Learning Conceptual Knowledge in the Engineering Sciences: Overview and Future Research Directions

RUTH A. STREVELER  
School of Engineering Education  
Purdue University

THOMAS A. LITZINGER  
Department of Mechanical Engineering  
Pennsylvania State University

RONALD L. MILLER  
Department of Chemical Engineering  
Colorado School of Mines

PAUL S. STEIF  
Department of Mechanical Engineering  
Carnegie-Mellon University

ABSTRACT

Learning conceptual knowledge in engineering science is a critical element in the development of competence and expertise in engineering. To date, however, research on conceptual learning in engineering science has been limited. Therefore, this article draws heavily on fundamental research by cognitive psychologists and applied research by science educators to provide a background on fundamental issues in the field and methods for assessing conceptual knowledge. Some of the most common conceptual difficulties from three domains: mechanics, thermal science and direct current electricity, are discussed to provide concrete examples of what students find difficult to learn. The article concludes with a discussion of possible sources of these difficulties, implications for instruction, and suggestions for future research.

Keywords: conceptual change, conceptual knowledge, student understanding

I. INTRODUCTION

Most fundamentally, concepts function as organizers. They carve up the world we already see and posit the unseen or even the unseeable. They sort things into plants and animals, living and dead, art nouveau and art deco, democratic and autocratic governments, the deductive and the inductive, velocity and mass and momentum (David Perkins, 2006, p. 41).

Concepts, as so eloquently described above by psychologist David Perkins, play a crucial role in how we make sense of the world. Not only do they allow us to categorize our physical surroundings but they also impact what we do with what we have categorized. Rittle-Johnson (2006, p. 2) offers a definition of conceptual knowledge that complements the definition of Perkins: “understanding of principles governing a domain and the interrelations between units of knowledge in a domain.” This definition makes clear that quantities such as force or heat, as well as relationships such as Newton’s laws and the laws of thermodynamics, are part of conceptual knowledge in the engineering domain.

According to Alexander’s model of domain learning, which describes the development of expertise through formal education, the development of “subject-matter knowledge … coherently organized around key domain concepts and principles” (in other words, the development of conceptual knowledge) is one of the key processes as a learner grows in competence within a domain (Alexander and Murphy, 1999, p. 566). In How People Learn, Bransford et al. (1999, p. 44) note that experts organize their knowledge around key concepts or ‘big ideas’ and that helping students acquire conceptual knowledge can also help students acquire more expert-like knowledge structures. Bransford, et al. also point out that learning with understanding, which we take to include building conceptual knowledge, can enhance transfer of knowledge to new problems.

Rittle-Johnson et al. (2001) discuss possible mechanisms through which conceptual knowledge may enhance procedural knowledge and performance:

- Conceptual knowledge may help students identify key features of a problem based on deeper understanding of the domain, as opposed to surface characteristics, leading them to properly “encode” the problem and generate a successful solution.
- Conceptual knowledge may help students recognize errors in their problem-solving procedures.
- Conceptual knowledge may influence generation of novel procedures by helping students identify essential elements of correct procedures and also by helping them evaluate whether alternative procedures are worth trying.

Redish and Smith (2008) provide an excellent example of the role of conceptual knowledge in problem solving. They describe a student who is trying to estimate the pressure difference between the floor and ceiling of a room. The student fails to engage key conceptual knowledge to determine the deep features of a problem and ultimately fails to solve the problem accurately.

The work of Sheppard et al. (2006) to define engineering practice gives a slightly different perspective on the importance of conceptual knowledge in engineering. Their work suggests that engineering practice may be thought of as consisting of three components:
II. PREVIOUS WORK ON CONCEPTUAL KNOWLEDGE

A. Fundamental Studies

The acquisition of concepts has long been a topic of study in psychology. At the most basic level, this research has focused on how children first acquire concepts, which are defined as categories characterized by attributes, e.g., the concept of a dog or a book; Vygotsky and Kozulin (1986) referred to these as “spontaneous” concepts that arise in the normal course of development. Although much is still not understood about the acquisition of conceptual knowledge, some psychological principles are now widely accepted. For example, knowledge is constructed by the individual (and by the community) from knowledge gained by prior experience.

The fundamental psychology studies of concept acquisition have been expanded to include the development of higher order concepts and conceptual knowledge derived through scientific endeavors, what Vygotsky called “scientific concepts through formal education” (Vygotsky and Kozulin, 1986). Issues addressed in this literature include the basic organization of students’ conceptual knowledge and explanations about why some misconceptions tend to be more difficult to correct than others. The literature on conceptual knowledge and conceptual change is very extensive and the theories involved are diverse and still evolving. diSessa et al. (2004, p. 844) wrote that “a huge diversity of views reigns concerning the entities and processes of conceptual change” Given the diversity and scope of this literature, we will summarize only a few research themes that seem most relevant to the focus of this paper.

One of the main issues in the psychology literature on conceptual knowledge is whether the students’ knowledge is organized in a coherent structure or whether it is fragmented. In the early work on acquisition of conceptual knowledge related to force and motion, McCloskey (1996) postulated that students’ conceptual knowledge, even when it is incorrect, is “theory-like” in that it is well organized and applied consistently. In particular he found evidence that students were using a pre-Newtonian model akin to impetus theory in thinking about force and motion. Subsequent research has called this view into question, but it still appears in the literature. Carey (1999) and Gopnik and Wellman (1994) also have reported research supporting the view that students’ conceptual knowledge is theory-like.

Other researchers advocate an opposing view, namely that students’ knowledge is not coherent or theory-like. Minstrell and colleagues (e.g., Hunt and Minstrell, 1994; Minstrell et al., 1992; Minstrell and Stimpson, 1996) have identified relatively independent explanatory facts, “facets,” that students use to explain phenomena, some of which are correct and others of which are incorrect. diSessa (1988) advocates a similar view that students’ knowledge is fragmented and “in pieces” and that it is not applied consistently in different contexts. Redish and Smith (2008) discuss the “context dependence” of student knowledge, which is consistent with the “knowledge in pieces” view.

These competing models describing the organizational nature of students’ native conceptual knowledge have different implications for informing the selection of instructional methods that would be most effective in helping students build correct and coherent bodies of conceptual knowledge. The implications of the two models for instruction have, however, received only limited attention in the literature. diSessa et al. (2004) discuss this topic briefly, noting that if students’ knowledge is coherent then instructional approaches that focus on comparison of a few models, including the correct one, may be an appropriate approach. The fragmented knowledge model would suggest that instructional methods must allow for substantial individual differences among students, so focusing on only a few competing models may not be the best instructional approach.

