FROM PRACTICE TO RESEARCH: USING PROFESSIONAL EXPERTISE TO INFORM RESEARCH ABOUT ENGINEERING STUDENTS' CONCEPTUAL UNDERSTANDING

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Abstract

This paper describes how practitioner input was used to inform three research projects that investigate students' understanding of important and difficult engineering concepts. Practitioner input was initially used to formulate lists of engineering concepts in thermal and transport sciences, electric circuits, and engineering mechanics that are important but difficult for undergraduate engineering students to understand. Content experts then used this input to create questions that probe students' understanding of the difficult concepts. Next, students were interviewed and asked to think aloud as they answered these conceptual questions. Practitioners subsequently reviewed the results of the think alouds as they created multiple choice questions for use in concept inventory assessment instruments. The results of the studies will ultimately be used to help practitioners repair student misconceptions. Thus a cycle of practice to research to practice is being created. Using this cycle has been very beneficial to our research and maps well to the principles outlined in *Learning that Lasts* (Mentkowski and Associates, 2000).

Introduction

The ability to solve problems is an important skill that engineering students must acquire during their undergraduate careers, but without an undergirding of conceptual understanding, flexible application of that knowledge is nearly impossible (Pellegrino, J.W., Chudowsky, N. & Glaser, R., 2001). Instead, students become proficient at retention "which involves responding to situations that are very similar, possibly identical to the original learning conditions" (Svinicki, 2004, p. 92), i.e., students learn to repeat procedures and solve problems just like those covered in class. Students may even be able to solve problems in a slightly different context than the original one, but when the context is very different, students are challenged to accomplish multiple tasks including problem identification and searching prior knowledge and concepts needed to help them solve the problem. In these situations, they may have difficulty solving problems if they do not possess the necessary deep understanding.

We believe that students' inability to develop profound understanding of some basic concepts may be attributed to fundamental misconceptions that they hold (Chi & Roscoe, 2002). For example, a significant number of engineering students describe heat as "a substance stored in hot objects" or contend that "molecular motion stops when equilibrium is reached." The literature suggests that often students' understanding is fragile (Shepard, 2001). Their knowledge is superficial and often riddled with misconceptions (Reiner, Slotta, Chi, & Resnick, 2000; Chi & Roscoe, 2002) that prevent the kind of deep understanding necessary to facilitate transfer.

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Chi and Roscoe (2002) stress that instructors must help students “repair” misconceptions before the students can hope to understand the underlying concepts which in turn make transfer possible. However, the ability of instructors to predict possible student misconceptions usually develops only after years of teaching experience. New instructors may not always be able to predict what topics a student will find difficult. Our projects (Developing an Outcomes Assessment Instrument for Identifying Engineering Student Misconceptions in Thermal and Transport Sciences [National Science Foundation DUE-0127806], and Center for the Advancement of Engineering Education [National Science Foundation ESI-0227558]) use the expertise of experienced instructors to help identify student misconceptions that hinder deep understanding. Our hope is that once these misconceptions are identified, even instructors with limited teaching experience may be able to help their students repair them.

The study described in this paper used practitioner input to inform three research projects that investigate students’ understanding of important and difficult engineering concepts. Practitioner input was initially used to formulate lists of engineering concepts in thermal and transport sciences, electric circuits, and engineering mechanics that are important but difficult for undergraduate engineering students to understand. Content experts then used this input to create questions that probe students’ understanding of the difficult concepts. Next, students were interviewed and asked to think aloud as they answered these conceptual questions. Practitioners subsequently reviewed the results of the think alouds as they created multiple choice questions for use in concept inventory assessment instruments. The results of the studies will ultimately be used to help practitioners repair student misconceptions. Thus a cycle of practice to research to practice is being created.

The objectives of this paper are to: (1) describe the theoretical framework for using practice (experts teaching in the field) to inform research, and (2) explain methodologies (in particular, Delphi surveys) that can be used to draw on professional expertise to inform research. Although we speak from the perspective of engineering education, our intent is to discuss methodologies that may be used in other professional fields.

Theoretical Framework

There are many ways in which educators approach improving their teaching in order to foster “learning that lasts” (Mentkowski and Associates, 2000). Far too often instructors encounter classes in which students just don’t seem to “get it.” In such classes, students’ learning is obviously superficial and clearly inadequate for addressing what faces them in their future careers. As they attempt to improve their teaching, instructors often begin with the research of others in their field for ideas.

