed to identify common student misconceptions, so that those misconceptions can be addressed.

Assessment “should not merely be done to students; rather, it should also be done for students, to guide and enhance their learning” (NCTM, 2000, p.21). Wiggins (1989) asserts that any good test is “central to instruction” (p. 704). Formative assessment is an evaluation of students’ work that can be used to “shape and improve the student’s competence by short-circuiting the randomness and inefficiency of trial-and-error learning” (Sadler, 1989, p. 120). This formative assessment normally takes place in the classroom in the course of instruction and is intended to be a tool to move learning forward (Shepard, 2001). The TTCI was created as a formative assessment tool to be used to identify student misconceptions.

Procedure

Creation of the TTCI Instrument

In order to uncover student misconceptions, we began with a generative round of a Delphi study in which 30 experienced engineering instructors and textbook authors were asked to provide a list of concepts in thermodynamics, heat transfer and fluids that they thought were very important, but poorly understood by most students. The concepts were subsequently rated by the experts and the ten most important and least understood concepts were chosen as the basis for the TTCI questions.

Initially, one or two questions on each concept were written and presented to students in think-alouds. These think-alouds confirmed that the concepts were poorly understood by students, and they provided information about confusing wording, labeling and diagrams. The students' explanations also supplied information about student misconceptions and their incorrect answers formed the basis of many of the distractors when the essay questions were rewritten in multiple-choice form.

After at least two more questions had been written for each concept, and additional think-alouds conducted, the concept questions were beta tested at six universities. Because of the complexity of many of the questions, the TTCI was administered in three sections: thermodynamics, heat transfer and fluid mechanics. In that way, the questions were more targeted to specific classes and could be administered in a reasonable amount of time. These beta results were tested for validity and reliability, but this paper addresses only two of the statistical measures implemented: factor analysis and crosstabulation.

Crosstabulation

Crosstabulation served two main purposes for this study. First, it was able to check if students were taking the test seriously or simply guessing, and second, it helps to identify common misconceptions. As shown in Table I, a cross-tabulation table is a convenient way to display data that allows the answers to two questions to be compared. In cross-tabulation tables, we can see frequency counts of how many students selected each answer pair. By observing the individual entries in each row and column, we can determine how many students answered both questions correctly. More importantly, when students answer both questions incorrectly using wrong answers that are related conceptually, we have obtained evidence of a misconception which carries across the context of both questions.

Reliability: Are students guessing?

Some of the questions on the TTCI were two-part questions or "testlets." In checking for the possibility of guessing, our testlets were extremely valuable. For example, a testlet focusing on the melting of two blocks of ice that we called *MeltIce*, constituted a paired set of questions (labeled *MeltIce1* and *MeltIce2*). If students were not simply guessing, answers to the first part of the testlet should correlate very strongly to specific responses in the second part. We found that the correlation was very strong (over 80%) which suggests that students were not simply guessing, but seem to have answered the questions seriously and consistently. This provides further evidence of reliability based on beta test results. For reference, the *Meltice* question is included in this paper as Appendix A.

Table 1
Cross Tabulation Results Comparing Correlated Answer Pairs for the two questions related to melting ice

		MeltIce Question 2 answer choices					Total
		e	f (correct)	g	h	i	
MeltIce Question 1 answer choices	a	39	3	0	2	1	45
	b	0	0	16	0	0	16
	c (correct)	2	19	2	0	2	25
	d	0	2	0	0	8	10
Total		41	24	18	2	11	96

Robust misconceptions: Are the same misconceptions being seen across questions?

In addition to a statistical check on reliability, the cross-tabs can also be used to search for the presence of underlying misconceptions. The results in Table I indicate a strong correlation for the correct answer pair (c,f) as well as two sets of incorrect responses (a,e) and (b,g); the incorrect response pairs can then be analyzed to determine if a consistent misconception can be identified from these incorrect responses. For example, the crosstabulation in Table 1 demonstrates that only 19 students out of 96 were able to answer both questions correctly, while 39 students chose the incorrect pair (a,e) and 16 chose the incorrect pair (b,g). Both sets of incorrect choices indicate that many students incorrectly believe the <u>rate</u> of heat transfer rather than the <u>amount</u> of heat transferred will determine how much ice is melted. In the case of the (a,e) set, the heat transfer rate is increased because of larger heat transfer area (associated with two cooler blocks rather than 1 hotter block) while in the case of the (b,g) set the higher heat transfer rate is caused by a larger temperature difference between blocks of ice.

All of the heat transfer questions in the TTCI were cross-tabulated and the results analyzed to identify other possible misconceptions. Presently, we have identified significant misconceptions in three overall categories:

- energy vs. temperature
- steady-state vs. equilibrium processes
- rate vs. amount of heat transferred

Confirmatory and exploratory factor analyses have also been used to determine which concept inventory questions cluster together and whether the clusters agree with the predetermined question categories established by experts in thermal and transport sciences. Two distinct factors were identified: one clustered the Melt Ice questions from Table 1 with two thermal equilibrium questions about a fluid heated in a pipe; a second factor clustered three questions focused on apparent differences in temperature which are confounded by heat transfer issues (e.g. walking barefoot on tile vs. carpet which results in an apparent but erroneous predicted difference in floor temperature). We are still analyzing the underlying misconceptions associated with each set of clustered questions, but preliminary analyses suggest that questions are clustering according to Chi's theory of emergent vs. direct processes in which students incorrectly apply direct cause and effect of everyday experience to the random motion and emergent patterns of molecular-scale processes.

Conclusions/Implications

Using the TTCI as a formative assessment tool at five diverse universities has identified some of the common misconceptions that exist. The testing showed, for example, that approximately 13% of junior and senior engineering students in the beta test do not understand how heat capacity is related to temperature change or that different substances have different heat capacities. Nearly as many do not understand how temperature is related to energy. Although these numbers seem low in absolute terms, when compared with the number of students who were able to correctly answer both questions in conceptually-related pairs (~13-30% depending upon specific question combinations), it is clear that a significant number of highly-educated engineering students still possess strongly-held fundamental misconceptions about basic heat and heat transfer fundamentals.

Using the TTCI as a formative assessment identifies strongly held student misconceptions, and the direct/emergent theories of Chi and her colleagues (Chi and Roscoe, 2002; Reiner, Slotta, Chi, and Resnick, 2000) give us important clues about why these misconceptions are robust. Next steps in our research include developing ways to help students repair their incorrect beliefs and creation of effective instructional materials that confront the most fundamental student misconceptions. Thus, the TTCI represents an important formative assessment tool to monitor the conceptual development of engineering students. A similar approach can be applied to any professional education program of study.

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Appendix A

Meltice Concept Question

You are in the business of melting ice at $0^{O}C$ using hot blocks of metal as an energy source. One option is to use <u>one</u> metal block at a temperature of $200^{O}C$ and a second option is to use <u>two</u> metal blocks each at a temperature of $100^{O}C$.

All the metal blocks are made from the same material and have the same weight and surface area.

(*MeltIce1*) Which option will melt more ice?

a. the 100 ^{O}C blocks

b. the 200 ^{O}C block

c. either option will melt the same amount of ice

d. can't tell from the information given

(*MeltIce2*) because:

e. 2 blocks have twice as much surface area as 1 block so the energy transfer rate will be higher when more blocks are used

f. energy transferred is proportional to the mass of blocks used and the change in block temperature during the process

g. using a higher temperature block will melt the ice faster because the larger temperature difference will increase the rate of energy transfer

h. the temperature of the hotter block will decrease faster as energy is transferred to the ice

i. the heat capacity of the metal is a function of temperature