Another important theme in the literature on conceptual change focuses on why errors in students’ conceptual knowledge are difficult to correct. Work by Reiner et al. (2000) explored reasons why four basic conceptual quantities important in engineering, force, heat, electric current, and light, have been found to be the source of “robust misconceptions” among students. For all of these concepts, Reiner et al. noted that students tend to have a “substance-based” model, e.g., they view electric current as a fluid that flows through wires as if they were pipes. They also postulate that as students try to make sense of these concepts that they do so by forming analogies to their experiences with physical substances for which they are already familiar. The links to models that students feel are valid based on their experience may be a contributing factor in making the faulty conceptual knowledge related to force, heat, current, and light difficult to correct.
More recent work by Chi (2005) has developed an alternative argument for why some misconceptions are more robust than others. She posits that there are two classes of phenomena: “direct” and “emergent”. Direct phenomena are those in which causal connections are readily observable and in which the components involved have clear functions, e.g., the pumping of blood through the cardiovascular system. In emergent processes the observed phenomena are not directly caused by the underlying physical processes, but rather emerge indirectly from them. For example, in molecular diffusion, random molecular motion results in a net transfer of chemical species directly from them. For example, in molecular diffusion, random molecular motion results in a net transfer of chemical species from regions of high concentration to regions of lower concentration even though individual molecules move randomly in all directions. Chi argues that the concepts that are most difficult to learn are often emergent processes which people misattribute to direct causation. In the example of molecular diffusion, the concentration gradient is often thought to be the cause of the diffusion, when in reality, observable diffusion patterns emerge from random molecular motion, which is not observable. Chi’s work provides a useful perspective for trying to identify why some concepts are more difficult than others for students to learn and may also suggest areas where one might find commonalities between misconceptions in a variety of fields of engineering science. Her theory may have particular relevance in engineering applications which occur at small length scales such as nanotechnology for which the dynamics may be complex and are not directly observable.

B. Applied Research

In addition to the fundamental research on conceptual knowledge, a great deal of applied work has been conducted. The work can be broadly divided into two categories: investigating the effects of instruction on conceptual knowledge and developing methods to assess conceptual knowledge.

The literature on the role of instruction in the construction of accurate conceptual knowledge by students is truly vast. Duit’s Web site, “Science Teachers’ and Students’ Conceptions and Science Education,” contains a bibliography of over 7,700 articles on the acquisition of conceptual knowledge in a wide range of domains from biology and chemistry to physics and astronomy (Duit, 2007). Among this large set of studies, the work best known to the engineering community is that of Hestenes, Wells, and Swackhamer (1992) on conceptual learning related to force and motion; an outcome of their work was the development of the Force Concept Inventory (FCI), an instrument designed to assess students’ understanding of the Newtonian conception of force and motion. Hake (1998) assembled a large database of test results from the FCI that demonstrated two important trends: traditional teaching methods, based on lecture and homework, did not lead to substantial improvements in Newtonian thinking as measured by the FCI, and interactive engagement generated much more substantial learning gains on the FCI. These results were highly influential in motivating the work being done within the engineering education community to develop concept inventories over a wide range of domains from thermodynamics to material science (Allen, 2006; Evans et al., 2003; Hestenes, Wells, and Swackhamer, 1992; Miller et al., 2005; Miller et al., 2006; Nelson et al., 2006; Olds et al., 2004; Reed-Rhoads et al., 2007; Steif and Dantzer, 2005; Steif and Hansen, 2006; Streveler et al., 2003; Wage et al., 2005).

Concept inventories are one of many methods that can be used to assess conceptual knowledge and represent a method aimed at rapid assessment. At the other end of the spectrum of efforts to gauge conceptual knowledge are research-oriented, in-depth studies of small groups of students, which explore prevalent patterns of thought or mental models of phenomena. In the remainder of this section, we discuss a range of such methods and want to emphasize that each has a potential role to play in the process of conducting research and/or designing assessment and instruction.

Some approaches are aimed at inferring mental models by observing students engaged in mental activities. Only a finite set of students (often a small number) are observed; yet we seek to form a picture that fairly represents a larger group of individuals. This is a reasonable enterprise, as articulated, for example, by the proponents of phenomenography, who refer to “a limited number of distinctively different ways of understanding…” (Marton, 1994, p. 4424). The great majority of students could be viewed as having, at most, a small number of distinct mental models of a given phenomenon.

Mental activities of interest can vary from those needed to solve numerical problems in which proficiency may be the goal to activities involving physical situations or problems devised to probe a student’s conceptual knowledge. Data could include the transcript of thorough questioning of the student who is asked to explain his or her thinking, to the string of utterances when a student is asked to “think aloud,” to just the work-product itself. Differences between observational methods reside partly in the degree to which the observations disturb the natural course of carrying out the task.

The classic method of this type, that is a mainstay of work in cognitive psychology, is to have a subject think aloud while engaged in a task, such as solving a problem, which could be carried out entirely alone. Subjects are not asked nor expected to explain why they are doing what they are doing, but rather to say aloud what is running through their minds at that instant. The concurrent verbal protocol, which is believed to open a window into rapidly changing contents of an individual’s working memory, is recorded for later analysis along with the work-product. It is believed that this method does not disturb naturally carrying out the task (Ericsson and Simon, 1993).

In physics education research, it is common to gain insight into conceptual knowledge by showing the student a physical situation and asking what will happen and why. In such a “demonstration interview” (McDermott, 1984) additional follow up questions are common. The entire interview is recorded for later analysis. This approach is similar to that taken in phenomenography, which has been applied to physics and engineering among other subjects (Baillie, Emanuelsson, and Marton, 2001; Bowden et al., 1992). The goal in phenomenography is to understand how people experience, perceive, apprehend, and conceptualize phenomena in the world (Creswell, 1998). Unlike the problem solving task, a critical part of the protocol is the follow-up questioning, which would not occur without interaction with the questioner. Thus, the observation process itself clearly alters the course of the subject’s thinking. In addition, unlike the concurrent verbal protocol taken from a problem solving task, the subjects are specifically asked to explain their thinking, which provides additional information, but also undoubtedly alters their thinking. As an alternative to contemplating a physical situation, exam problems or conceptual questions could be posed to students, who are then questioned on the solution process (Streveler et al., 2006a, 2006b). In any event, the outcome of such a
process should be a description of the different mental models, or ways of conceiving, that students have of the phenomena under consideration.

