AC 2008-2916: IDENTIFYING ROBUST STUDENT MISCONCEPTIONS IN THERMAL SCIENCE USING MODEL-ELICITING ACTIVITIES

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Identifying Robust Student Misconceptions in Thermal Science using Model-Eliciting Activities

The conceptual change literature indicates the presence of robust, strongly-held misconceptions in thermal science (e.g., heat transfer, fluid mechanics, thermodynamics) even after many years of formal and informal learning. For example, data collected using the Thermal and Transport concept inventory suggests that a significant number of seniors in chemical and mechanical engineering confuse the rate of energy transfer vs. the amount transferred, do not understand how temperature and energy are related, and believe that the thermal efficiency of a heat engine can be increased to 100% if all heat losses and mechanical efficiencies are eliminated[1].

While concept inventories are one method for identifying student misconceptions, we are now exploring the development and use of a new pedagogical technique called model-eliciting activities (MEAs). MEAs were first developed to elicit problem-solving strategies from students in mathematics classes, but have now been expanded to other disciplines including ethics and engineering science[2,3].

Through a collaborative, large-scale National Science Foundation project, MEAs are now being developed to elicit student misconceptions about important but poorly understood concepts in thermal science. For example, misconceptions about the second law of thermodynamics and its effect on energy quality are being explored in an MEA where students estimate the overall thermal efficiency of electric vs. hybrid vs. gasoline cars. Student teams must use a systems approach and include all relevant energy conversion steps in their problem solving process.

In this paper, we will describe MEAs and how they are being used for misconception identification. Potential MEA topics and a sample MEA are provided and discussed in detail.

Introduction to Model Eliciting Activities

The following is an introduction to a comprehensive four-year effort by a team of researchers from six universities that focuses on *models and modeling* as a foundation for undergraduate STEM curriculum and assessment. This effort is focusing on improving engineering education, with the present discussion focusing specifically on using models and modeling to elicit student misconceptions in thermal sciences.

Our approach builds upon and extends a proven methodology: model-eliciting activities (MEAs)[2,4,5]. MEA research, which originated in the mathematics education community[6], uses open-ended case studies to simulate authentic, real-world problems that small teams of students address. The most salient of its distinctive features is the emphasis on developing systems thinking in problem-solving. A typical MEA requires applying mathematical or other structural interpretations (a model) to situations that cut across multiple disciplines and constraints. Students may need to make new connections, combinations, manipulations, predictions or look at the problem in other ways in order to develop a solution to an MEA.

MEAs do not resemble the problem-solving activities involved in most course textbooks, differing in length of time, access to information resources, number of individuals involved in problem-solving, and type of documentation that is required. However, the most important difference is the emphasis on building, expressing, testing and revising conceptual models.

The format of an MEA is such that the students are first introduced to the context through an advanced organizer. In a typical MEA, an advanced organizer is a newspaper article, a memo from the client, or a company profile that helps students enter into the problem. The organizer includes questions to help students individually begin to think about the situation in which they are being placed or assist them in organizing their conceptual understandings in a manner that will be advantageous to them as they work on the engineering task. Moore and Diefes-Dux [7] provide more information about the framework and development of engineering content MEAs.

The problem statement introduces students to the task. It is written in such a way as to make the students define for themselves the problem a client needs solved. The students must assess the situation and create a plan of action to successfully meet the client's needs. The problem solving session requires that a group of students go through multiple iterations of testing and revising their solution to ensure that their procedure or algorithm will be useful to the client. By carefully crafting each MEA, students are given just enough information to make informed decisions about when the client's requirements have been met. One of the main differences between this type of task versus typical engineering problem solving activities is that most traditional problem solving activities are focused solely on the creation of a physical product; whereas, MEAs are directed at the development of procedures or processes for solving the problem.

Due to the nature of the problem statement, teams of students solve the problem to meet the client's needs. The teams are necessary for two reasons. First, there is a time constraint on the solution of the problem. Therefore, students do not have the luxury of mulling over the task for hours to think of things they might have missed. By requiring multiple perspectives, the teams come to better solutions in less time. Also, engineers working in industry often must rely on the expertise of team members to complete tasks assigned to them. Being able to effectively work in teams is not a skill that most people automatically possess. Therefore, it is necessary to put students in situations where it is essential to work in teams to allow them to develop teaming skills.