Mentkowski et al. (2000) suggest that:

> Knowledge about learning and what kinds of education foster it can be built in several distinct yet overlapping ways: formal research, collaborative inquiry, and review of literature and practice in higher education. A fourth way is learning by educating--knowing that emerges from the continually changing context of educators’ experience and their constantly modified practice (p.30).

Our project reflects Mentkowski et al.'s (2000) support for an integration of all four approaches to studying ways to foster "learning that lasts." As described in detail later in the paper, we have tried to build our *formal research* on collaboration with content experts through use of the Delphi method (*collaborative inquiry*), and have relied on practitioners' expertise to create questions that probe engineering students' conceptual understanding.

We have grounded our work in educators' practice (*learning by educating).* From their extensive teaching experience (each expert taught a minimum of five years and most more than ten), our experts identified the concepts that we used in the next phase of our research. They generated the concepts and came to consensus on their importance and the degree of student understanding of those concepts. Once the concepts were identified, we examined existing educational literature on those concepts and reviewed textbook coverage of them (*review of literature and practice*). This was helpful in creating the questions that were used to probe students' understanding of these concepts. Thus our research cycled from practice to research to practice multiple times.

Method

Our research team has investigated student misconceptions in three fundamental areas of engineering: thermal and transport science (fluid mechanics, heat transfer, and thermodynamics - fundamental topics in chemical and mechanical engineering), engineering mechanics (topics such as statics, dynamics, and strength of materials – necessary for mechanical and civil Engineers), and engineering circuits (the entry course into electrical engineering).

We used a three-phase process to investigate students' understanding of these fundamental engineering topics. During the first phase, we used the Delphi method, asking practitioners to identify persistent misconceptions (Streveler, R.A., Olds, B.M., Miller, R. L. & Nelson, M.A., 2003). In the second phase, we took the concepts identified by practitioners as most important and least understood and created open-ended questions using student input and existing examples from the research literature (Olds, B.M., Streveler, R. A., Miller, R. L. & Nelson, M. A., 2004). In the third phase, used only with the thermal and transport science concepts, we developed multiple-choice questions based on student responses to the open-ended questions. The result was the Thermal and Transport Science Concept Inventory (TTCI), which we have since alpha and beta tested to ensure validity and reliability (Miller et al., 2005).

Participants

Practitioners

Practitioners were experienced engineering instructors and textbook authors in the fields of thermal and transport sciences, electric circuits, and engineering mechanics from over 50 universities in North America, Europe, and the Middle East. Some demographics for the practitioners in all three Delphi studies are summarized in Table 1.

Table 1. Delphi Practitioner Demographics

Delphi survey	Number of practitioners	Average number of years taught at college level	Number of textbook authors	Number of years worked in industry
Thermal and Transport Sciences	30	23	8	**
Circuits	10	19	1	2.9
Mechanics	13	17	6	3.4

** This information was not requested in this Delphi study.

Students

Students participating in the think alouds for all three topics, and later in alpha/beta testing for the TTCI, were primarily undergraduate juniors and seniors from six universities across the United States whose majors included: chemical engineering, electrical engineering, mechanical engineering, and civil engineering.

Procedure

We used the Delphi method for all three topical areas. The procedures described below were the same for all three studies, unless otherwise noted. The method will be described in general in this section. In the results section, examples will be from the Thermal and Transport Science Delphi since it has been carried through all three phases.

Phase One: Identify Persistent Misconceptions

The Delphi method was used to obtain practitioners' expertise in identifying persistent student misconceptions. This method is a structured process that collects and distills knowledge from a group of experts by means of a series of questionnaires interspersed with controlled opinion feedback. The method takes its name from the Oracle at Delphi, an ancient Greek soothsayer able to predict the future, and was originally developed at the RAND Corporation by Dalkey and Helmer (1963) as a tool for forecasting likely inventions, new technologies and the social and economic impact of technological change (Adler & Ziglio, 1996).

Generative Round

We began by locating and identifying practitioners who would be willing to participate in each respective Delphi survey. These participants were experienced, practicing teachers. Their qualifications are discussed in the Results section. At the start of the Delphi, participants were asked to individually generate a list of what they considered the most important and least understood concepts in the study's topical area. We subsequently coded their answers and identified those concepts that were cited by at least two participants. These concepts were then used in Rounds One through Three.