Another method, which can be more efficient although admittedly less probing, is to ask each student to answer a question, for example one that is conceptual in nature, by submitting a written explanation (Newcomer and Steif, 2008). While this is less probing, it does not involve the observer interacting with the subjects' thought processes. On the other hand, subjects are asked to be reflective; they are not merely doing something, but thinking about their reasons. This method can be made efficient by taking advantage of electronic submission via classroom management systems. It might be viewed as an intermediate methodology: it does not include the repeated probing of the purely research studies based on oral demonstration interviews of a few students, but it is much more probing than close-ended assessment methods described below.

To the extent that students' conceptual difficulties have been uncovered for a particular topic or phenomenon, an instructor may wish to determine whether those models are prevalent among his or her own students. One formal approach would be to administer an assessment which is specifically designed to measure student conceptual knowledge. Ideally, such an instrument would have been carefully devised with the relevant student models in mind (to provide appropriate distracting wrong answers) and subjected to psychometric evaluation to determine validity and reliability of the measurements. Some assessment instruments designed to measure conceptual knowledge are referred to as concept inventories, which derive their name from the Force Concept Inventory. There have been efforts to develop concept inventories in many engineering subjects (Allen, 2006; Evans et al., 2003) with different inventories having undergone varying degrees of development and beta testing.

Often, concept inventories are used to assess conceptual knowledge at the end of a course; while students taking the test may not benefit directly, a reflective instructor's subsequent students might benefit from the results of that test as he or she revises the course to address common misconceptions. A concept inventory that focuses on prerequisite material could be taken by a class at the beginning of a term, and the instructor might seek to provide remedial instruction, if deemed appropriate.

A less formal, but also widely-used approach is in-class assessment, in which students in class contemplate multiple choice concept questions. This approach was popularized by Eric Mazur (1997), who developed this approach for his physics class in response to relatively poor performance on the Force Concept Inventory. Consideration of questions could be handled in various ways, for example, with students voting on the answers (with colored cards, or electronic "clickers"), followed by discussion between peers and, possibly, re-voting. An important element of this approach is making clear to individual students whether the answers they chose were correct (providing feedback to students). The instructor should also be clear as to whether the class as a whole had difficulty in answering each question, and what alternative answers they preferred (providing feedback to the instructor). There should also be opportunities for discussion (between peers and/or in the class as a whole) to rectify misconceptions.

There are trade-offs with all of the above approaches that provide a window into students' thought process: the demands for explanation and additional questioning might reveal more, but we may disturb the normal thought process more. There is also a trade-off associated with asking students to explain their answer to a question that is posed in an open-ended fashion instead asking them to explain their choice among a finite set of answers (e.g., as a multiple choice question). By giving the multiple choice options, one might divert the student from the more natural process and potentially fail to uncover the answer which the student was most inclined to give. But, if the task of considering each of the multiple answers is posed properly, student thinking on a wider range of possibilities may be revealed, including why a student Rejects certain answers.

Thus, the applied literature related to conceptual knowledge provides examples of multiple methods for assessing students' conceptual knowledge as well as many examples of attempts to improve conceptual knowledge via different modes of instruction. This literature, along with the fundamental research on conceptual knowledge, provides a solid foundation on which to build studies of conceptual knowledge in the engineering sciences.

### III. Examples of Difficult Concepts in Engineering Science

As noted in the discussion of fundamental research on conceptual knowledge, acquiring accurate understanding of foundational concepts such as force, heat, and electric current have been found to present substantial challenges to students. In this section we discuss examples of conceptual knowledge from the three related domains of engineering science, mechanics, thermal science, and electric circuits, to illustrate the types of difficulties that students encounter. For each of the three domains we look at student understanding of basic conceptual quantities as well as student understanding of relationships among those quantities.

#### A. Mechanics

Mechanics courses deal with bodies that are subjected to forces and may undergo motions. Students' first experiences of mechanics are in physics courses in high school or introductory university courses. These courses focus primarily on dynamics of a particle. Later, in engineering statics and dynamics, engineering students study the response of bodies of finite size, where one accounts for both rotational and translational motion. Still later, in strength of materials and fluid mechanics these students encounter bodies that can deform under the action of forces. The discussion here will focus mainly on particle dynamics, since many of the prime difficulties can already be seen there. We will briefly point out difficulties that arise in the more advanced mechanics courses. Consistent with the definition of concepts offered above, we consider in sequence the quantities of mechanics, followed by the principles that inter-relate them.

1) Student Understanding of Basic Quantities: The quantities of mechanics generally fall into one of three very broad types: motions, interactions (forces), and the relevant properties of materials or bodies. For particle dynamics, motion is described by displacement, velocity, and acceleration. These characterize the changes in position of the particle in question. Primary difficulties that students encounter with motion are:

- Interpreting the quantity given information about some physical situation (e.g., ascribing a value to the acceleration given information about position at different times (Reif and Allen, 1992)).
Distinguishing different descriptions of motions (e.g., confusing velocity and acceleration (Trowbridge and McDermott, 1980, 1981)).

By comparison with motions, the concept of force presents substantial challenges for students. Rather than simply describing something about a body (a particle), the force describes how two bodies interact with each other. With the exception of the gravitational force, interactions of interest in mechanics are associated with contacting bodies. Primary difficulties that students encounter with force are:

- Extending the concept of force to its full range of applicability.
- Accounting for the two-body nature of the force concept.

As an example of failing to fully extend the force concept, students generally believe that immovable, apparently rigid obstacles (tables, walls, surfaces guiding a body along some path) do not exert forces; rather such obstacles just “get in the way” (Halloun and Hestenes, 1985; Minstrell, 1982). Force, as understood by students, appears to require visible capability of action.

The two-body nature of force (that it is an interaction) is a very subtle idea, but it is essential to the scientific concept. One can see difficulties with this aspect, for example, when students analyze cords or springs. The tensile force is viewed as quantifying the state of the cord, rather than as quantifying the intensity with which neighboring parts of the cord, or the cord and an attached body, pull on each other (McDermott, Shaffer, and Somers, 1994). This can interfere with problem solving. One suspects that students would catch some errors of drawing forces on a body (free body diagrams) if they were always to ask whether each drawn force could be attributed to a contacting body (Steif, 2004).

