Larry Shuman, University of Pittsburgh
Larry J. Shuman is Senior Associate Dean for Academics and Professor of Industrial Engineering at the University of Pittsburgh. His research focuses on improving the engineering educational experience with an emphasis on assessment of design and problem solving, and the study of the ethical behavior of engineers and engineering managers. A former senior editor of the Journal of Engineering Education, Dr. Shuman is the founding editor of Advances in Engineering Education. He has published widely in the engineering education literature, and is co-author of Engineering Ethics: Balancing Cost, Schedule and Risk - Lessons Learned from the Space Shuttle (Cambridge University Press). He received his Ph.D. from The Johns Hopkins University in Operations Research and the BSEE from the University of Cincinnati. He is an ASEE Fellow.

Mary Besterfield-Sacre, University of Pittsburgh
Mary Besterfield-Sacre, Associate Professor and Fulton C. Noss Faculty Fellow in the Department of Industrial Engineering and Center Associate for the Learning Research and Development Center at the University of Pittsburgh. Dr. Sacre’s principal research interests are in engineering education assessment and evaluation methods. She has served as an associate editor for the Journal of Engineering Education and is currently associate editor for the Applications in Engineering Education Journal. She received her B.S. in Engineering Management from the University of Missouri - Rolla, her M.S. in Industrial Engineering from Purdue University, and a Ph.D. in Industrial Engineering at the University of Pittsburgh.

Tuba Pinar Yildirim, University of Pittsburgh
Tuba Pinar Yildirim is a dual doctoral candidate of Industrial Engineering and Marketing at University of Pittsburgh. She received her MS degree in Industrial Engineering at the University of Pittsburgh, and BS degrees in Industrial and Mechanical Engineering fields from Middle East Technical University in Turkey. Her primary research interests are modeling and cognitive and affective processes that motivate or hinder modeling skills. Her publications appeared in Journal of Engineering Education, International Journal of Eng. Education and Journal of Marketing. Her other research is under review at American Economic Review, Journal of Marketing and Marketing Science. She was also the recipient of the IERC Best Paper Award in Engineering Education in 2007.

Nora Sieworiek, University of Pittsburgh
Nora Siewiorek is a graduate student in the Administrative and Policy Studies department in the School of Education at the University of Pittsburgh where she also received her MS in Information Science. Her research interests include: engineering education and educational assessment and evaluation. Her K-12 outreach activities are organizing a local science fair and a hands on workshop in nanotechnology. Her other research interests are: higher education administration, comparative and international education.
CCLI: Model Eliciting Activities:  
Experiments and Mixed Methods to Assess Student Learning

Abstract
As part of a seven university CCLI Type 3 collaborative effort addressing models and modeling as a foundation for undergraduate curriculum enhancement and assessment, we are building upon and extending the model eliciting activity (MEA) construct, originally developed and validated by mathematics education researchers. Our overall goal is to enhance problem solving and modeling skills and conceptual learning of engineering students through the use this construct. At the University of Pittsburgh, we have pursued two main research avenues: MEAs as teaching tools and MEA as learning assessment tools. This paper summarizes our results to date. Under the first – using MEAs as a teaching tool – we have focused on three main activities: development of effective MEAs, implementation of (new or adapted) MEAs, and enhancing the learning benefits of MEAs:

Under the second stream - using MEAs as a learning tool - we have focused on two additional activities: assessing the effectiveness of MEAs in various dimensions including improving conceptual learning and problem solving, and assessing the MEA motivated problem solving process.

We summarize our achievements in these five activities over the first two and half years of our four year project. We provide an overview of the 18 MEAs we have developed or modified. Particular emphasis is placed on our mixed measurements of student learning and achievement, including the use of pre and post concept inventories, deconstruction of MEA solution paths and conceptual understanding, rubric scoring of completed MEAs and student reflections of the just completed problem solving process.

