# Developing an Outcomes Assessment Instrument for Identifying Engineering Student Misconceptions in Thermal and Transport Sciences[1]

## Project Introduction and Overview

Engineering is a discipline that has historically and successfully relied upon a macroscopic and largely empirical description of how the physical world works. As we move into the 21st century, however, more and more technological advances are being made at the microscopic, molecular, and atomic levels in many fields of engineering (e.g. biotechnology, genetic engineering, microelectronics, nanoscale machines, molecular computers, materials engineering, pharmaceuticals, catalyst design) and engineering curricula will be expected to respond. For example, the recent NSF report entitled "Societal Impacts of Nanoscience and Nanotechnology" [1] calls for introducing nanoscale scientific and technology concepts into all levels of engineering and science courses so that the next generation of engineering graduates possesses a strong conceptual understanding of dynamic engineering and scientific processes at small scales.

Unfortunately, evidence in the literature suggests that science and engineering students do not conceptually understand many fundamental molecular-level and atomic-level phenomena including heat, light, diffusion, chemical reactions, and electricity. [2, 3] The problem is more than simply one of confusion or misunderstanding, but instead involves fundamental <u>misconceptions</u> by students about differences in the way that molecular-scale processes differ from observable, macroscopic causal behavior we experience in our daily lives. [4] Thus, students who can correctly apply macroscopic models of thermal or transport systems to solve problems in fluid dynamics, heat transfer, mass transfer, or thermodynamics often still believe that "heat flows from hot objects to cold objects" or that "molecular processes stop when they reach equilibrium." Any faculty member who has taught these subjects to engineering students will have heard similar comments.

For many traditional processes, the macroscopic models and metaphors ("heat flows") still work well and students must still be proficient in their use. However, they must now also understand when these models will break down and when the metaphors are no longer applicable to describe molecular-scale processes such as the ones listed above. Unfortunately, recent research by Chi and colleagues suggests that students (and apparently more than a few engineering and science faculty) will persist in incorrectly applying macroscopic causal models to processes in which dynamic, molecular behavior dominates. [5] As a result, many students have difficulty learning important concepts in thermodynamics, fluid mechanics, and heat and mass transfer and are ill-prepared to engineer the next generation of advanced technologies which rely on these disciplines.

Recent research studies have shown that students arrive in science and engineering classes with preconceived and often naive notions about how the physical world works; in addition to being incomplete, their prior knowledge is often incorrect but strongly held (for example see [6], chapters 1 and 7) thus indicating why students who can correctly apply engineering models still do not correctly understand the concepts and limitations underlying the models. Such robust misunderstandings are termed "misconceptions" and have been studied extensively in science education. For example, over 3600 misconception research papers have been published with about 66% related to physics, 14% to chemistry, and 20% to biology education. [7] To our knowledge, no systematic studies of misconceptions in engineering education have been conducted and published.

Why should student misconceptions be important to engineering educators? Simply put, prior knowledge provides the conceptual framework within which students will add new knowledge to form an updated mental model that describes each new learned concept (see [6], chapters 1, 3, and 10). If the framework contains misconceptions, new topics will be difficult or impossible for the student to conceptualize correctly. The importance of assessing students' prior knowledge to improve learning has been recognized by assessment expert Tom Angelo [8] and by the American Association for the Advancement of Science. [9, p. 198] In order to repair students' flawed mental models of thermal and transport processes, engineering educators must first determine that the misconceptions exist and then discover as much about the nature of the misconceptions as possible. As Chi has demonstrated using computer-based modules describing electrical current flow, once misconceptions are properly identified, well-designed interventions can help students repair even strongly held misconceptions. [10] Our goal in this project is to provide educators with a tool with which to identify these misconceptions.

As described more fully in the following sections of this proposal, we propose is to create an easy-to-use assessment tool which will allow engineering faculty members to identify significant misconceptions held by their students about thermal science (thermodynamics, heat transfer) and transport science (fluid mechanics, heat transfer, mass transfer) topics. These disciplines have been selected for two reasons: 1) students find these courses to be among the most difficult in undergraduate engineering curricula, and 2) most advanced technologies under development involve one or more of these processes. The assessment tool will be designed so that it may be applied at the course level for either formative or summative assessment of individual students or at the program level to collect assessment data for curricular improvement and accreditation purposes.

We will base our assessment tool development on recent misconception work by Chi and colleagues that suggests the misapplication of macroscopic causal models as the primary source of student misconceptions when describing molecular-scale processes (Chi's theory is described in detail beginning on page 5). We will pattern our instrument development after the highly successful Force Concept Inventory (FCI) developed for assessing Newtonian mechanics misconceptions in introductory college physics (the FCI instrument is described more fully beginning on page 4). If successful, the results of this project will improve engineering education by allowing faculty members to identify important student misconceptions which impede learning thermal and transport science concepts and provide guidance for developing effective interventions to repair students' flawed mental models.