Students also have difficulty with the quantitative aspect of force as a two-body interaction. Newton’s 3rd Law states that the forces between interacting bodies are equal in intensity and opposite in sense (e.g., each pushes or pulls on the other). One contrary, but common sense belief of students (Halloun and Hestenes, 1985), sometimes referred to as the dominance principle, is that the “stronger” (heavier, more active) body exerts a larger force on the “weaker” body than that of the “weaker” on the “stronger.” Students certainly have correct intuition regarding the fate of relatively massive and light bodies colliding. By comparison, the lighter body will have its motion more altered by the interaction (or be more damaged). The student who takes the massive body to exert a larger force is likely to be confounding the interaction with its effect. In the Newtonian force concept, the interaction, and its quantification, is carefully distinguished from the effect that interaction has on each body.

2) Student Understanding of Relationships Among the Basic Quantities: Although many important principles in mechanics are encapsulated by apparently simple equations, there are many facets of properly using such principles. We focus here on Newton’s 2nd Law, \( F = ma \), which in one form or another is found in all mechanics courses. In a correct implementation of this principle, one must choose some region of matter (of mass \( m \)) on which to apply the principle, recognize and correctly represent all the external forces acting on this mass, take the vector sum of these forces (denoted by \( F \)), and equate that sum to the mass (\( m \)) times the vector acceleration (denoted by \( a \)). In the context of particle dynamics, primary difficulties that students encounter with the principle relating force and motion are:

- Viewing the net force as related to acceleration (mistakenly relating it to velocity).
- Recognizing and representing all of the forces that act on the designated body (free body diagram), and combining them properly.

Perhaps the most widely cited misconception in mechanics pertains to the student belief that force is proportional to velocity (Clement, 1982). According to this belief, bodies are naturally at rest, and external exertion is necessary if they are in motion. Such a belief is not in the least surprising. Everyone has the experience of pushing an object along the floor, applying a force even to move it at constant speed. The obvious interpretation is that force causes velocity, and the body stops moving when no force is applied. Going beyond the obvious to the scientifically correct interpretation requires great care in acknowledging all forces acting on the object, including the retarding force of friction, and grasping that the relation we seek is that between motion and total force on the object. Not that this misconception is confined to such situations. Certainly, some students believe that a puck sliding on ice must feel some force (some impetus) that keeps it moving. But the prevalence of this belief is likely sustained by faulty use of the quantities and principles of mechanics when interpreting common situations.

The failure to combine forces properly (“concatenation of influences” in the FCI taxonomy (Halloun and Hestenes, 1985)) includes such misconceptions as believing that the largest force dictates the result of a combination of forces, or the last applied force (Halloun and Hestenes, 1985). The issue of how to combine forces begs the question: which forces should one combine? The free body diagram depicts the external forces acting on a chosen body, and therefore contains the forces to be combined. This difficulty of deciding what to combine is not articulated in the FCI taxonomy.

Although students surely draw incorrect free body diagrams in physics, perhaps such errors pale relative to the consequences of other misconceptions in particle dynamics. However, this difficulty becomes very significant in statics (Steif, 2004), particularly when one chooses to draw a free body diagram of a combination of bodies taken from a larger system.

As an example, the following question from the Statics Concept Inventory (Steif and Hansen, 2007) seeks to capture the difficulty of what forces to include. The student is shown the system in Figure 1, and asked to choose the correct free body diagram for the subsystem consisting of blocks 2 and 3 and cord D.

The answer choices are shown in Figure 2. The most commonly chosen incorrect answers are those which include internal forces, namely the tensions in the cords. It has been found that students choosing such answers believe they are following instruction stating that the free body diagram should include “all the forces.”

As students progress beyond physics into engineering, mechanics courses analyze additional, more complex variants of motions, forces, and their inter-relations that must be quantified. For example, in engineering statics and dynamics, quantities must be defined for rotational motion (angular rotation, velocity, and acceleration), and for interactions that produce rotational motion (variously referred to as couple or moment or torque in engineering). In fact, as a further complication, there is even an intermediate quantifier of the rotational effect of interactions (designated as the moment of the force in engineering, but as a torque in physics). In strength of materials, quantities are defined to characterize deformation, such as elongation and strain, which must be carefully distinguished from...
displacement. Making this distinction is a common difficulty of students, stemming perhaps from the exposure to springs in physics. There, coverage of the Spring Law, $F = kx$, probably fails to make clear that $x$ represents the displacement of the end of the spring only when the other end is fixed; more generally, $x$ is the elongation of the spring. Likewise, failure to properly interpret $F$ in the spring law as the internal force in a body causes many difficulties for students.

B. Thermal Science

Typical engineering curricula divide the study of thermal science into separate courses in fluid mechanics, heat transfer, and thermodynamics although some movement has been made in recent years to recombine these disciplines into unified thermal science courses or course sequences. While a significant number of misconceptions have been identified in all areas of thermal science, in this section we focus on misconceptions in basic quantities and key processes in heat transfer.

1) Student Understanding of Basic Quantities: Unlike mechanics, most students encounter little or no formal study of thermal science topics prior to college. However, they have received significant informal exposure to these topics, particularly energy and heat, in their daily lives and have constructed mental models (often robust and flawed) about how energy and temperature are...
related and how energy transformations impact their world. According to the misconception literature, thermal science presents a wide range of conceptual challenges for students at all educational levels including undergraduate engineering students (Erickson, 1985; Linn and Songer, 1991). In Duit’s (2007) massive bibliography of student misconceptions in science, we conservatively estimate that approximately 500–600 of the 7,700 articles included discuss some aspect of energy, heat transfer, or temperature. The confusion is wide-spread for all age groups and levels of education but seems to focus on the following five conceptual themes (Carlton, 2000; Thomaz et al., 1995):

- Heat and temperature are equivalent.
- Temperature determines how “cool” or “warm” a body feels.
- Heat is a substance transferred between bodies.
- Addition of energy as heat always increases the temperature in a body.
- Temperature should change in a phase transition (e.g., boiling) since energy is being added or removed.

Temperature and heat are viewed as being equivalent by a significant number of students at all grade levels (Arnold and Millar, 1996; Erickson, 1980; Krajcik, 1991; Linn and Songer, 1988). Many also believe that temperature is all that is required to quantify thermal energy without regard to physical state or thermal properties. When asked if 100 mL or 40 mL of liquid in beakers would lose more energy as they each cooled to room temperature, a common response was that both beakers lose the same amount of energy because the temperature change is the same (Krajcik, 1991). Few students responded that the larger quantity of liquid would lose more energy because it has a greater mass and therefore, had more internal energy stored at the beginning of the experiment. Similarly, gases and liquids at the same temperature are often assumed to possess the same amount of thermal energy.