Introduction
“Collaborative Research: Improving Engineering Students' Learning Strategies Through Models and Modeling” is a CCLI Type 3 project involving seven university partners: California Polytechnic State University, Colorado School of Mines, Purdue University, United States Air Force Academy, University of Pittsburgh, University of Minnesota-Twin Cities and Pepperdine University. We are building upon and extending the model-eliciting activities (MEA) constructor originally developed by mathematics educators, that has recently been introduced into engineering education. These posed scenarios simulate authentic, real-world problems that teams of students then address. MEAs were first developed as a mechanism for observing the development of student problem-solving competencies and the growth of mathematical cognition. However, it has been increasingly documented that MEAs provide a learning methodology that helps students become better problem solvers.

We are taking the theoretical framework from mathematics education and research results from a series of NSF funded studies in order to create a strategic, scalable approach for addressing crucial goals in engineering education. These include:
- Developing effective, transferable competencies in problem-solving and creativity;
- More effectively learning and retaining important concepts; and
- More effectively identifying misconceptions and nurturing positive ethical frameworks.
We also are investigating and extending a suite of assessment approaches that have been developed and tested in recent MEA research. Here, our specific objectives are to:

- Expand the MEA methodology and application,
- Study students' problem solving strategies and extend the use of MEAs to specific aspects of undergraduate reasoning and problem-solving,
- Determine solution paths first-year engineering students use in solving MEAs,
- Execute a comprehensive dissemination and infusion effort, and
- Develop a comprehensive research agenda for models and modeling in undergraduate education.

In particular, we are extending MEA implementation and complementary student and faculty assessments across our partner institutions; broadening the library of usable MEAs to different engineering disciplines; and extending the MEA approach to identifying and repairing misconceptions, using laboratory experiments as an integrated component, and introducing an ethical decision-making dimension [1].

Our overall research goal is to enhance problem solving and modeling skills and conceptual learning of engineering students through the use of model eliciting activities. In order to accomplish this goal at the University of Pittsburgh, we are pursuing two main research routes: MEAs as teaching tools and MEA as learning assessment tools. Under the first – using MEAs as a teaching tool – we are focused on three main activities:

1. *Development of effective model eliciting activities:* The creation of MEAs for upper level students that effectively use the six principles of the MEA construct that can enhance problem solving skills and/or conceptual learning. To date, we have developed or modified 18 MEAs.

2. *Implementation of (new or adapted) MEAs:* focuses on implementing and assessing the developed and adapted MEAs in classroom settings as a means to study the problem solving and modeling processes. It provides an opportunity to evaluate both the MEAs and the various assessment tools.

3. *Enhancing the learning benefits of MEAs:* focuses on adding new conceptual dimensions to MEAs in order to enhance student learning. In particular, we are adding an “engineering ethics” dimension to the MEAs as a means of improving students’ ability to recognize and resolve ethical dilemmas, and have thus created E-MEAs (ethical MEAs).

Under the second stream - using MEAs as a learning tool - we have focused on two additional activities:

4. *Assessing the effectiveness of MEAs in various dimensions including improving conceptual learning and problem solving:* focuses on understanding and measuring the educational benefits of using MEAs.

5. *Assessing the MEA motivated problem solving process:* focuses on understanding different problem solving processes used by the student teams, as well as the various types of problems that can be addressed and how these process lead to conceptual understanding.

In the following sections, we provide the details on each of these five research foci.
Development of Effective MEAs
Our initial focus was to develop or adapt MEAs; below is a description of eleven new MEAs have been created and tested within the classroom at least once. These are primarily designed for industrial engineering students and students in engineering statistics courses. We briefly describe these below, see Shuman, et. al [2] for additional detail.

**SUV Rollover** targets experimental design with a cost constraint; statistical decision making using ANOVA; public welfare vs. non-disclosure. The case is modeled after the Ford Explorer – Firestone Tire rollover incidents. Students must first design an experiment, and then, analyze the simulated data. They must deal with the ethical question of whether to disclose their findings if the perceive that the safety of the public is at stake.

**CNC Machine Replacement** focuses on statistical hypothesis testing; each team must determine if a CNC machine investment would be justifiable, Concepts of mean and variance, economic analysis, and sub-optimization. The ethical issue focuses on pressure/intimidation from a supervisor who expects a particular result regardless of what the data indicates.

**Hazardous Materials** deals with analyzing categorical data, missing data and the value of life. Students must create a procedure for deciding whether a small, rural Pennsylvania county faced with a series of hazardous material spills on its sole major highway should invest $2 million in countermeasures that might lead to a reduction in such accidents.