## Project Objectives and Expected Significance to Engineering Education

Based on the overall goal of this project to develop an easy-to-use outcomes assessment instrument that will allow engineering faculty at the course and program levels to identify fundamental student misconceptions in thermal and transport sciences, we propose to complete the project objectives listed below:

[1] DUE - 0127806, Miller, Streveler and Olds

- ♦ Develop a list of the most important student misconceptions in thermal and transport sciences by surveying experienced engineering faculty about the misconceptions they find among their students and then validating this list through student interviews.
- ♦ Create a multiple-choice pencil-and-paper instrument patterned after successful misconception instruments such as the Force Concept Inventory; misconceptions to be included in instrument questions will be based on the list created to meet the first objective.
- ♦ Field test the instrument to demonstrate validity and reliability of the misconception results obtained and usefulness of the instrument for both course-level and program-level assessment of student misconceptions in thermal and transport science topics.

If successful, this project has the potential to positively impact engineering education by providing faculty with a tool for reliably identifying robust and persistent misconceptions about key concepts in engineering thermal and transport sciences – the first step before designing ways to help students repair the misconceptions. As mentioned earlier, topics in courses such as thermodynamics, fluid mechanics, heat transfer, and mass transfer are among the most important for developing cutting-edge technologies in the 21$^{st}$ century but remain among the most difficult for most students to understand.

The instrument will be designed for use in both individual courses where faculty can assess students for prior knowledge as they begin a new course and for use as a program assessment tool for improving student understanding during completion of an undergraduate engineering curriculum. As Chi and Ferrari have shown, correctly identifying student misconceptions is the first step in creating effective interventions such as computer simulations to help students repair their flawed mental models of dynamic molecular-scale processes. [10]

The instrument will be designed to allow for pre-testing (at the beginning of a course or curriculum) and post-testing (at the end of a course or curriculum) to measure changes in student mental model development. Results from the instrument will also useful as part of the ABET (Accreditation Board for Engineering and Technology) outcomes assessment requirement for engineering program assessment. In particular, data collected using the instrument will provide data on outcomes 3a, "an ability to apply knowledge of mathematics, science, and engineering," and 3e, "an ability to identify, formulate, and solve engineering problems." [11]

To be useful as an assessment tool, any method of identifying student misconceptions must be easy to administer and must provide rapid, reliable results. Typical objective examinations focus on solving closed-ended problems using established macroscopic models (i.e. Fourier's law of heat conduction) and will not indicate the presence of student misconceptions (i.e. students can correctly solve most textbook problems and still persist in their misconceptions about how the processes work on a molecular scale). Most educational research techniques (e.g. focus groups, verbal protocol analysis, "think-aloud" problem-solving) are too cumbersome for faculty to use on a routine basis, but several pencil-and-paper instruments have been developed to help identify student misconceptions in specific disciplines such as physics [12], chemistry [13], biology [14], and astronomy [15]. Unfortunately, no misconception assessment tools are readily available for use by faculty teaching critically important subjects in engineering where molecular-scale processes dominate (e.g. thermodynamics, fluid mechanics, heat transfer, mass transfer).

The most widely-used of these assessments is the Force Concept Inventory (FCI) which consists of 29 multiple-choice questions designed to assess students' conceptual framework of newtonian and non-newtonian mechanics. The FCI is constructed so that correct answers to short problems will be obtained only by using the correct conceptual framework.

The FCI has demonstrated that simple instruments can be developed to help faculty identify and then repair student misconceptions in specific technical disciplines. Versions of the FCI have been used at both the high school and college levels and the instrument has undergone extensive reliability and validity testing and analysis [12]. Although some questions remain about whether the FCI actually measures the force concept, results from the instrument have been used to measurably improve introductory physics curricula and pedagogy at many institutions. [16]

As described more fully beginning on page 5, we will base our instrument development on Chi's misconception theory of emergent vs. causal processes, which is particularly relevant to describing misconceptions of important thermal and transport science topics. Chi's theory explains why students persist in their misuse of causation to describe molecular-level thermal and transport processes and her theory will be used to inform our identification and assessment of persistent causal/emergent misconceptions in engineering students.

The following features of this proposal represent improvements over present practice in assessing students' conceptual misunderstanding:

- To our knowledge, no significant study of engineering student misconceptions has been reported. Given the importance of graduating engineers who will be capable of understanding and applying 21st century molecular-level technologies, we need to provide engineering faculty with tools for assessing such misconceptions.
- Our study will be guided using Chi's theory of causal vs. emergent processes that represents a more sophisticated and useful framework for analyzing misconceptions in engineering students than traditional misconception theories.
- We will create an easy-to-use, valid, and reliable assessment instrument for classroom and programmatic use.
- The instrument will be developed by an interdisciplinary research team consisting of two chemical engineering professors (Drs. Miller and Dean), an educational psychologist (Dr. Streveler), a qualitative assessment expert (Dr. Olds), an expert in student misconceptions (Dr. Chi), and an expert in test construction (Ms. Nelson, Ph.D. student in psychometrics under the direction of Dr. Shepard).
- If we are successful in this project, the instrument we create will help engineering faculty identify causal/emergent misconceptions in their students, the first step towards effective intervention strategies to help students "repair" their flawed conceptual models of thermal and transport science topics.