Thermal Science Misconceptions

Over the past ~20-30 years, science and engineering educators have become increasingly aware that students who are capable of solving routine problems and answering straight forward questions are likely to possess incomplete or incorrect knowledge about fundamental conceptions in their discipline. This lack of conceptual understanding can manifest itself in students' inability to describe what professors might consider simple concepts and potentially will interfere with our graduates' ability to perform their jobs[8].

Thermal science is no exception and while most engineering students have not received formal thermal science instruction prior to college, they are aware of energy and heat in their daily lives. Based on a constructivist model of learning, such exposure results in students' construction of mental models (often robust and flawed) about how energy flows and transformations impact their lives.

A survey of the misconception literature compiled by Duit[9] suggests that conservatively 500-600 of the 7700 included articles 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[10,11]:

> 1) Heat and temperature are equivalent (i.e., a body that is at a higher temperature always contains more energy regardless of heat capacity or phase).
>
> 2) Temperature determines how “cool” or “warm” a body feels (i.e., a tile floor is at a lower temperature than nearby carpet because it feels colder).
>
> 3) Heat is a substance transferred between bodies (i.e., a hotter body contains more “heat” substance and a colder body contains more “cold” substance).
>
> 4) Addition of energy as heat always increases the temperature in a body (phase change is ignored).
>
> 5) Temperature should change in a phase transition (e.g., boiling) since energy is being added or removed (energy and temperature are once again equated).

In a recent project to identify key concepts and misconceptions in thermal and transport science, Streveler and colleagues conducted a Delphi ranking study involving 30 experienced thermal science professors and textbook authors[12]. 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:

> 1) Heat vs. energy
>
> 2) Temperature vs. energy
>
> 3) Steady-state vs. equilibrium processes

This list aligns closely with the common misconceptions listed earlier above. For example, “heat vs. energy” and “temperature vs. 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 vs. 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.

Developing MEAs to Elicit Misconceptions

One of the biggest challenges in repairing a student misconception is to first identify the existence and extent of the misconception. Various classroom and research techniques have been applied to this type of assessment including think-aloud protocols, interviews, and concept inventories[1]. With the recent emergence of model-eliciting activities (MEAs) as both a pedagogical and assessment tool in engineering education, we have proposed that MEAs can be constructed to elicit student misconceptions in thermal science. If successful, this type of MEA will complement other tools for measuring student misconceptions. In addition, concept MEAs may have the advantage of also helping repair misconceptions as students work to complete an MEA.

For example, an MEA which asks students to determine the maximum amount of work which can be extracted from a heat engine for various combinations of steam temperature and pressure, equipment efficiencies, and sink temperature will require students to create a mathematical model to compare all possible combinations of these variables. In the process of creating the model, conceptual understanding (or misunderstanding) about the 1^{st} and 2^{nd} laws of thermodynamics and relevant heat transfer concepts will be revealed.

The first step in developing MEAs which elicit student misconceptions is to understand what exactly MEAs are and how they differ from standard homework-type problems. In general, model-eliciting activities emphasize applied mathematical activities with the following characteristics:

1) Solutions generally require a small group of students at least 15-60 minutes to construct, and they provide powerful prototypes for dealing with issues that are important to the students.

2) The issues addressed encourage students to engage their personal knowledge, experience, and sense-making abilities.

3) Solution procedures encourage students to use engineering tools and resources, such as computers, reference material, consultants, colleagues, etc.

4) Evaluation procedures recognize more than a single type and level of correct response.

5) Overall activities contribute to both <u>learning</u> and <u>assessment</u> … because student simultaneously learn and document what they are learning.

The following six principles were developed to test whether a particular task given to students qualifies as a MEA. See Lesh, et al.[4] and Diefes-Dux, et al.[3] for more detailed information regarding these principles and how they are used to design MEAs.

<u>The Reality Principle</u>: The task provided to students should occur in "real life." Students should be able to make sense of the situation based on extensions of their own personal knowledge and experiences. The context of the MEA needs to be *realistic* to the students,

and they need to see the situation as important work that should be done by engineers. Often times, certain simplifying assumptions must be included in an MEA to make it accessible to the level of intended student audience; however, students must still feel that the task is similar to the work done by engineers.

The Model Construction Principle: The task must create the need for a model to be constructed, modified, extended, or refined. The task will typically involve constructing, explaining, manipulating, predicting, or controlling a structurally significant system. An MEA should focus attention on underlying patterns rather than on surface-level characteristics.

The Self-Assessment Principle: Criteria for self-assessment should be clear. Students should be able to determine for themselves when their solution is adequate. The client and their reasons for posing the task should be presented. Often carefully selected and manipulated data are used to force students to go beyond their first, often naïve, models.