Round One

The practitioners were given a list of all concepts mentioned at least twice in the

Generative Round. Two of the Delphi studies contained 28 concepts and the other contained 27. Each expert was asked to rate every concept on a scale of 1 to 10 for understanding (1 = students had no understanding of the concept; 10 = students have complete understanding) and 1 to 10 on importance (1 = the concept is not at all important; 10 = the concept is extremely important). The interquartile ranges (IQRs) and the medians were computed from those ratings for each concept on both understanding and importance scales

Round Two

Practitioners were then given the IQRs and the medians computed from Round One for each concept. They were asked to rate the concepts again, and were also asked to provide a written justification if their rating was outside the IQR computed in Round One.

Round Three

In the third round, the IQRs and medians calculated in Round Two were provided to the practitioners, along with any justifications of ratings outside the IQR. The experts were asked to rate each concept a third time, and a third set of IQRs and medians were computed. In this final round, practitioners were not required to justify ratings outside the interquartile ranges. Studies show that there is little movement of median or interquartile ranges after three iterations of a Delphi study (Linstone & Turoff, 1975).

Phase Two: From Concepts to Open-Ended Questions

Once the Delphi study was completed, we selected the concepts that were rated as most important and least understood. Scatter diagrams with "importance" on the horizontal axis and "understanding" on the vertical axis were created using the median results computed in Round Three. In the first Delphi (Thermal and Transport Sciences) a "cluster" of concepts emerged as being the most important and least understood. Those concepts represented by the points in the triangular cluster became the target concepts that eventually were developed into questions for the Thermal and Transport Sciences Concept Inventory (TTCI). The scatter diagrams for neither the Circuits nor the Engineering Mechanics Delphi survey produced a clear high importance/low understanding cluster. Though many concepts were rated as important, few were considered poorly understood.

Since the Delphi results for circuits and mechanics did not point clearly to concepts that warranted further study, we again sought out professional expertise. The research team hosted an interactive workshop (Miller, Streveler, Olds, and Nelson, 2004) at an engineering education conference. Workshop participants were invited to gather according to discipline (chemical, mechanical, or electrical engineering) and then examine and comment on the Delphi results that most closely matched their expertise. They were asked to consider whether, based on their expertise, the results made sense. We also requested that they report which topics they considered "most difficult" and "most important." Session attendees were allowed to agree or disagree with the numerical findings of the Delphi surveys. The results of this session were taken into consideration when determining concepts of interest for the Circuits and Engineering Mechanics studies.

For all three Delphi studies, once the lists of target concepts were agreed upon, content experts wrote specific questions for each concept. At this point, the respective experts either created questions themselves or used outside sources such as engineering textbooks, previously-developed concept inventories, or contributions from engineering faculty around the country. The result of this phase of the research was a list of open-ended questions.

Phase Three: Open-Ended Questions to Multiple Choice Questions.

Engineering students were invited to participate in the research by answering the open-ended questions generated in Phase Two. The think aloud method was used (van Someren, Barnard, Sandberg, 1994) to discover students' mental models of the target concepts. The think aloud sessions were taped, transcribed, and coded.

The Thermal and Transport Science portion of the research was taken a step further. The goal was to create the Thermal and Transport Sciences Concept Inventory (TTCI) similar to the Force Concept Inventory (Hestenes,D., Wells, M. & Swackhamer, G., 1992). During the coding of the think aloud data, some common misconceptions emerged (Olds, et al., 2004). Using student explanations, we were able to develop "believable" distractors for the TTCI that correspond to common student misconceptions. Other distractors were taken from a review of literature. One multiple-choice question was written for each concept and alpha tested at Colorado School of Mines. Later two or more additional TTCI questions were developed for each concept, and think alouds were again used to uncover common misconceptions to use as distractors.

Once the open-ended questions were turned into multiple-choice questions, we began beta testing the TTCI at five universities. Beta testing typically involves a wider audience to help test for external validity. Some of our results are explained below. When our instrument is proven to be valid and reliable, we will disseminate it widely in the hope that engineering instructors will use the results to identify the most common misconceptions held by their students. Our assumption is that if instructors know where student thinking is errant, they will be better able to help students repair those misconceptions, thus completing the cycle from practice to research and back to practice.