## Relation of Proposed Work to State-of-the-Art in Student Misconception Theories

As mentioned earlier, over 3600 studies of students' scientific misconceptions have been reported with nearly all focused on physics, chemistry, or biology education, many at the K-12 level. [7] To our knowledge, no systematic studies of fundamental engineering student misconceptions have been conducted, particularly ones focused on molecular-level processes.

Engineering instructors find that molecular-scale topics such as viscous fluid flow, conductive heat transfer, diffusional mass transfer, and thermodynamic equilibrium processes are very difficult for students to learn and, even after instruction, students persist in their misconceptions. For example, engineering students often describe molecular momentum transfer as faster molecules "dragging slow molecules along," heat as a "substance stored in hot objects" as opposed to cold which is described as a "substance stored in cold objects," heat transfer as a "flow of hot molecules to cold objects," and molecular processes as "stopping" when they reach equilibrium. None of these conceptually flawed explanations is correct and each leads to incorrect explanations of other related phenomena (for example, incorrectly predicting the absence of a temperature effect on equilibrium processes or predicting that no molecular diffusion occurs in laminar fluid flow).

Why are these concepts so difficult for students to learn? Part of the reason seems to be that certain beliefs are very entrenched and not easily changed. [17] Based largely on life experience, these beliefs are formed early in a student's career (perhaps even before the start of formal schooling) and become the basis for future learning via the construction of increasingly complicated mental models. [18] If the student's prior knowledge is incomplete or incorrect, new concepts are difficult if not impossible to correctly assimilate and a fundamental conceptual change in the student's mental model will be required before the new concept can be understood.

Posner and his colleagues proposed a model of misconceptions that has been used as the foundation for much of the research on student misconceptions. [19] In Posner's model, four conditions must be fulfilled for conceptual change to occur: 1) there must be dissatisfaction with existing concepts; 2) a new concept must be intelligible; 3) a new concept must appear initially plausible, and 4) a new concept should suggest the possibility of a fruitful research program. Note that the idea of fruitfulness of research is of more concern for changing a scientific paradigm [20] and generally would not be an issue for students.

Posner's theoretical framework (and similar ones proposed by others) has not been very useful in helping instructors correct student misconceptions. [21] The theory puts the onus on the instructor to convince students that the view the instructor is presenting (for example, the scientifically "correct" view) is more accurate than the pre-existing view held by the students. Since student misconceptions are often derived from everyday observations and seem to adequately describe how the world works (at least on a superficial level), students are not necessarily dissatisfied with their conceptual frameworks and are therefore not open to the need for conceptual change. For example, the macroscopic descriptions of heat "flowing" from hot to cold objects or chemical reactions "stopping" at equilibrium adequately describe our visual and tactile observations about how these processes occur and students do not see a need to improve their conceptual understanding of these and related phenomena. Therefore, the traditional view of conceptual change does not provide much insight or guidance about how to help students "repair" their flawed mental models

Electricity, fluid flow, heat transfer and molecular equilibrium are examples of emergent processes (processes that involve uniform, parallel, independent events with no beginning or end but in which observable patterns eventually emerge). Chi has proposed that conceptual misunderstandings arise when students incorrectly think of emergent processes as having the attributes of the causal processes they see in everyday life. [4] (Causal processes involve distinct, sequential, goal-oriented events that have an observable beginning and end). Therefore, students may view the observed structure or patterns emerging from a series of events such as Brownian molecular motion (the result of an emergent process) as actually being the result of a causal process. They often incorrectly describe molecules as moving with intent in a linear and sequential process that stops at some point. Thus, Chi's theory explains why students persist in their belief that molecules move with intent and that heat is a substance which flows and can be stored. [2] There is also evidence in the literature that causal explanations are often incorrectly invoked as metaphors in textbooks and by faculty members. [2,10] Although the metaphors can be useful, students do not know when relying on the metaphor is appropriate and when it must be abandoned for a more realistic conceptual explanation of a process.

Table 1 provides a detailed example (diffusion of colored dye in a beaker of water) about how students incorrectly classify most processes in which structure or pattern emerges from a series of separate events as a causal process involving directed action of individual objects with a defined beginning and end. Marek and colleagues have shown that less than 2% of high school students correctly understand diffusion after completing a biology or chemistry course. [22] We would expect similar numbers for college engineering and science students based on research by Hestenes that misconceptions developed in elementary and secondary schools persist into college. [12]