Lewis and Linn (2003) report findings that suggest children and adults both rely upon intuitive concepts about the temperature of different substances based on how the materials feel. When asked the temperature of a metal spoon and wooden spoon, both of which sat in a 65°C oven for 2 hours, only about 20 percent of the respondents said the temperature of both spoons was 65°C. About 43 percent stated that the metal spoon was at a higher temperature because metal absorbs heat better than wood or that the metal spoon would feel hotter to the touch. In addition to equating energy and temperature, heat viewed as a substance is also a widely prevalent misconception (Arnold and Millar, 1996). For these students, heat is incorrectly conceived as a state quantity of a body, rather than a quantity transferred along a process path. Hewson and Hamlyn (1984) and Harris (1981) report that students’ substance-based conception of heat does not vary much from Lavoisier’s original caloric theory from the late eighteenth century. This mental model gives rise to the idea that warm substances contain less “cold” and more “hot” than cooler substances and that heat transfer occurs as a flow process much like water flowing in a pipe (i.e., the “substance-based” model proposed by Reiner et al., 2000). The idea that heat (cold) is a property of a substance naturally derives from a caloric model and allows students to explain why a metal spoon feels cooler than a wooden spoon when both are at the same temperature. This idea seems logical because it explains common experience but is scientifically incorrect according to the accepted theory of energy and heat.

2) Student Understanding of Relationships Among the Basic Quantities: As part of a recent project to develop concept questions in thermal and transport sciences for engineering students, Streveler et al. (2003) conducted a Delphi ranking study involving 30 experienced thermal science professors and textbook authors. Results of the study identified the following important conceptual distinctions in thermal science that significant numbers of engineering students do not understand, even after completing engineering coursework in thermal science:

- heat versus energy
- temperature versus energy
- steady-state versus equilibrium processes

This list aligns closely with the common misconceptions listed earlier in this section. For example, “heat versus energy” and “temperature versus energy” are distinctions that, if not well understood, can easily lead students to believe that “heat and temperature are equivalent” and that “temperature determines how ‘cool’ or ‘warm’ a body feels.” The misconceptions associated with steady-state versus thermal equilibrium processes cause confusion about how heat is transferred between bodies and how energy transfer is related (or not related) to temperature changes. Not understanding the difference between energy and temperature can lead students to believe that any transfer of energy into a body must increase temperature regardless of, for example, the presence or absence of a phase change or change in chemical composition.

Recent data collected during development of the Thermal and Transport Concept Inventory (TTCI) suggest that misconceptions identified in studies with younger students do not necessarily disappear during engineering education. For example, consider the item shown in Figure 3 which asks students to determine which of two fluids received the same amount of energy since temperature change was the same for each. Another 24 percent could not determine how the amount of energy added to each fluid was related to its heat capacity and temperature change.

Another common misconception cited is student confusion about thermal equilibrium. Clark and Jorde (2004) suggest that personal experiences in touching different materials contribute to the confusion, since materials (e.g., metal versus wood versus plastic) can feel “hotter” or “colder” even when students “know” that the materials are at the same temperature. Arnold and Millar (1996) showed that only 48 of 70 middle-school students who were studying heat transfer could explain that heat transfer occurs between hot and cold metal blocks in mechanical contact and that the blocks would all eventually reach the same temperature. A typical item to probe misconceptions in thermal equilibrium is shown in Figure 4 where only about 70 percent of students can correctly describe why a tile floor feels colder than carpet. Note that the distractors for this question describe convoluted and complicated explanations to what most engineering faculty would consider a fairly straightforward heat transfer process. The fact that significant numbers of senior-level engineering students choose these incorrect answers is an indication of robust misconceptions in thermal science formed early in students’ lives.

The concept of equilibrium is also often confused with rate processes. In a study of undergraduate chemistry students, Thomas
and Schwenz (1998) showed that students describe equilibrium in terms of rates and how quickly a system or process will approach equilibrium. When asked why an equilibrium constant for a chemical reaction is temperature dependent, several students described the effect of temperature on reaction rates as the determining factor.

Similar confusion about thermal equilibrium and processes operating at thermal steady-state was observed. As shown in Figure 5, about 17 percent of chemical and mechanical engineering seniors assessed thought that a heated pipe was in thermal equilibrium with cooler water within the pipe even though the item explicitly states...
that the water temperature is always lower than the pipe wall temperature. An additional 24 percent thought that the pipe control volume was not at steady-state even though the problem stated that the inlet temperature and pipe wall temperature were both uniform and constant. The most common explanations for these incorrect answers were: (1) steady-state could never be reached until the fluid exited the pipe in thermal equilibrium, and (2) the control volume could never come to steady-state while heat transfer occurred (i.e., a temperature gradient still existed between water and pipe wall). For these students, the nature of thermal equilibrium is not apparent and is being commingled with processes for which a net rate of heat transfer is time invariant. Chi (2005) has described clinical studies in which students describe processes at equilibrium as “stopping” and do not consider the dynamic nature of equilibrium processes such as mass diffusion and heat conduction at the molecular level.

An additional misconception involving heat transfer rates has been identified as a result of TTCI development and pilot testing. In this case, the misconception involves a misunderstanding of the relationship between heat transfer rate and the amount of energy transferred. A typical item designed to probe the concept is shown in Figure 6, where students are asked which form of ice (shaved ice chips or large ice cubes) should be used to cool a soft drink to a lower temperature. As the figure indicates, over 45 percent of the students incorrectly answered “ice chips” (Miller et al., 2006). Data collected with a similar item reported by Prince et al. suggested that 25 percent of chemical engineering students in a heat transfer class also assumed more cooling would occur with ice chips (Prince and Vigeant, 2006). The most common reason given was that ice chips had more surface area and would therefore cool the drink faster. While true, this was not the question asked and the results indicate confusion about the rate of cooling versus the eventual amount of soft drink cooling. Similar data have been reported for other concept questions which focus on the rate versus amount misconception (Miller et al., 2006; Prince and Vigeant, 2006).