The Model-Documentation Principle: The response required of students should explicitly reveal how they are thinking about the situation (givens, goals, possible solution paths). This will include the kind of system (mathematical objects, relations, operations, patterns, regularities) about which they are thinking. This is often accomplished by having the teams provide their solutions to the client in the form of a written memo or letter that addresses the client's need and the student team's proposed solution.

The Generalizability Principle: This principle is often called "The Model Share-Ability and Re-Usability Principle." The model needs to be communicated in a manner that others can use the model for their own purposes ("share-able"). This is usually accomplished by requiring the student teams to create a model that a client will implement. In addition, the model should be applicable to a broader range of similar situations than just those presented in the problem statement ("re-usable"). A typical homework problem encourages single-purpose ways of thinking, whereas a well-constructed MEA will challenge students to produce reusable, sharable, and modifiable models.

The Effective Prototype Principle: The concepts that students must ingrate, formulate, construct, modify, etc. must be robust in terms of their applicability to the future academic and professional life of the engineering students. A high-quality MEA will help students work with several important and common concepts. An MEA will only be effective as a learning tool if the student is likely to need the same "kind of thinking" as used in the MEA at a later time. The construct required should not be overly complex, while still creating the need for a significant model. After the completion of an MEA, structurally similar situations will induce recall of the thought processes used while solving the MEA.

To ensure that the MEAs developed address each of these principles, we use checklists with each principle explicitly stated and how a given MEA addresses each principle. While all of these principles are important, the Effective Prototype Principle is paramount for using MEAs to elicit misconceptions. This principle restated says that the model developed by students should not be so complex that it masks the underlying fundamental principles involved. The simpler the model, the easier it is for the evaluator to identify what misconceptions are deeply held by students.

At present, we are in the midst of developing our first MEAs which elicit student misconceptions. We started this process by brainstorming a list of potential topics that could be developed into MEAs. Our brainstorming effort was performed by two faculty members (specifically a senior- and a junior-faculty member) and an undergraduate researcher. Having collaborators to consult during this effort proved fruitful. Undergraduate thermodynamic and physics textbooks were reviewed at this point as reference material. In particular, the homework problems were evaluated to see which, if any, could be expanded into an appropriate MEA. These three team members have been meeting approximately every other week with additional collaborators who are focusing on other applications of MEAs. Some of these meetings were in person, and others regularly utilized video conferencing.

A sample of topics from this brainstorming effort includes:

1) First and second law efficiencies of simple household devices such as the hairdryer, refrigerator, or clothes dryer.

2) Energy usage and exergy analysis of human performance in various contexts (e.g., working versus relaxing).

3) Comparison of energy and exergy content of different fuels derived from fossil fuel and renewable energy sources.

4) Development of a model to determine if certain quantities discussed in thermodynamics (heat transfer, work, entropy, etc.) are properties based on data provided to students.

5) Assuming students are familiar with the ideal gas law, students would be given pressure, temperature, and volume data of substances. Much of the data will follow the ideal gas law, but some deviation from the ideal gas law will be observed. The students will be asked then to expand the ideal gas law model to accommodate these deviations from ideal gas behavior. The established way to account for these deviations is the compressibility chart, but they will all have their own model to address this.

6) Students would be given a set of data (probably columns of work and heat transfer data, but it could be pressure, temperature, volume, etc.) and then they would be asked to develop a model for determining if the system violates the first law of thermodynamics. Their model would have to account for the fact that the system could be open or closed.

After brainstorming this list of over 30 items, we turned our attention to expanding some of the possible MEA topics into draft MEAs. Right now, we are focusing on three specific MEA topics. An example of one of these is titled "**Determining the Most Efficient Solar Energy Collector for a Home.**" The greater context for this MEA is that there is increasing societal interest in using solar energy wisely and inexpensively to address climate change concerns. For this MEA, a hypothetical start-up company is developing their business model. As part of this, they are debating whether it makes more sense to install photovoltaic (PV) panels on a house to create electricity from solar energy or alternately, install solar heating panels which produce hot water from solar energy to be used for heating or consumption. In this exercise, the students will help this company by developing models which allow one to compare two sets of options:

- Option 1 – electricity generated with PV panels vs. purchased electricity from the utility company
- Option 2 – hot water from solar panels vs. hot water created in a household hot water heater fueled by natural gas

The basis upon which the students will make these comparisons can vary, but typically engineers are concerned with lowest cost options – so an economic analysis can determine which investment in solar energy equipment will be paid back more quickly. A second option is that a comparison can be performed to determine which option represents the largest amount of available energy (or exergy) as defined by the 2nd law of thermodynamics and which option uses the available energy more efficiently.