Consider the simple experiment of adding a droplet of colored dye into a beaker of quiescent water. What we see at the macroscopic level is slow movement (diffusion) of dye into the water until the resulting dye/water mixture has the same color throughout the beaker. At this point (equilibrium) no further movement of dye is apparent to the naked eye. As shown in the left column of Table 1, this experiment can be (incorrectly) described using a causal model in which dye molecules "want" to mix with water and individual dye molecules move with intent to create a uniform dye/water mixture at which time they stop further movement. (What really happens is that dye and water molecules will randomly bounce into spaces formerly occupied by other dye and water molecules eventually resulting in a uniform mixture in which both types of molecules continue to move. The initial concentration difference between dye and water means that on average more of the dye molecules will initially move into regions populated by water molecules). Students who describe this complex, dynamic process using the causal explanation possess a mental model that is fundamentally incommensurate with accepted theories of molecular motion. Since the causal model seems to describe the macroscopic behavior of the dye/water experiment, students are comfortable with this view (as are many faculty members as evidenced by typical textbook descriptions of this process) and they hold tightly to the misconception, especially that the dye molecules stop moving once equilibrium is reached. This approach provides students with simple equations for describing the rates of diffusional processes (i.e. Fick's law of diffusion in mixtures, Fourier's law of heat conduction, Newton's law of viscosity for momentum transfer) and allows them to predict the macroscopic behavior of simple diffusional systems.

If the macroscopic models are successful in describing the global behavior of simple systems, why should we care if students persist in incorrectly applying causal models to processes such as dye diffusion into water? The answer is simple – the causal models can predict some but not all important behavioral characteristics of molecular diffusional processes. For example, students will not be able to predict the effect of changing the initial amount of dye or the effect of temperature on diffusion rates using a causal model. Given the increasing importance of dynamic molecular behavior in many fields of engineering and science, we believe identifying persistent student misconceptions about important concepts in thermal and transport sciences is an important step towards improving the quality of student learning in these disciplines.

Table 1 – Comparison of Causal vs. Emergent Processes Explanations for Diffusion of Colored Dye in Water [4,5]

| **Causal Model**<br>(the action of a class of molecules) | **Emergent Model**<br>(interactions of a dynamic collection of molecules) |
|---|---|
| *"Dye molecules move towards water molecules."*<br>(distinct actions – event is composed of distinct subevents) | *"All molecules exercise Brownian motion."*<br>(uniform interactions – interactions follow the same rules for all members of the collection) |
| *"Dye molecules flow from area of high concentration to area of low concentration."*<br>(sequential actions – subevents happen in a particular order) | *"All molecules move at the same time."*<br>(simultaneous interactions – interactions among members occur simultaneously) |
| *"Dye molecules are "pushed" into the water by other dye molecules."*<br>(dependent actions – a subevent is dependent on the event that came before it) | *"Molecules collide independently of prior collisions. What happens to one molecule doesn't affect interactions of other molecules."*<br>(independent interactions – each member collision occurs independently of others) |
| *"Dye molecules want to mix with water molecules."*<br>(goal-direct actions – actions are taken to achieve a goal) | *"The local conditions around each molecule affect where it moves and at what velocity."*<br>(local and decentralized interactions – interaction determined by local conditions) |
| *"Dye molecules stop moving when dye and water become mixed."*<br>(termination – action stops when goal is achieved) | *"Molecular interactions continue when equilibrium is reached."*<br>(continuous interactions – interactions continue irrespective of what is observable at the macro level) |

## Project Work Plan

In this section, we discuss how we will complete specific tasks to meet the objectives listed on pages 2-3. Four tasks are listed: training; creating a list of misconceptions; creating a multiple-choice instrument based on the list of misconceptions; and checking the instrument for validity, reliability and bias. Explanations of each task are provided with specific assignments for each of the project investigators.

<u>Task 1</u> **- Training in emergent processes theory and development of rubrics for scoring verbal protocols and textbook examples.**

Chi's theory describing why causal explanations of emergent phenomenon may lead to student misconceptions is the foundation of this project. However, even experts may not be trained to think about emergent phenomenon. [21] Therefore, it is essential to this project that all personnel be clear about the differences between causal and emergent explanations of emergent phenomenon. To ensure that all members of the project are clear about the emergent vs. causal processes theory, Dr. Chi will spend 4 days on site at CSM training project staff (Miller, Streveler, Olds, Dean, Nelson).

This on-site session will also provide the ideal time for developing the scoring system to use on textbook examples of causal explanations of emergent phenomenon (see Task 2) and to ensure the proper scoring of verbal protocols that will be used to validate the questions in this instrument (see Tasks 3 and 4). During the training, rubrics will be developed to aid in coherence of scoring of both textbook examples and verbal protocols. A brief agenda for the 4-day training follows.

<u>Training agenda</u>

- Day 1 – Emergent vs. causal processes (Chi). Examples from engineering (supplied by Miller).
- Day 2 – Training in verbal protocol analysis. Chi brings examples from her previous research. All project personnel participate. Streveler and Olds get more in-depth training (as they will be scoring the student think-aloud and interview transcripts). Rubric drafted for scoring protocols. Streveler and Olds work through 2 or 3 iterations using the rubric and refine it.
- Day 3 – Textbook examples of emergent processes shown as causal. Miller provides examples from several engineering texts. All project personnel participate. Miller, Dean and Chi develop rubric they'll use for scoring these examples as causal descriptions of emergent phenomenon.
- Day 4 – Link this project to the bigger picture. Begin discussion of the pedagogical implications of this work. Look at interventions that help students learn these concepts. Chi brings examples from work with Ferrari and current work funded by the Spencer Foundation.