**Dam Construction** addresses on multi-criteria decision making, economic analysis, and presents an international perspective; ethical issues involve the impact of dams on society and risk. The MEA concerns the proposed construction of dam in the South Eastern Anatolia (Turkey). Having approved the initial plans, the Turkish Government, for economic reasons, now must reduce the dam’s budget. Students must evaluate various alternatives.

**Ethanol Production** presents issues of facility location, optimization, economic analysis, and the ethical issue of growing corn for fuel or food. Students create a procedure for determining whether a “green,” socially-conscious Midwest agricultural company in should become an ethanol producer or remain solely in grain production for food and livestock. If the company is to become an ethanol producer, the team also must evaluate various sites for the production facility, which might use any one of several feed stocks. In the second part, the company has decided to move forward and locate its ethanol production facility in Ames, Iowa. The students next must determine whether it should pursue a centralized or de-centralized distribution scheme, given a set of potential distribution center locations.

**Trees** involves recognizing and resolving an ethical dilemma - to reduce auto accidents by preserving old growth trees; skills targeted also include economic analysis, data analysis. There have been a series of accidents although the primary cause may be excessive speed (once the students examine the data provided). The county’s department of transportation had decided to remove the trees. However, a citizen’s environmental group when it learned of the decision has begun to protest. The team must now assist in resolving that dispute. In part 2 students are told that the trees are redwoods. Will they now come up with a different decision?
Outsourcing Gown Manufacturing requires students to determine whether or not to outsource offshore, and if so, where to outsource; they must address the ethical issues of moving manufacturing offshore; possible use of child labor; and protection of intellectual property (IP). The MEA is built around a U.S. company planning to outsource its wedding gown manufacturing facility to one of three countries with the idea of also selling its gowns in that country. The team must also determine adjustments to the gowns according to the anthropometry measures of females in the selected country. Costs of outsourcing versus remaining in the U.S. must be addressed.

Medsafe Cardiac Devices is built around understanding the central limit theorem and the basis for sampling and hypothetical testing. A company that makes implantable defibrillators is concerned about defective leads. Students must propose the minimum size sample that should be tested to determine if a batch of leads meets specification with a given precision. The ethical issue involves when to recall defibrillators that have already been implanted if there is concern about the quality of the leads.

Quality Process Control is designed for students to understand how to dynamically follow a quality control process and obtain a manufacturing process that is capable. Here a car parts manufacturer needs to demonstrate to its potential Japanese client that it can produce parts at the desired quality level. The ethical issue is embedded in the manner that the manufacturer requests the report from the “consultants.” There is pressure to verify that the process is of the required quality using personal relationships. Also there is a suggestion.

Wind Energy requires deciding whether or not to build a wind energy farm, and if so, should it be located onshore or offshore? Students must utilize long term planning, forecasting, and economic analysis skills; they must consider trade-off between onshore and offshore. The primary ethical issue involves a consideration of both the potential benefits and harm that is caused by the wind energy including, if it is offshore, the right of those living on the coast to an unobstructed view.

Disaster Decision Modeling targets Bayesian decision nets. The students must develop a model to support a regional evacuation decision prior to an impending hurricane. A real-time information source in the form of a simulated expert is available on the scene. The teams determine their information needs from the expert. The ethical issue involves appropriate preparation for natural disasters.

Adapting and Implementing MEAs Developed by Other Researchers
We have also adapted and implemented MEAs developed by other researchers. Prior to the start of this research project we created a course to pilot various MEAs, most of which had been developed by colleagues (primarily at Purdue for freshmen [3]), and then modified by us for upper level engineering students. Almost all of these modified MEAs were piloted in a course designed to improve engineering students’ problem solving skills. In extending these MEAs to upper-level engineering students, we required students to use concepts and skills from prior coursework. In this manner, the MEAs also served as a concept integrator.
As a way to enhance problem solving and assess this process, we have required students to reflect on the process they used to resolve each MEA. Consequently, we modified and incorporated the set of Reflection Tools as first proposed by Hamilton et al. [4]. As noted later in this paper, the use of reflection and reflection tools has become an important assessment methodology.