Results

In this section, we give specific examples of what was found in each step of the practice to research process. Since only the thermal and transport science (heat transfer, thermodynamics, and fluid mechanics) study involved all three phases, examples from that study are provided.

Phase One: Identify Persistent Misconceptions

In the Generative Round of each Delphi study, practitioners created lists of engineering concepts that were considered most important and least understood. Individuals' lists ranged from two to nineteen concepts. To illustrate the types of comments we received, Table 2 presents the comments of practitioners in Delphi One related to concepts of temperature, heat, and heat transfer.

Table 2. Delphi One – Examples of Generative Round Comments Related to Heat

"Confusion between temperature and heat transfer. Many students believe that if the path to a

state involves a heat transfer input the temperature of the system will increase – even if the heat transfer is coupled with work leaving the system.”
“Students do not appear to have precise understanding of heat in the sense that it is used in thermodynamics.”
“Students have difficulty identifying heat and work interactions between the system and the surroundings.”
[Students] “have trouble with work and energy relationships.”
“There is always student confusion about heat vs. internal energy.”
“There is always student confusion about internal energy and enthalpy.”
“Misconception: Temperature is a measure of energy. Example: Students often believe that if you add energy, heat for example, to any system, the temperature must go up. A corollary to this is that students often believe that if the temperature goes up the energy (internal energy or enthalpy) must have increased. A good example of a system that is very confusing is an evaporative cooling process in psychrometrics where the enthalpy of the moist air stays constant but the temperature decreases.”
“Heat, like energy, is a familiar term but its common use differs from thermodynamic definition.
“Heat as transferred energy. No matter how often you make the point, some [students] insist on talking about the heat content of a system.”
“Confusion about the difference between heat and temperature. How can a process occur where heat is added but the temperature drops?”

Each Delphi participant’s comments were coded and our content expert distilled the codes into 28 concepts. These concepts were then used for Rounds 1, 2 and 3 of the Delphi study where interquartile ranges (IQRs) and medians were computed. As Linstone and Turoff (1975) suggested, the median and interquartile ranges in all of our Delphis stabilized after three iterations. Table 3 displays the IQRs and medians from Delphi One. The table demonstrates that both the importance and understanding ratings stabilized after only two rounds.

TABLE 3: Results of Thermal and Transport Concepts Delphi One Study (*Italicized* concepts refer to low understanding/high importance rankings.)

CONCEPT	Understanding Data Median (interquartile range)			Importance Data Median (interquartile range)		
	Round 1	Round 2	Round 3	Round 1	Round 2	Round 3