Personnel Responsibilities for Task 1:

| **Personnel** | **Responsibilities** |
|---|---|
| Chi | • Prepare for and conduct training |
| Dean | • Attend training<br>• Score textbook examples<br>• Develop rubric for text book examples |
| Miller | • Assemble engineering examples for discussion on Day 1<br>• Collect textbook examples for Day 3 |
| Nelson | • Attend training |
| Olds | • Attend training<br>• Develop verbal protocol rubric |
| Streveler | • Organize training<br>• Attend training<br>• Develop verbal protocol rubric |

**<u>Task 2</u> – Identify misconceptions prevalent in the thermal and transport sciences.**

In this task we will develop a list of the 15-20 most widely held student misconceptions in the thermal and transport sciences by identifying molecular-level emergent processes to which engineering students tend to incorrectly apply causal models. The list will be created from data collected in two ways: 1) by consulting with engineering faculty, and 2) by consulting relevant engineering textbooks. The list will be validated in Task 3 through student interviews.

To identify candidate misconceptions, approximately 20 engineering faculty from at least 5 prominent US engineering colleges will participate in a Delphi study. The purpose of a Delphi study is to reach consensus about a particular topic – in this case the most widely held student misconceptions. [23]

In order to be part of the study, a faculty member must have at least 5 years experience teaching undergraduate courses in thermodynamics, fluid mechanics, heat transfer, and/or mass transfer. Potential participants will be identified through the American Society of Engineering Education and personal contacts of project investigators. The Delphi study will consist of a series of repeated email questionnaires to the group of faculty. After receiving the initial response from each faculty member, a second questionnaire containing information from the first round of replies will be sent to the group. Individuals are encouraged to reconsider and, if appropriate, to change their previous reply in light of the replies of other members of the group. After two or three iterations of the Delphi study, group results will be averaged to determine the 15-20 most significant misconceptions held by undergraduate engineering students in thermodynamics, fluid mechanics, heat transfer, and mass transfer.

Since many engineering texts incorrectly explain emergent concepts using causal models [10], we will also consult the 20 most commonly used textbooks in thermodynamics, fluid mechanics, heat transfer, and mass transfer for misconception examples. Miller will find candidate examples, copy appropriate pages and send them to two raters [Dean – content expert, Chi – expert on emergent processes]. Both Chi and Dean must agree that an emergent process is explained as causal by a textbook to be considered a candidate misconception. In case of a dispute, Miller, Dean, and Chi will attempt to reach a consensus decision. If consensus cannot be reached, the candidate misconception will not be considered for inclusion in the assessment instrument.

The list of misconceptions created during the first iteration of the Delphi study will be compared with the list of incorrect causal explanations listed in the textbooks. Finding examples of causal explanations of emergent processes in textbooks will be seen as a validation of the concept as a misconception. Textbook examples NOT found on the first list of misconceptions will be added to the questionnaire sent out during the second iteration of the Delphi study. Through this iterative process, a list of the 15-20 most widely-held misconceptions will be created.

Personnel Responsibilities for Task 2:

| **Personnel** | **Responsibilities** |
|---|---|
| Chi | • Act as rater of textbook concepts |
| Dean | • Act as rater of textbook concepts |
| Miller | • Assemble engineering textbooks<br>• Identify list of faculty to invite to be part of Delphi study<br>• Look for causal models in textbooks. Copy and send to Dean, Chi.<br>• Act as third party to discuss textbook examples with Chi, Dean when there is a dispute. |
| Olds | • Assist with Delphi study of faculty |
| Streveler | • Conduct Delphi study of faculty |

**<u>Task 3</u> – Create a multiple-choice instrument to identify misconceptions in engineering students.**

In this task, we will first develop at least one conceptual or computational problem for each of the 15-20 misconceptions identified in task 2 and will validate these questions through think-aloud sessions with novices and experts, through expert review of the instrument problems, and by interviews with a large sample of students after they have answered the problems.

We will pattern the format of the instrument after the Force Concept Inventory. [12] Each problem will be constructed so that incorrect approaches to solving the problem will indicate misapplication of a causal model to the emergent process analyzed in the problem. Two preliminary questions are shown in Table 2 to illustrate the types of questions we anticipate including in the instrument (actual instrument questions will be a mix of conceptual and computational problems).