It is unfortunately impossible to know in advance which misconceptions in thermal science will be elicited from a given MEA. Because this Solar Energy Collector MEA focuses on conversion of solar energy into other energy types, it will no doubt identify misconceptions regarding conservation of energy. In addition, the fact that the performance of option 1 is reduced on hot days (PV cell efficiency decreases with temperature) whereas the performance of option 2 is enhanced on hot days will force students to think carefully about their understanding of the concept of temperature and its impact on system performance. By choosing an MEA topic which addresses basic thermal science concepts like heat transfer, temperature, and energy conversion, we expect this MEA to successfully elicit deeply rooted misconceptions in these areas.

At this point, a team member with significant experience in MEA writing was brought in. This provided an interesting opportunity for us; while some team members were learning about MEA writing, another team member was learning basic thermodynamics. Some of this collaboration occurred via video and phone conferencing, but eventually it was determined that a 2-day face-to-face effort would prove most fruitful. The outcome of this meeting was several draft MEAs that were ready for the initial stages of our assessment plan.

Even at this early point in MEA development, it has become clear that consideration of the size/scope of the MEA is paramount to success. If the scope is too large, students can get easily overwhelmed by the sheer number of possible solutions. If the scope is too small, students do not get all the benefits of a true MEA experience. Directly related to scope is the time required of students to develop their model. We have found creative efforts of our students can take much longer than we anticipate. One way to reduce the class time required to perform a given MEA is to provide some aspects of the MEA to students ahead of time. In addition to saving time, this "read-ahead" will give the students opportunity to ponder aspects of the problem as independent thinkers, prior to being confronted with group dynamics.

Assessment Plan

Because of the difficulty in creating a successful MEA, we are planning three levels of initial assessment to refine and improve the assignment. The first steps will be to simply have our team, possibly with the addition of one or two graduate students, do a trial run. This will help identify key aspects of the MEA that might need to be adjusted and should help us ascertain if the six principles are being addressed. For the second level of assessment, we plan to hire undergraduates currently in thermodynamics to actually do the MEA. We will ask them to answer several concept questions before and after participating, will videotape the session, and will also conduct a post-MEA survey and interview. Depending on the outcome of these tests and the level of MEA revisions, additional trial groups may be hired. Finally, we will beta test the MEA on an entire class. This testing will again be assessed using videotaping and conceptual quizzes.

It is also important to assess student performance on these open-ended problems. A Quality Assurance Guide, as used by Moore[13] and by Self and Widmann[14], provides an overall assessment that measures "How useful is the solution (mathematical model) for the purposes of the client?"

Table 1. Quality Assurance Guide[13].

Quality Score	Performance Level
1	Requires Redirection
2	Requires Major Extensions or revisions
3	Requires only minor editing
4	Useful for the specific data given
5	Sharable or reusable

Additional tools may also be utilized to assess performance on MEAs. A grading rubric based on technical content is being developed by Diefes-Dux, et al. (NSF Award 0535678). This project "Assessing and Evaluating Student Work on Modeling Activities Imbedded in a First-Year Engineering Problem Solving Course" focuses on improving assessment techniques in MEAs. These assessment tools include formative feedback for MEA draft solutions and methods to ensure grade consistency across multiple sections.

Finally, we will administer the Thermodynamics Concept Inventory before and after the course to help determine if the MEAs improved the conceptual understanding of the students. The normalized gains for the overall scores and for the specific questions that relate to the MEA will be examined. By comparing normalized gains of class sections completing the MEAs to those who do not, the effectiveness of the MEA can be determined.

Future Work

In addition to using MEAs to identify student misconceptions, we plan to expand our efforts to develop MEAs to directly repair these misconceptions. We expect to be able to address both challenges and provide a way for classroom instructions that help students better learn key concepts. The fact that MEAs are client-driven solutions that are tested and revised by students suggests that they may be effective tools for the reparative task.

While a well-constructed MEA will force students to delve into a problem and construct solutions that might help repair misconceptions, it may be insufficient to fully convince them that their long-held mental model is incorrect. Because of this, we will further extend the MEA construct to incorporate physical demonstrations and laboratory experiences. Many of the thermal science misconceptions previously discussed can be effectively addressed via "hands-on" experiences.

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