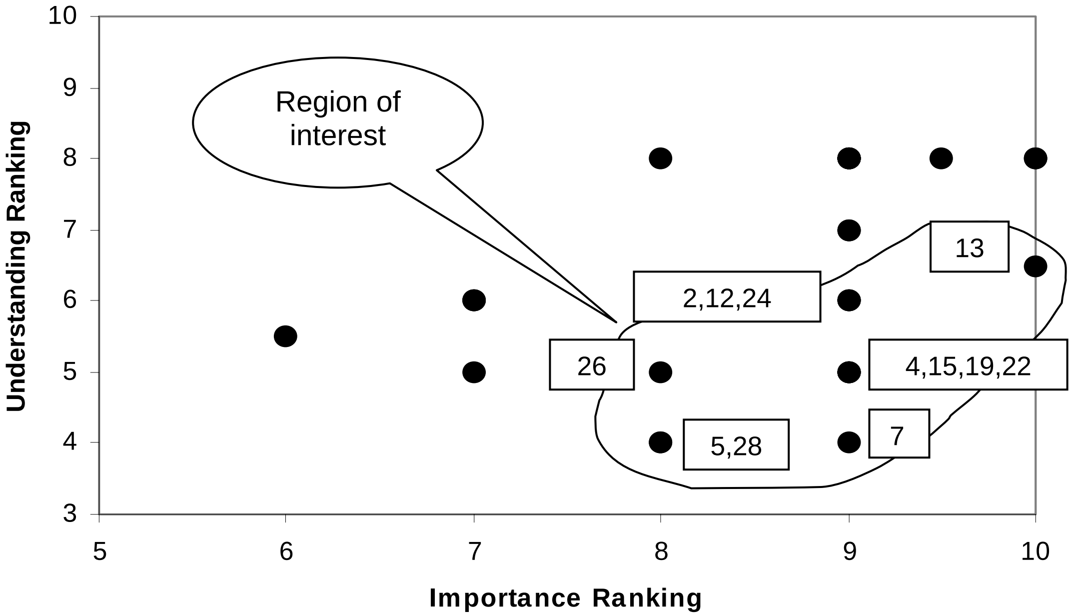
1.Adiabatic vs. Isothermal Processes	7.5 (6-8)	8 (6-8)	8(6.75-8.25)	9 (8-10)	9 (9-10)	9 (9-10)
2.Bernoulli Equation	7 (4-8)	6 (5-7)	6 (5-7)	9 (7-10)	9 (8-9)	9 (8-9)
3. Compressible vs. Incompressible Flow	5 (3-7)	6 (4-6.5)	6 (5-7)	7.5 (6-8)	7 (7-8)	7.5 (7-8)
4. Conservation of Linear Momentum	5 (3-6)	5 (4-6)	5.5 (5-6)	9 (8-10)	9 (8-10)	9(8-9.25)
5. Differential vs. Integral Analysis	4.5 (3-6)	4 (3-5.25)	4 (4-5)	7 (6-9)	8 (6-8)	8 (7-9)
6. Dimensional Analysis	6 (4-7)	5.5 (4.25-7)	6 (5-6.25)	7 (5-7)	6 (5-8)	7 (5-8)
7. Entropy & 2nd Law of Thermodynamics	4 (2-6)	4 (3-5)	5 (3-5.25)	8 (7-9)	9 (8-9)	9 (8-10)
8. Extensive and Intensive Properties	8 (6-9)	8 (7-8)	8 (7-9)	7 (6-9)	8 (7-9)	8 (7-9)
9. First Law of Thermodynamics	8 (7-9)	8 (7-9)	8 (8-9)	10 (10-10)	10 (10-10)	10 (10-10)
10. Fluid vs. Flow Properties	7 (5-8)	6 (5-7)	6 (5-6)	7 (5-9)	7 (5-8)	7 (5-8)
11. Heat Transfer Modes	8 (6-9)	8 (6.25-8)	8 (7-9)	9 (8-10)	9 (9-10)	9 (9-10)
12. Heat vs. Energy	6 (5-8)	6 (5-7)	6.5 (5-7)	9 (8-10)	9 (8-10)	9 (8-10)
13. Heat vs. Temperature	6 (4-8)	6.5 (5-8)	7 (6-8)	9 (8-10)	10 (9-10)	10 (9-10)
14. Ideal Gas Law	8 (7-9)	8 (8-9)	8 (8-9)	9 (8-10)	9 (9-10)	9 (9-10)
15. Internal Energy vs. Enthalpy	6 (3-7)	5 (4-6)	6 (5-6.25)	8 (7-9)	9 (8-9)	9 (8-9)
16. No-slip Boundary Conditions	8 (6-9)	8 (7-9)	8 (8-9)	8 (7-9)	9 (8-9)	9 (8-9)
17. Nozzles and Diffusers	6 (5-8)	6 (6-7.5)	7 (6-7)	7 (5-9)	7 (6-8)	7 (6-8)
18. Pressure	8 (6-9)	8 (7-8)	8 (7.75-9)	9 (8-10)	10 (9-10)	10(9.75-10)
19. Reversible vs. Irreversible Processes	5 (4-7)	5 (4-6)	5 (5-6)	8 (8-9)	9 (8-9)	9 (8-9)
20. Spatial Gradient of a Function	4 (3-7)	5 (4-6)	5 (4-5)	7 (3-9)	7 (6-8)	7 (6-8)
21. Specific Heat Capacity	7 (6-8)	7 (6-7)	7 (6-8)	8 (7-10)	9 (8-9)	9 (8-9)
22. Steady-state vs. Equilibrium Process	5 (3-8)	5 (3-6)	5 (4-5.25)	8 (5-10)	9 (7-9)	9 (8-9)
23. Steady-state vs. Unsteady-state Process	8 (7-8)	8 (7-8)	8 (7-8)	9 (8-10)	9.5 (9-10)	9.5 (9-10)
24. System vs. Control Volume	7 (4-8)	6 (5-7)	6 (6-7)	8 (6-10)	9 (8-10)	9 (8.5-10)
25. Temperature Scales	7 (5-9)	8 (8-9)	9 (8-9)	8 (6-10)	9 (8-10)	9 (9-10)
26. Thermal Radiation	6 (4-8)	5 (5-6)	5 (5-6)	7 (5-9)	8 (6.75-8)	8 (7-8.25)
27. Thermodynamic Cycles	7 (5-8)	7 (6-7)	7 (7-8)	8 (8-10)	9 (8-10)	9 (8-9.25)
28. Viscous Momentum Flux	5 (3-7)	4 (3.75-5)	4 (3-4)	7.5 (6-9)	8 (7-8)	7 (7-8)