Table 2 – Preliminary Sample Conceptual Problems for Misconception Assessment Instrument

| |
|---|
| A drop of red dye is placed in a beaker of water that is not moving. After a long time the pink color of the water will be the same throughout the beaker. What causes this process to occur?<br><br>a. Dye molecules want to move away from each other.<br>b. A concentration difference causes the dye molecules to move into the water.<br>c. Water and dye molecules randomly collide and move in the beaker. (*correct answer*)<br>d. Dye molecules push each other into the water. |
| A chemical reaction involves reactants (A) and (B) to produce species (C). After a long time, the concentrations of A, B, and C do not change with time and we say the reaction has come to equilibrium. Which of the following statements about the equilibrium state is true?<br><br>a. The reaction stops and no further concentration change will occur.<br>b. Rates of forward reaction ($A + B \rightarrow C$) and reverse reaction ($C \rightarrow A + B$) are equal (*correct answer*)<br>c. Concentrations of reactants and products are equal.<br>d. Need more information to decide. |

In order to initially validate that the problems are indeed uncovering causal versus emergent thinking, two undergraduate students and two engineering faculty will be asked to think aloud as they solve selected sample problems. Streveler and Olds will score the think-aloud transcripts. [24] Using the verbal protocol coding method developed by Ferrari and Chi [10], Streveler and Olds will code responses with regards to words that signify causal thinking (for example, looking for goal orientation – "the molecules want to go this way" and termination – "the reaction stops when equilibrium is reached") or emergent thinking (for example, describing a diffusion process as "the result of autonomous molecular motion" or describing the process as one that "has no true beginning or end" on a molecular level). Transcripts will be recoded if inter-rater reliability falls below 0.9. We expect to see the undergraduates (novices) misapplying causal thinking and arriving at incorrect answers and to see if the faculty (experts) use emergent thinking to arrive at correct answers. Chi will check coding of the transcripts from one expert and one novice. Streveler and Olds will recode the transcripts if 90% of their ratings do not agree with Chi's ratings.

To further validate the instrument problems, we will then ask a total of 30 undergraduate and graduate engineering students from the Colorado School of Mines and from the College of Engineering, University of Washington who have completed at least two courses in thermodynamics, fluid mechanics, heat transfer and/or mass transfer to work the conceptual and computational problems and then be interviewed to explain why they solved the problems as they did. The interviews will be transcribed and scored by Streveler and Olds, again using the verbal protocol coding method developed by Ferrari and Chi. Transcripts will be recoded if inter-rater reliability falls below 0.9. Chi will check 3 of the 30 transcripts and compare results with Olds and Streveler. Olds and Streveler will recode if there is not at least 90% agreement with Chi's coding.

The interview results will be analyzed to determine language commonly used by students using causal models or emergent models to explain fluid flow, heat transfer, mass transfer, and thermodynamic phenomena. Misconceptions that cannot be explained by misapplication of causal vs. emergent models will be noted for further study, but are beyond the scope of this project. Preliminary discussions with experts in the thermal and transport sciences suggest that most, if not all, of the most widely held misconceptions in these areas will be due to misapplied causal explanations. [25]

Interview statements will be used to create the first draft of a multiple-choice instrument to identify engineering students who possess flawed mental models of emergent processes. Four multiple-choice problems will be created for each of the 15-20 concepts identified in task 2 with emergent statements used to construct the correct answer and causal statements used to construct alternate answers. A panel of three experienced engineering faculty, not involved in the Delphi study in Task 2, will review the questions and answers and validate that the correct answers can be derived by correct views of emergent processes and that the incorrect answers are the result of misapplication of causal explanations.

We will hire Mary Nelson, a Ph.D. student in the Research and Evaluation Methodology program at the School of Education at the University of Colorado, Boulder to assist us on this task and help ensure that proper test construction procedures are employed as the instrument is developed. Ms. Nelson will be supervised by Dr. Lorrie Shepard, Professor of Education and Dean of the College of Education at the University of Colorado, Boulder.

Personnel Responsibilities for Task 3:

| **Personnel** | **Responsibilities** |
|---|---|
| Chi | • Spot check verbal protocol analysis for quality control |
| Dean | • Provide second opinion on multiple-choice items |
| Miller | • Create multiple-choice items |
| Nelson | • Construct instrument under the direction of Dr. Shepard |
| Olds | • Assist with scoring of verbal protocol analysis |
| Streveler | • Conduct verbal protocol analysis |

**Task 4 – Field test the draft assessment instrument with undergraduate engineering students to create a valid and reliable tool for classroom use.**

In this task, we will administer the conceptual change instrument developed in task 3 to approximately 100 undergraduate engineering students who have completed thermodynamics, fluid mechanics, and heat transfer courses at the Colorado School of Mines or at the University of Washington. Since we will develop four multiple-choice questions for each concept, we will be able to calculate the split-half reliability of the instrument (i.e. we can statistically compare student responses to pairs of questions which are designed to assess the same misconception and compute the correlation of responses for each pair of questions). A subset of these students (approximately 20) will be interviewed after completing the misconception instrument using the same protocol used in task 3 (i.e. why did they solve problems on the instrument the way they did?) to determine the validity of instrument questions (i.e. are the questions actually measuring the students' conceptual views that we think are being measured?). Item and factor analysis techniques will be used in conjunction with the reliability and validity data to identify questions that are not providing statistically significant results. [26] These questions will be revised or replaced and the instrument re-administered to an additional 20 undergraduate engineering students from the Colorado School of Mines or the University of Washington to collect additional reliability data. Once again about 20% of the students will be interviewed to determine instrument validity. This process will be repeated until the instrument is determined to be sufficiently reliable and valid for use. Ms. Mary Nelson, supervised by Dr. Lorrie Shepard, will assist us on this task to help ensure that proper test reliability and validity procedures are employed. At each iteration, results will be checked for cultural or gender bias.