In summary, the concepts of heat, energy, and temperature are among the most difficult for students of all ages to master. Concept inventory data suggests that many of these misconceptions are robust and persist in our undergraduate engineering students and likely beyond.
C. Direct current circuits

The physics community has conducted extensive studies of students' understanding of resistive direct current (DC) circuits. This body of work is summarized in a recent paper by Engelhardt and Beichner (2004), and it is more extensively reviewed in Engelhardt's thesis (Engelhardt, 1997). As in mechanics and thermal sciences, the literature on simple circuits presents evidence of student conceptual difficulties with basic quantities, such as current and potential difference, as well as the relationship among these quantities expressed by Ohm's law.

1) Student Understanding of Basic Quantities: McDermott and Shaffer (1992) used a variety of research methods including interviews during problem solving in their studies of students in physics classes, most of which were calculus-based. The conceptual difficulties that McDermott and Shaffer (1992) discuss in their work include the following:

- The belief that a battery is a source of constant current; a belief that McDermott and Shaffer refer to as "perhaps the most pervasive and persistent difficulty that students have with DC circuits" (McDermott and Shaffer, 1992, p. 997).
- Failure to understand that an ideal battery maintains a constant potential difference between its terminals.
- The belief that current is consumed.
- Failure to distinguish between potential and potential difference.
- Failure to understand the concept of a complete circuit.

Picciarelli et al. (1991) probed understanding of simple electric circuits of second year university students, the majority of whom were engineering majors. In their study they used a series of multiple choice questions developed by Cohen et al. (1983) but they also asked students to explain their choices. In explaining what would happen to current and voltage in a branch of a circuit containing a resistor when a second resistor was added in parallel, students who saw the battery as a source of constant current offered the following type of explanation: "The battery produces a constant current which, when encountering the two parallel resistors, is divided into two currents, each inversely proportional to the resistance; at the exit we will find a current equal to that entering. Therefore the ammeter reading will not change." Students who offered this type of answer seemed to have grasped Kirchhoff's current law, but not the fact that the battery was not a constant current source. This same type of justification was offered by students for incorrect answers on six different multiple choice items.

When McDermott and Shaffer (1992) asked students to reason through the relative brightness of two bulbs in series, the most frequent incorrect explanation was that the second bulb is dimmer because the first bulb "uses up" some of the current. They offer the following example:

"You have 'X' current coming through here and you think this bulb uses some and so there's not enough here … there's not as much left for bulb number 2" (McDermott and Shaffer, 1992, p. 997).

Students who did not recognize the distinction between potential and potential difference said that the first bulb was brighter because it was at a higher potential than the second one.

The work of Fredette and Lochhead (1980) demonstrates the failure to understand the relevance of a complete circuit in lighting a bulb. They asked 57 engineering students in a first-year course whether the two configurations shown in Figure 7 would result in lighting of the bulb. These two configurations were selected because they were the most common incorrect configurations used by
students in a separate study in which they attempted to light a bulb given the bulb, three wires, and a battery. In each of these circuits, the wires form a (short) circuit, but the bulb is not included properly in the circuit. Only one third of the students responded correctly that neither configuration would light the bulb.

Students’ incomplete and inaccurate understanding of basic quantities leads to difficulty in using them correctly in qualitative descriptions of what is happening in circuits. McDermott and Shaffer (1992) note that students often fail to refer to current, voltage, energy, and power in a rigorously correct manner. They report that students sometimes use these concepts interchangeably and fail to distinguish among them. In many cases, the lack of consistent use of terms was so extreme that it was impossible to interpret what the student really meant when they used a specific term.

2) Student Understanding of Relationships Among the Basic Quantities: Given that many students have incomplete and often incorrect understanding of basic quantities such as current and potential difference, it is not surprising that they also demonstrate difficulties in understanding and applying relationships among these quantities. This difficulty is demonstrated in the work of McDermott and Shaffer (1992) by students who were asked to discuss the relative brightness of three circuits in Figure 8. When discussing the relative current flow through the three circuits, some students explicitly stated that the current delivered by the battery would be equal in all three cases, indicating that they did not grasp Ohm’s law and perhaps not even the concept of an ideal battery.

The work of Picciarelli et al. (1991) included investigation of students’ understanding of the relationship of voltage and current as expressed in Ohm’s law. One of the conceptual difficulties reported in their work was that students attributed the existence of a potential difference to the presence of a current. When asked what would happen when bulb N was removed from the circuit in Figure 9, some students indicated that opening that branch of the circuit meant that there was no potential difference between points D and E because there was no current flowing through the branch D-F. Another example of erroneous reasoning occurred for some students when they were asked what would happen to current and voltage in the branch of a circuit containing a resistor when a second resistor was added in parallel to the existing resistor. A typical response for a student who did not grasp Ohm’s law was “When a resistor is added in parallel to the resistor already present in the circuit, the total resistance will decrease. This fact implies an increase in current $I$ with consequent increase in $V$” (Picciarelli et al., 1991, p. 61).

Other significant difficulties related to students’ ability to reason conceptually about circuits are reported by McDermott and Shaffer (1992). Students often exhibit the belief that the order of elements in a circuit, and consequently the direction of current flow, affects behavior. This belief could stem from their misconception that current is “used up” by elements in a circuit. Another important observation from McDermott and Shaffer (1992) is that students rarely exhibit a coherent conceptual model for reasoning about simple DC circuits. This observation is consistent with diSessa’s (1988) “knowledge in pieces” model of conceptual knowledge in novices.

IV. DISCUSSION

Perkins has written on theories of difficulty and suggests that one of the most important questions an educator can ask is: “what makes this hard?” (Perkins, 2007). Perkins notes that reasons some concepts are more difficult to learn may have developmental causes (for example there may be logical arguments embedded in the content that the learner of a certain age is not yet equipped to learn). However, this is not likely to be a key issue for engineering students. He also notes that epistemic causes, which focus on distinct patterns of how the learner constructs concepts and theories, can be significant.

Chi’s (2005) work on why some misconceptions are more robust than others is an example of an epistemic theory of difficulty and provides a useful starting point for thinking about which engineering science concepts will be the most challenging for students to
learn. Two elements of her work seem most salient: concepts are more difficult to learn when: (1) they are not directly observable, and (2) when a macroscopic pattern emerges from unobservable microscopic phenomena. The inability to directly observe key conceptual quantities such as force and energy almost certainly contributes to the difficulty in learning about them. They are abstract concepts that were developed over a substantial span of time within the engineering and scientific community while trying to understand motion and the operation of heat engines. So it should not be surprising that students do not come into our classes with a scientific view of these quantities or others like them such as moments, heat, current, stress, etc.