We describe the MEAs that are developed by others and adapted by us below. Most of these MEAs did not include an ethical dimension, since they were part of a pilot course we taught in anticipation of the project beginning.

**Condo Pricing** is focused on linear regression as a modeling tool. Specifically, the students were asked to develop a model to price the units of a new condominium based on various features. A dataset consisting of features, both numerical and categorical, as well as prices of units for a nearby building were provided.

**Quality Improvement** targeted control charting and root cause analysis. A manufacturing client is faced with both high scrap and quality variation. In the first part the team is given diameter measurements from two shifts and asked to formulate an investigation plan. In part two, the team is challenged to develop a comprehensive improvement plan that also addresses customer complaints.

**Compressor Reliability** addressed the use of the Central Limit Theorem for failure-time data. The client requests a procedure for calculating the probability of interest, based on a non-normal dataset. To uncover the failure characteristics, the team must develop a procedure to statistically determine the failure type (burn in vs. wear out), using samples provided.

**Volleyball Team Formation** involved categorical data analysis; assignment problem. The engineering team had to synthesize multiple player attributes characterized by continuous, categorical, and qualitative data to build three equitable volleyball teams at a girl’s summer camp. Although a small dataset is provided, the camp organizers requested a plan for handling 1,000 or more players for next summer.

**CD Compilation** targeted model building; 0-1 Integer/linear programming. Here the students must develop a procedure to create music CDs considering cost, time, and genre. A heuristic approach is anticipated. What selections should be chosen? What is the order that they should be placed on the CD?

**Campus Lighting** is used as an introduction to engineering economics. Students must decide what costs and criteria to use in selecting the best way to improve campus lighting given several alternatives and a budget constraint.

Table 1 below summarizes the various courses in which these MEAs have been implemented and the data collected. We have included the purpose of the MEA for the particular implementation [5]. These are:

- Integrate learning from previous courses with new information (**integrator**);
- Reinforce the concepts that are currently being covered (**reinforcer**); and
Discover a concept that has yet to be formally introduced (discoverer).

Table 1: MEA Implementations at University of Pittsburgh

<table>
<thead>
<tr>
<th>Course</th>
<th>Student Profile</th>
<th>MEAs Implemented</th>
<th>Nature of MEA Implementation</th>
<th>Data Collected</th>
</tr>
</thead>
</table>
| Open Ended Problem Solving      | Industrial Engineers / Juniors    | Supplier Development, Condo Pricing, Quality Improvement, Compressor Reliability, Volleyball, CD Compilation, Disaster Decision Modeling, Trees, Gown Manufacturing | • Instructor trained  
• MEAs used as integrator and discoverer  
• In class assignments | Reflections               |
| (Pilot MEA course)              |                                  |                                                                                  |                                                                                                  |                       |
| Engineering Ethics              | Mixed Engineering Disciplines / Juniors and Seniors | Trees                                                                            | • Instructor and TA trained  
• MEA used as integrator  
• Take home assignments | PDA Data  
Reports               |
| Statistics II                   | Mixed Engineering Disciplines; Sophomores | SUV Rollover, Hazardous Material Transport                                      | • Instructor trained  
• MEA used as reinforcer: students apply fundamentals learned in the class  
• Take home assignments | PDA data  
Reports               |
| EMPOWER Energy Sustainability   | Mixed Engineering Disciplines; Juniors and Seniors | Ethanol, Windmills                                                              | • Instructor trained  
• MEA used as reinforcer: students had mixed understanding of the energy concepts  
• Take home assignments | Wikis               |
| Decision Models                 | Mixed Engineering Disciplines; Graduate students and Seniors | Ethanol, FEMA Disaster Relief Dam Construction                                  | • Instructor trained  
• MEA used as reinforcer  
• Take home assignments | No data collected |
| Engineering Statistics I        | Mixed Engineering Disciplines; Juniors and Seniors | Tire reliability, Defibrillator Lead, CNC Machine                               | • Both Instructors trained and not trained  
• MEA used as reinforcer  
• Take home assignments | PDA Data  
Reports  
Test questions  
Reflections  
Pre and Post Confidence Inventories               |
| Engineering Statistics I        | Mixed Engineering Disciplines; Juniors and | Tire reliability, CNC Machine                                                   | • Instructors not trained  
• MEA used as reinforcer | Behavioral Observation  
Reports  
Test               |
<table>
<thead>
<tr>
<th>Course</th>
<th>Student Profile</th>
<th>MEAs Implemented</th>
<th>Nature of MEA Implementation</th>
<th>Data Collected</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Seniors</td>
<td>• Take home assignments</td>
<td>questions</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Transport BioEng Juniors</td>
<td>• Instructor trained</td>
<td>Reflections</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wet Suit (developed by Miller and Moore; CSM)</td>
<td>• Used as reinforce</td>
<td>Pre and Post Confidence Inventories</td>
</tr>
<tr>
<td>Engineering</td>
<td>Section of IEs; section mixed</td>
<td>Campus Lighting Dams and Earthquakes</td>
<td>• Instructor trained</td>
<td>Reflections</td>
</tr>
<tr>
<td>Economics</td>
<td></td>
<td></td>
<td>• Used as discover and reinforcer</td>
<td>Pre and Post Confidence Inventories</td>
</tr>
<tr>
<td>Engineering</td>
<td>Industrial Engineering; Sophomores</td>
<td>Process Quality Control</td>
<td>• Instructor trained</td>
<td>Reflections</td>
</tr>
<tr>
<td>Statistics II</td>
<td></td>
<td></td>
<td>• MEA used as discover and discoverer</td>
<td>Pre and Post Confidence Inventories</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Assigned as an in-class followed by take home exercise</td>
<td>Reports</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Test questions</td>
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</tbody>
</table>