Understanding Scale	**Importance Scale**
0 = no one understands the concept	0 = not at all important to understand the concept
10 = everyone understands the concept	10 = extremely important to understand the concept

Phase Two: From Concepts to Open-Ended Questions.

In order to identify the concepts with the lowest understanding and the highest importance rankings, a scatter diagram was created. Figure 1 shows the scatter diagram for Delphi One based on median rankings.

Figure 1: Scatter diagram of the medians of concepts in Delphi One



1. Adiabatic vs. Isothermal Processes
2. *Bernoulli Equation*
3. Compressible vs. Incompressible Flow
4. *Conservation of Linear Momentum*
5. *Differential vs. Integral Analysis*
6. Dimensional Analysis
7. *Entropy & 2nd Law of Thermodynamics*
8. Extensive and Intensive Properties
9. First Law of Thermodynamics
10. Fluid vs. Flow Properties
11. Heat Transfer Modes
12. *Heat vs. Energy*
13. *Heat vs. Temperature*
14. Ideal Gas Law
15. *Internal Energy vs. Enthalpy*
16. No-slip Boundary Conditions
17. Nozzles and Diffusers
18. Pressure
19. *Reversible vs. Irreversible Processes*
20. Spatial Gradient of a Function
21. Specific Heat Capacity
22. *Steady-state vs. Equilibrium Process*
23. Steady-state vs. Unsteady-state Process
24. *System vs. Control Volume*
25. Temperature Scales
26. *Thermal Radiation*
27. Thermodynamic Cycles
28. *Viscous Momentum Flux*

The scatter diagram allowed us to identify those concepts that practitioners ranked as most important and least understood. Their practice thereby informed the research that followed. Once these concepts were identified, open-ended questions for each were written by the engineering content experts. For example, rate of heat transfer was one concept from Delphi One that the practitioners identified as having high importance with little understanding. Working with the comments made in the Generative Round of Delphi One (see Table 2), the research group developed an open-ended question, which has been labeled the “SWIM” question: “If 20 degrees C (68 degrees F) air feels warm on our skin, why does 20 degrees C (68 degrees F) water feel cool when we swim in it?”

Third Phase: Open-Ended Questions to Multiple Choice Questions.

When engineering students were asked the open-ended SWIM question during the think aloud sessions, specific responses became the bases for the multiple-choice distractors used in the alpha testing, as shown in Table 4. In this case, a little rephrasing helped to create the actual distractor used in the multiple-choice version. The entire SWIM question is found in Appendix A.

TABLE 4: Question – Response – Distractor for "SWIM" Question

QUESTION If 20 degrees C (68 degrees F) air feels warm on our skin, why does 20 degrees C water feel cool when we swim in it?	
Student think aloud response	**Distractor used in beta (alpha?) testing**
the difference "would be opening of your pores and exposing even more of your skin…to the actual cold water"	"Water opens pores in human skin better than air does, so the heat transfer area is larger with water."

Think aloud sessions confirmed the "understanding" predictions of the Delphi experts. The majority of students participating in think alouds demonstrated limited understanding of the concepts being addressed. The think alouds also provided possible distractors for the multiple choice version of the test, and identified problems in unclear labeling of diagrams or ambiguous wording of questions.

The input from our Delphi participants together with the responses of our students in think alouds resulted in the alpha version of the TTCI which addressed ten basic concepts. Alpha results identified some common student misconceptions and helped us find some distractors that had never been chosen and thus needed to be replaced. With these results in mind, our thermal and transport expert modified the alpha questions and also created two additional questions for each concept. The new questions were the basis of a further round of think alouds and were similarly converted to multiple choice questions used in the beta version of our concept inventory, which was tested on one hundred students at five universities.