Personnel Responsibilities for Task 4:

| **Personnel** | **Responsibilities** |
|---|---|
| Chi | • Look over a sample of verbal protocols |
| Dean | • If needed, reword multiple-choice problems |
| Miller | • If needed, reword multiple-choice problems |
| Nelson | • Compute statistics on tests – reliability, item analysis, check for bias (culture/gender) |
| Olds | • Score verbal protocols |
| Streveler | • Score verbal protocols |

## Proposed Project Timeline

To complete the tasks listed in the previous section, we propose to follow the timeline shown in Table 3 during the 36-month lifetime of the project.

Table 3 – Project Timeline

| | |
|---|---|
| Spring 2002 | Gather textbooks<br>Begin list of potential participants in Delphi study<br>Make arrangements for summer training<br>Meet with Mary Nelson and Dr. Lorrie Shepard and make list of concerns regarding validity, reliability, gender or cultural bias |
| Summer 2002 | Provide training in emergent processes, coding verbal protocols, rating of textbook examples.<br>Develop rubrics for verbal protocols<br>Develop rubrics for textbook examples<br>Send out first iteration of questionnaire for Delphi study |
| Fall 2002 | Rate textbooks examples<br>Complete Delphi study<br>By November 30, 2002 develop list of misconceptions to be used |
| Spring and Summer 2003 | Create multiple-choice questions<br>Validate multiple-choice questions through think-aloud protocols with experts and novices<br>Score think-aloud protocols<br>Validate multiple-choice questions by expert review<br>Revise multiple-choice questions if necessary based on think-aloud and expert review<br>If necessary, conduct second think-aloud and expert review<br>Create acceptable multiple-choice questions by August 1, 2003 |
| Fall 2003 | Pilot multiple-choice instrument at Colorado School of Mines and University of Washington<br>Interview students to validate instrument |

| | |
|---|---|
| | Score verbal protocols of interviews<br>Complete item analysis of results – check reliability and bias, discard or revise items<br>Revise instrument by November 30, 2003 |
| Spring and Summer 2004 | Complete second round of testing<br>Interview students to validate instrument<br>Score verbal protocols of interviews<br>Complete item analysis of results – check reliability and bias, discard or revise items<br>Revise instrument by June 30, 2004 |
| Fall 2004 | Refine instrument if needed<br>Once sufficient reliability is met, begin to distribute instrument to engineering instructors through ASEE and professional engineering societies<br>Continue dissemination through articles, presentations |

## Qualifications of Project Investigators

As indicated by the biographical information included with this proposal, project work will be conducted by an experienced, interdisciplinary team of investigators with backgrounds in chemical engineering, educational psychology, cognitive psychology, assessment and evaluation, and testing and measurements. Dr. Ron Miller will act as project principal investigator and will be responsible for day-to-day management of the project as well as acting as content expert on engineering misconceptions. He has extensive experience in engineering pedagogical and assessment research and has directed five educational research projects funded by NSF, FIPSE, and the National Endowment for the Humanities. Dr. Ruth Streveler will be responsible for conducting the Delphi study of engineering faculty to identify misconceptions, helping conduct verbal protocol studies, and assisting Dr. Miller in managing project activities. She has extensive experience in identifying student misconceptions using advanced assessment tools such as multidimensional scaling. Dr. Barbara Olds will be responsible for conducting verbal protocol studies and assisting Dr. Streveler with the Delphi study. She is an expert in qualitative outcomes assessment including use of portfolios, focus groups and verbal protocol analysis. Dr. Michelene Chi will act as project lead consultant. She has an international research reputation in the areas of conceptual change and cognitive assessment of learning. Dr. Lorrie Shepard will act as Ph.D. advisor to Ms. Mary Wilson who will be responsible for constructing the misconception assessment instrument including assessing reliability and validity data. Dr. Shepard had extensive experience in educational measurements and test construction, and is the Dean of the College of Education, at the University of Colorado, Boulder. Dr. Tony Dean, the Coors chair in chemical engineering at the Colorado School of Mines will assist Dr. Miller as a content expert consultant during the project. Dr. Dean has extensive research experience in molecular modeling of dynamic chemical systems and pedagogical applications of molecular dynamic models.