Diffusion of mass, momentum, and energy carry the double challenge that the underlying physical processes are not directly observable and that these processes are governed by random molecular dynamics resulting in what appears to be well-ordered behavior on the macroscopic level. Combined, these characteristics make it even more difficult for students to grasp the correct connection between the macroscopic and microscopic phenomena. There is nothing in their everyday experience that would lead them intuitively to an understanding of the random nature of molecular motion that manifests itself in the macroscopic behavior that they observe, such as the color change of diffusing liquids. As discussed in the next section, helping students recognize the emergent patterns resulting from system interactions may assist them in learning these difficult concepts (Slotta and Chi, 2006).

So what does this mean for those who teach engineering science courses? First, be cognizant that students come into classes with conceptual knowledge that is under development and is likely to contain incorrect information. Their knowledge may be in the form of a coherent framework that is applied consistently, in which case, the instructional challenge will be to identify and uproot the incorrect conceptual model. Alternatively, their knowledge may be fragmented and contain some ‘facets’ that are incorrect and some that are correct. The first pedagogical challenge is to discover what conceptual knowledge students bring to a course and how it is structured in their conceptual framework. Once that is understood, instructors can begin to craft appropriate teaching and learning methods to help the students construct, or perhaps reconstruct, their conceptual knowledge into a correct framework.

Chi’s work also suggests that instructors must be sensitive to the fact that concepts that are abstract and not readily observable such as force, heat, stress and current present special challenges. Furthermore, instruction about emergent processes such as diffusion adds to the level of difficulty for students and the challenges for the instructor. As discussed in the next section, Chi’s work is also informing ongoing research involving use of theory-based curricular materials coupled with well-designed computer simulations of molecular processes to help engineering students “see” unobservable dynamics at small length scales and form more accurate mental models of these processes.

V. FUTURE RESEARCH DIRECTIONS

As mentioned previously, there is a substantial literature on student conceptual knowledge and misconceptions in science (Duit, 2007). However, relatively little research has been conducted at the post-secondary level or with a focus on engineering science. Therefore, many important research questions about the conceptual learning of engineering students remain to be investigated.

A key question that remains largely unanswered is what makes some concepts so difficult to learn and some misconceptions so difficult to repair? Few studies have investigated why students have difficulty with the types of elementary quantities and basic relationships discussed in this paper. Chi and colleagues’ work on emergent phenomena is a starting point (Chi, 2005; Cohen, Eylon, and Ganiel, 1983) but it has not yet been tested with engineering students. Miller, Strveeler, and Slotta (2008) are now beginning research that will assess whether helping engineering students develop a schema for emergent phenomena will help them learn about related concepts in the thermal sciences and other engineering domains. In this project, training materials are being developed which teach engineering undergraduate students about emergence and how characteristics of emergent processes such as crowds at a sporting event, a traffic jam, mass diffusion, and heat conduction differ from direct causal processes such as building a skyscraper or the hunting patterns of a pack of wolves. Computer simulations depicting both molecular-scale and macroscopic dynamics for diffusion and conductive heat transfer are used to help students visualize how random movement at a small scale can result in observable patterns at larger scales. The hypothesis is that the experimental group of students completing the training will develop an emergent schema which will allow them to construct more accurate mental models of emergent phenomena of engineering interest.

To measure the direct effect of the schema training materials, the control group (with no emergent training but with an otherwise comparable learning experience) will be compared to two experimental groups. Each of the experimental groups will receive the emergent schema training but one will see references to emergence in other parts of the instruction and the second group will not. All three groups are assessed by answering a series of concept questions in diffusion and heat transfer specifically designed to probe for evidence of an emergent schema. Interviews and analysis of written open-ended responses to probe questions are also analyzed. Finally, a far transfer topic (separation of virus and bacteria particles in microfluidic channels) will be used to assess the ability of the experimental group to apply their new schema to a context with which none of them are familiar. If successful, this work could lead to transformational instructional approaches that repair misconceptions across domains by providing evidence that well-designed curricular materials coupled with computer simulation technologies can repair strongly held misconceptions, misconceptions which are resistant to repair by traditional classroom methods.

Interaction between enhanced conceptual knowledge and related procedural knowledge is a fertile area for investigation. It seems reasonable to think that conceptual knowledge can help engineers make better decisions about how systems will perform under various operating conditions, constraints and process upsets, especially when conceptual knowledge extends to an intuitive appreciation for the relationships between various quantities in a system. However, no causal evidence links increased conceptual understanding with increased procedural knowledge (Rittle-Johnson and Siegl, 1998).

For example, in the area of statics one could ask whether an improved understanding of force enhances students’ ability to solve statics problems. And if so, what are the mechanisms
through which improvement occurs? There is limited work on such questions in the literature and none that we could find related to engineering. Redish and Smith (2008), who address the use of mathematics in engineering, highlight an important idea related to conceptual knowledge. In their example about traxoline and putting meaning into mathematics, they point out that “We not only expect our students to be able to understand mathematics (syntax); we expect them to combine this knowledge with knowledge of what the math is talking about in a tightly integrated way—the meaning of the symbols.” Just as we view conceptual knowledge as applying meanings (as rich as possible) to words such as force, heat, and so forth, Redish and Smith (2008) rightly insist that modeling requires meaning applied to the symbols. This may indeed be a pathway for transition from conceptual knowledge to problem solving ability, because problems generally involve the manipulation of symbols.

Another important area of research is how conceptual knowledge evolves as students move from novice toward expert performance. Important research questions include: Are there common trajectories or pathways that students take as they acquire greater conceptual knowledge in engineering science fields? How does conceptual knowledge evolve as a learner moves from novice toward expert performance? Future research may track the longitudinal development of conceptual knowledge over the course of several years. For example, Montfort and Brown (in preparation) investigated students’ conceptual knowledge of normal stress due to bending in a sequence of four sequential structural engineering courses. While students in higher-level courses were better able to solve problems, they did not demonstrate more conceptual understanding than students in the earlier courses. However, seniors did attempt to reconcile their previous beliefs and intuition with course content. This could be seen as a sign that seniors were undergoing conceptual change.

There are other unanswered questions about the longitudinal trajectory of conceptual knowledge. For example, are there key events in this process? Does growth in conceptual knowledge proceed in discrete jumps, or is it a continuous process? Light has posited stages of understanding when students learn about size and scale in context of nanotechnology (Redish and Smith, 2008). If learning does occur in steps, are some of the steps more important to learn than others? Meyer and Land (2006) have proposed the idea of “threshold concepts” which are described as portals for understanding a range of concepts in any field. The engineering community is just beginning to investigate the possibility of threshold concepts in engineering science. For example, Streveler and her colleagues posit that “emergence” may be a threshold concept in thermal sciences (Streveler, Miller, and Olds, 2008). Baillie and Goodhew (2006) have also looked for evidence of threshold concepts in engineering.