We are currently analyzing the results from the beta testing in order to identify any common heat transfer misconceptions that students might hold. A question that we named "HOTPLATE" (see Appendix B) addresses the same basic concept as the SWIM question. A cross tabulation table of the results of these two questions (Table 5) demonstrates that 30% of students correctly understand the concept (HOTPLATE answer A and SWIM answer C). Ten percent of students incorrectly answered both questions with the combination of HOTPLATE "e" and SWIM "a" or "b". These students apparently fail to understand the mechanism of energy storage in a system. Recognizing that some students have this fundamental misconception may inform educators' practice, enabling them to better scaffold student learning when addressing this concept.

Table 5: Crosstabulation Results[1] of HOTPLATE and SWIM

	SWIM				Total
	a	b	C	d	

HOTPLATE	a	5	5	30	3	43
	b	0	0	1	0	1
	c	4	2	11	1	18
	d	2	1	8	1	12
	e	5	5	15	0	25
Total		16	13	65	5	99

[1]Shaded row and column represent correct responses to questions

Conclusions and Implications for Further Research

We agree with Mentkowski et al. (2000) that starting our studies with practitioner input is an effective way to ground educational research. We called on the wisdom of research literature and relied heavily on collaboration with engineering faculty. Our Thermal and Transport Science Concept Inventory (TTCI) evolved from the concepts that our Delphi participants identified as important but poorly understood. Student interviews, focus groups, alpha and beta testing all confirmed the experts' opinions that these concepts are not well understood even by students nearing college graduation. Beta testing has enabled us to identify common misconceptions that need to be addressed. Hopefully, when we finalize the TTCI, it will represent the most important concepts in thermal sciences validated by students and instructors alike.

Our work in circuits and engineering mechanics, although not resulting in the creation of a concept inventory, will shed light on the mental models students use to understand, or misunderstand, fundamental concepts in electrical and mechanical engineering. The content experts who created the open-ended questions for these studies have reported that their involvement in the study has changed the way they teach, even though each has over 20 years of experience teaching engineering undergraduates. Thus we are seeing practice to research to practice cycle already occurring.

Our next step is to determine ways to repair robust misunderstandings in these fields so that students can develop deep understanding of the most basic concepts in engineering. We will continue incorporating professional expertise into our research as we continue to investigate engineering students' understanding of important and difficult engineering concepts. Thus we will continue to be part of the practice to research to practice cycle.

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Appendix A: SWIM Question

If 20° C (68° F) feels warm on our skin, why does 20°C water feel cool when we swim in it?

a. When water contacts human skin, it vaporizes at the surface which causes the water to feel cooler than air.

b. Water holds energy better than air does, so air feels warmer since it is transferring energy faster.

c. The heat transfer rate in water is faster than the rate in air because of differences in fluid physical properties.

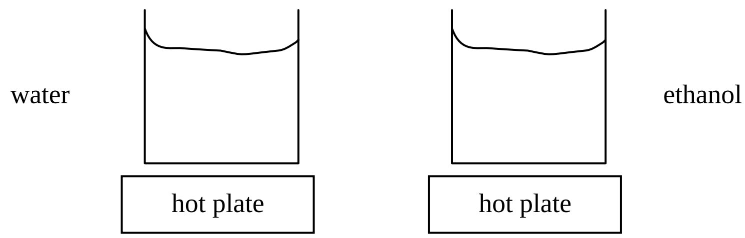
d. Water opens pores in human skin better than air does, so the heat transfer area is larger with water.

Correct answer: C

Appendix B: HOTPLATE Question

Two identical beakers contain equal masses of liquid at a temperature of 20 ^{O}C as shown below. One beaker is filled with water and the other beaker is filled with ethanol (ethyl alcohol). The temperature of each liquid is increased from 20 ^{O}C to 40 ^{O}C using identical hot plates.

It takes 2 minutes for the ethanol temperature to reach 40 ^{O}C and 3 minutes for the water to reach 40 ^{O}C. Once a liquid has reached 40 ^{O}C, its hot plate is turned off.



To which liquid was more energy transferred during the heating process?

a. Water because more energy is transferred to the liquid that is heated longer.

b. Alcohol because more energy is transferred to the liquid that heats up faster (temperature rises faster).

c. Both liquids received the same amount of energy because they started at the same initial temperature and ended at the same final temperature.

d. Can't determine from the information given because heat transfer coefficients for water and ethanol are needed.

e. Can't determine from the information given because heat capacities of water and ethanol are needed.

Correct Answer: A