## Broader Impact of the Project

Results from this project have the potential to significantly and positively impact the quality of learning for engineering students studying topics in thermal and transport sciences. At the end of the project, we will have developed an easy to use, reliable, and valid outcomes assessment instrument that will help engineering faculty identify important student misconceptions about molecular processes such as heat conduction, molecular momentum transport, diffusional mass transfer, and equilibrium thermodynamics. In physics education, development and use of the Force Concept Inventory [12] has positively influenced how introductory college physics is taught and consequently dramatically improved the students' understanding of newtonian mechanics. We believe that our instrument will provide a similar influence on learning and teaching in the transport and thermal sciences.

## How Under-represented Groups are Involved in the Project

Women and ethnic minorities, groups traditionally under-represented in science and engineering, [27] will be included in the sample of students studied. In the Spring 2001 semester, the undergraduate student body at the Colorado School of Mines was comprised of 25.2% women, and 13.8% ethnic minorities. [28] At the University of Washington, 21% of the engineering degrees granted in 1997-98 were awarded to women, 5% were granted to underrepresented minorities, and 29% were granted to Asian Americans. [29] Because cultural differences are a concern in science assessment [30, 31] our results will be rigorously checked to be sure gender and cultural bias has not occurred.

## Project Evaluation Plan

Given the nature of this project, evaluation activities are necessarily embedded in each of the four project tasks described earlier. Therefore both formative and summative evaluation will be conducted throughout the project to determine when each of our objectives has been successfully met. A summary of on-going evaluation activities is provided in Table 4 below along with a brief summary of our methods for implementing the tasks required to achieve each project objective.

Table 4 – Summary of Project Implementation and Evaluation Strategies

| Project Objective | Implementation Strategy | Evaluation Strategy |
|---|---|---|
| Develop a list of the 15-20 most widely held misconceptions in the thermal and transport sciences | Delphi study of experienced engineering faculty. Search commonly used engineering textbooks for examples of emergent phenomenon given causal explanations. Two raters rate textbook examples. | Can the faculty in the Delphi study reach consensus on 15-20 most commonly held misconceptions? What is inter-rater reliability of textbook examples using causal models (when emergent models are appropriate)? |
| Create a multiple-choice instrument to assess engineering students' causal/emergent misconceptions | Develop a conceptual or computational problem related to each of the 15-20 misconceptions identified above. Conduct think-aloud with experts and novices. Expert review of questions; 30 undergraduate engineering students work problems and are interviewed about why they solved the problems as they did. Use interview text to draft 4 multiple-choice questions for each of the 15-20 misconceptions. | Do think-aloud protocols results validate that questions test for causal vs. emergent thinking? Does each student consistently answer questions for each concept correctly or incorrectly? Do questions for a given concept provide consistent information about incorrect application of a causal model? Does expert review validate the instrument? |

| | | |
|---|---|---|
| Field test the instrument to demonstrate validity, reliability, and absence of bias. | One hundred engineering students work through multiple-choice questions and 20 are interviewed. In interviews, students explain their answers and these answers are coded as causal or emergent. Student interview responses measure validity. Use split-half statistical method to measure reliability. Item analysis for reliability and to test for cultural and gender bias. | Does coding of student interviews show that emergent answers match correct responses on corresponding multiple-choice questions, and causal answers match incorrect responses on corresponding multiple-choice questions? Are split-half measures of reliability within acceptable levels? Do the results show any cultural or gender bias? |

## Project Dissemination Plan

Since the overall goal of this project is to create an outcomes assessment tool for faculty use, we consider dissemination of our results and tools to the widest possible target audience as a professional obligation. Two types of mechanisms will be used to conduct our dissemination activities. First, we will report findings of our work to interested colleagues by presenting papers and workshops at regional and national engineering and educational conferences including American Society for Engineering Education, Frontiers in Education, American Educational Research Association, American Association for Higher Education and others. Results will also be published in education journals published by these organizations. Second, we will offer free copies of our assessment instrument with documentation to any faculty members interesting in measuring thermal and transport science misconceptions in their students. All we will ask from these faculty will be a willingness to share with us their results and how they used the data to improve learning in their courses. The instrument will be made available and supporting documentation will include a user manual describing how to administer the instrument, how to interpret and apply the results, and hints for creating classroom interventions that will help repair students' flawed mental models. To protect the integrity of the misconception assessment, we do not anticipate offering the instrument directly to students without faculty participation. Based on concerns by the American Association for the Advancement of Science about misconceptions in science textbooks [32], we will also share our findings with publishers of the texts we review in this project.

## Benefits of Project to Society at Large

To quote President George W. Bush, "Science and technology have never been more important for the defense of our nation and the health of our economy." [33] At the same time, the number of new American engineers and scientists is continues to decline. [34] One barrier to educating new engineers is the large number of concepts in engineering and science (such as the dynamic emergent processes we discuss in this proposal) that are difficult for students to learn. This project proposes a method for striking at the heart of why these concepts might be so difficult – the persistence of student misconceptions. Developing a way to assess the existence and degree of student misconceptions is the first step in developing improved methods of instruction to help students understand difficult science concepts. When these concepts become more accessible, and more understandable, we believe this will encourage more students – and very possibly more students in under-represented groups – to enter science and engineering fields. References Cited

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