Based on our experience, we have identified the major factors that contribute to the success of MEA implementation [5]. An important factor influencing MEA success is the guidance from the instructor throughout MEA implementation. Limited, corrective guidance can best ensure that students are properly focused and are addressing the targeted concept(s), especially where the solution time is constrained. Such guidance may be positively correlated with instructor’s training on MEA implementation. We suggest that if the instructor appreciates the benefits that the students might receive from an MEA, he/she should more readily make the extra effort to properly guide students and provide necessary feedback; otherwise the positive effects of the MEA may be limited at best.

Feedback after completion of the MEA plays an important role in students’ understanding key concepts. Such feedback can reinforce student understanding as well as correct misconceptions. Dividing MEAs into several parts and providing feedback at points during the solution process also ensures that misconceptions are identified and corrected early allowing for student teams to redirect achieving the desired result.

Our research strongly suggests that MEAs can help educators assess their students’ problem solving process. Valuable data can be obtained through the use of PDAs, Wikis, and reflection tools, as well as the actual student reports and well-designed examination questions. Using such tools allows educators to gain insight into the team’s group processes, problem solving strategies, degree of involvement, and their process for iterating among the various problem solving steps as they proceed through the exercise. Further, such information can provide engineering educators with information about the quality of student learning.

**Enhancing the learning benefits of MEAs**
To enhance the educational benefits of MEAs, we have focused on introducing an ethical dimension [6]. As described above, we have accomplished this by embedding an ethical dilemma in many of the MEAs that we have developed. By introducing an ethical reasoning domain, we have created what we call ethical MEAs or E-MEAs. Our objective has been to encourage
students to consider how the engineering decisions that they make potentially influence the public, environment, other stakeholders, their firm and/or themselves. In addition, this allows us to better understand the various strategies student teams use to resolve complex ethical dilemmas. Table 2 provides a description of the ethical issues embedded to date in our MEAs.