Another largely unexplored research area concerns the interplay of affective and cognitive factors in the acquisition of conceptual knowledge. A central question here is the role that affective factors such as motivation play in conceptual change. Pintrich and colleagues coined the term “hot cognition” to describe the intersection between the cognitive and affective domains (Pintrich, Marx, and Boyle, 1993). Future research on conceptual change may need to take students’ motivation into consideration when explaining how conceptual knowledge is formed, and how faulty or incomplete knowledge can be corrected.

Intriguing examples of the effects of culture and world view on learning, called social constructivism, are just beginning to appear in the literature. The social constructivism view may have important implications for conceptual learning in engineering, especially as engineering becomes an ever more global profession. Hewson and Hamlyn (1984) found in their study of conceptions of “heat” among the Sotho people in Southern Africa that world view does seem to matter. The Sotho people view “heat” quite differently than their Western-educated countrymen. In the Sotho culture “heat” is synonymous with “agitation” and a person may be seen as becoming ill as the result of “too much heat.” This view of “heat” as “agitation” results in a mental model of heat as a kinetic process which is aligned with the scientifically correct view of thermal energy as the result of the motion of molecules.

Research such as that conducted by Hewson and Hamlyn (1984), which highlights the impact of culture on the development of our conceptions, is sometimes paradigmatically at odds with cognitive research that focuses on the individual mind of the learner. Recently researchers have tried to bridge the gulf between the cognitive and social constructionist paradigms so that one does not have to take an extreme stance on either end of the spectrum (Mason, 2007). For example, Stevens et al. (2008), explore three dimensions that impact the process of “becoming an engineer”: interdisciplinary knowledge, identification, and navigation. It is likely that future research on students’ conceptual knowledge will place a greater emphasis on how students’ worldviews affect their conceptual knowledge.

Although the literature on conceptual knowledge is extensive, a very practical research question remains largely unanswered—how can one construct learning experiences that help students learn difficult concepts in engineering science? Perkins argues that the pedagogy we use to help our students master difficult concepts needs to be aligned with why these concepts are difficult. He offers some heuristics for educators who want to help students overcome barriers to learning difficult concepts (Perkins, 2007, p. 45):

- “Don’t blame the learner or the conditions.”
- “Don’t settle for a formulaic fix.”
- “Get beyond the topic to the symptoms.”
- “Get beyond the symptoms to the causes.”

In a similar way, Redish and Smith (2008), also avoid a superficial, formulaic approach to instruction when addressing the development of modeling ability. They directly engage first year students in modeling systems with accessible physical principles. This approach to developing a complex skill recognizes that students often have weak modeling ability (which, Perkins might say, is a symptom), and identifies the cause of this deficiency as lack of direct experience which can be remediated by creative instructional design.

As we have illustrated, a sizable minority of advanced engineering students make errors when asked fundamental questions about key concepts in engineering science (Linn and Songer, 1988). If we wish to “get beyond the symptoms to the causes” of this phenomenon then research to identify students’ conceptual difficulties and understand their origin must continue.

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**Authors’ Biographies**

Ruth A. Streveler is an assistant professor in the School of Engineering Education at Purdue University. She holds a B.A. in Biology from Indiana University, a M.S. in Zoology from The Ohio State University and a Ph.D. in Educational Psychology from the University of Hawaii at Manoa. Prior to coming to Purdue, she was the founding director of the Center for Engineering Education at the Colorado School of Mines. She has been a co-PI on several projects funded by the National Science Foundation and served a stint as acting director of the Center for the Advancement of Engineering Education. She earned the 2006 and 2007 Helen Plants Awards for best non-traditional session at the Frontiers in Education Conference.

*Address*: School of Engineering Education, Purdue University, Neil Armstrong Hall of Engineering, West Lafayette, IN, 47907; telephone: (+1) 765.496.9031; fax: (+1) 765.494.5819; e-mail: streveler@purdue.edu.

Thomas A. Litzinger is director of the Leonhard Center for the Enhancement of Engineering Education and a Professor of Mechanical Engineering at Penn State, where he has been on the faculty since 1985. Prior to his appointment as Director of the Leonhard Center, he was the Penn State principal investigator and Coalition-PI for Student and Faculty Development for the ECSEI Coalition. His work in engineering education involves teaching and learning innovations, faculty development, curricular reform and assessment. In addition to his educational scholarship, he does research on the effects of fuel composition on performance and emissions of internal combustion engines, gas turbines and rockets. Prior to joining Penn State he completed his Ph.D. at Princeton, and he worked for General Electric for four years, during which time he completed a Master’s degree at RPI through GE’s Advanced Engineering Program.

*Address*: 201 Hammond Building, University Park, PA 16802; telephone: (+1) 814.865.4015; fax: (+1) 814.865.4021; e-mail: TAL2@PSU.EDU.

Ronald L. Miller is professor of Chemical Engineering and director of the Center for Engineering Education at Colorado School of Mines. He earned degrees in chemical engineering from the University of Wyoming and Colorado School of Mines. Dr. Miller has received three university-wide teaching awards and has held a Jenni teaching fellowship at CSM. He has received grant awards for education research from the National Science Foundation, the U.S. Department of Education FIPSE program, the National Endowment for the Humanities, and the Colorado Commission on Higher Education and has published widely in the areas of engineering education assessment, pedagogy, and curricular design.

*Address*: Chemical Engineering Department, Colorado School of Mines, Golden, CO, 80401; telephone: (+1) 303.273.3892; fax: (+1) 303.273.3730; e-mail: rlmiller@mines.edu.

Paul S. Steif is a professor of Mechanical Engineering at Carnegie Mellon University. He received a Sc.B. in engineering from Brown University (1979) and M.S. (1980) and Ph.D. (1982) degrees from Harvard University in applied mechanics. He has been active as a teacher and researcher in the field of engineering mechanics. In particular, Dr. Steif develops and implements new approaches and technologies to measure student understanding of engineering and to improve instruction.

*Address*: Department of Mechanical Engineering, Carnegie Mellon University, Schenley Park, Pittsburgh, PA, 15213; telephone: (+1) 412.268.3507; fax (+1): 412.268.3348; e-mail: steif@cmu.edu.