Table 2: Illustrative Ethical Issues that are embedded in MEAs Developed

<table>
<thead>
<tr>
<th>Domain of Dilemma</th>
<th>Common Dilemmas</th>
<th>Example – Issues</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental</td>
<td>Harm to Land/ water/natural resources</td>
<td>• Air pollution</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• waste in rivers</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Decreasing usable land for farming</td>
</tr>
<tr>
<td></td>
<td>Harm to Plants</td>
<td>• Cutting trees</td>
</tr>
<tr>
<td></td>
<td>Harm to Animals</td>
<td>• Destroying a natural land of animals</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Killing animals for testing / experimenting</td>
</tr>
<tr>
<td></td>
<td>Harm to climate</td>
<td>• Adding to global warming</td>
</tr>
<tr>
<td>Societal</td>
<td>Harm to individual or public health for economic, personal, political reasons</td>
<td>• Selling drugs</td>
</tr>
<tr>
<td></td>
<td>Racism / gender</td>
<td>• Not assigning the project to a woman</td>
</tr>
<tr>
<td></td>
<td>Harm to public welfare</td>
<td>• Creating a monopolist environment through illegal ways, tacit collusion</td>
</tr>
<tr>
<td>Economical</td>
<td>Waste of capital</td>
<td>• Creating extra cost for the firm for personal reasons, etc.</td>
</tr>
<tr>
<td></td>
<td>Waste of labor effort</td>
<td>• Making employees work extra due to lack of manager capability in decision making</td>
</tr>
<tr>
<td></td>
<td>Waste of manufactured goods or other resources to obtain personal or group advantages</td>
<td>• Using a resource that is almost about to be extinct to gain economic advantages</td>
</tr>
<tr>
<td>Political</td>
<td>Creating political issues between agencies, countries,</td>
<td>• Selling goods to a country with international embargo</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quality Related</td>
<td>Creating low quality work/ end goods to harm people, society, firm, nature</td>
<td>• Selling goods before testing for quality or imperfections in manufacturing or design stage</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Providing goods that are low quality- to provide a threat to society</td>
</tr>
<tr>
<td>Agency Issues/ Employers, employees</td>
<td>Creating extra work, changing results, manipulating objectives etc. to gain personal advantages by a manager</td>
<td>• Changing results of a project to gain extra salary or bonus</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Report results in an untruthful manner to get promoted</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Delegate work and responsibility to another worker to make sure he is not going to be risking his own status or income</td>
</tr>
<tr>
<td></td>
<td>Wasting employer’s resources for personal use</td>
<td>• Ordering extra tools to use them at home at employer’s cost</td>
</tr>
<tr>
<td>Historical Heritage</td>
<td>Creating harm to historical heritage</td>
<td>• Building a dam on historical ruins</td>
</tr>
</tbody>
</table>

Process we have used to develop an E-MEA can be summarized as follows:
1. Determining the key issues:
• the conceptual issue(s) requiring engineering ethical reasoning that will be presented,
• Other fundamental concepts required for resolution,
• How the E-MEA will be used (e.g., within a lecture, a recitation exercise, or in a workshop.)

2. Developing a storyline that describes a realistic situation in which the concept(s) will be embedded.

We have developed most of our storylines from incidents in the news; in addition we have also drawn on our own personal experience, and the experience of colleagues in industry. After the storyline has been developed, the ethical dilemma is introduced. The dilemma also may come from personal experience or adapted from a text or case. It should not be a “black or white” issue, but rather lie in a “gray area.” Ideally, its resolution would require a creative “win-win” resolution. It should be written in a way that requires the student to carefully read the exercise in order to recognize it. We have learned to frame the problem first, and then have the students identify and resolve the ethical dilemma once they have obtained their results.

Assessing the Impact of MEAs
In addition to extending MEAs to upper level industrial engineering courses and introducing an ethical component, a third focus of our research has been on the use of MEAs as a learning intervention. Specifically, we have identified two issues that need further attention:

• Problem solving process of students while working on MEAs and
• Testing and document the actual learning benefits of MEAs.

Data Collection Tools
We are using models and modeling in identifying the benefits of MEAs as a learning mechanism. We propose that MEAs can improve student learning in four specific domains: (1) conceptual understanding, (2) problem solving, (3) team work, and (4) ethical reasoning. We are collecting data to support this assertion using six tools:

Reflection Tools were originally suggested by Lesh, Hamilton and their colleagues. Following an MEA activity, reflection tools help students recall and then record significant aspects about what they have done (e.g., strategies used, ways the team functioned, etc.) so that the instructor might use this information to discuss with students the effectiveness of their various strategies, and types of engagement used [4]. Reflection tools enable students to better develop their conceptual frameworks for thinking about learning and problem-solving by requiring them to reflect on aspects of the exercise or process just completed.

Our reflections tools take the form of a semi-structured instrument. We have migrated from paper to online instruments to provide ease of data classification and collection. When implemented to assess the underlying problem solving process, reflection tools provide powerful information about three major identifiers of students’ problem solving process:

• Whether or not students functioned as a team or relied primarily on a single individual,
• The extent that they used an iterative problem solving approach, and
• The stages of the problem solving process the students primarily focused on.
An example of the summary response from a reflection tool is given in Figure 1.

**Figure 1.** Example of a Team Problem Solving Analyzed using Reflection Tools

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**Team 1 – CNC Machine MEA**

We started with a group discussion, but we each had our own idea about the problem. We started with some critical thinking and tried to figure out how we could solve the problem. Once we had a plan things took off and we really started to get an idea on how to solve the problem. We began to work as a group to solve the problem, which worked well as we sited through the information, but then after about 20 minutes we got stuck and went to individual thinking. After about 40 minutes we began to second guess our method and kind of hit a wall with the problem solving. After a semi-constant progression we decided to go with our gut feeling and it really pushed us into solving the problem the best that we could. We brainstormed each of our ideas and formulated them into one plan. Later, at about 50 minutes we made little progress and actually went back on some ideas we originally had.

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Starting off as group hack, then switching to individual work, then going back to group work.

Working on problem discussion for sometime, then problem solving for 20 minutes, and interpreting for 20 minutes, and 10 minutes for finishing the work.

Iterations between activities: going back and forth different tasks.

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**Student Reports**, i.e., the actual assigned MEA report (typically provided in memorandum format to the client), provide an artifact to assess the success of the MEA implementation. This enables us to assess the extent that the team used the targeted concepts, their level of understanding of these concepts and whether they used them correctly. Indications of how concepts are incorrectly used include:

- Inappropriate background to understand the targeted concept
- Insufficient guidance to students about expectations
- Insufficient time to fully solve the problem or students failed to allocate sufficient time and effort to properly solve the MEA
- Poorly written report; did not clearly communicate the problem and its objectives.

A successful report should clearly provide a general model for resolving the type of problem presented by the client as well as a specific solution to the given problem. If an ethical dilemma is embedded in the MEA, the report should also identify it and provide an appropriate resolution, in addition to pointing out other issues that might affect the recommended solution.
**PDA Recordings** - To analyze problem solving patterns, we have used personal digital assistants (PDA) to collect data. At specific time intervals when solving the MEA students are asked to record their current task. To capture the process, we utilized software enabling students to identify (1) the specific problem solving task being addressed, (2) the progress at that point (not making progress, satisfactory, very good progress) of effort, and (3) whether the work on the task was done as a group or individually. The PDAs were programmed to query the students every 10 minutes, at each time the student recorded the task, his/her progress and whether it was done in an individual or team setting. The number of recorded data points depended on the total time each student devoted to the project. Figure 2 provides an example of one student’s problem solving pattern.

In Figure 2, the vertical axis shows the general problem solving tasks; non-productive tasks are shown below the timeline to indicate no progress at these instances. Triangles denote that the team is working on the task together; the squares indicate individual task work. The larger the triangle or square, the more engaged the student(s) is (are) and progressing for that particular task (and the project, in general). PDAs have allowed us to capture not only the problem solving steps for each team member, but also the combined process followed by the team, as will be explained subsequently.

**Figure 2. An example for PDA output for one student in a group**

**Wikis** are especially useful for the teams that meet virtually (i.e., students are in different locations). In this case, we have asked students to upload their work-in-progress to a common website and converse on this site via Wikis. As a result we were able to observe (or recreate) the student work as the group progressed and final report evolved, since the Wiki format enabled us to view their text/chat conversations while addressing the MEA. This revealed how the student teams divided up tasks and worked on various aspects of the MEA. It also enabled us to
examine the various solution approaches attempted, each team’s discussions concerning these approaches, and how the team traversed the problem solving process.

**Test Questions** - Following the submission of the MEA and the instructor’s feedback to the students, follow-up exam questions can be used as one way of measuring the extent that the concepts were learned. Using well-crafted questions, the instructor may be able to determine which students’ had mastered the primary concept embedded in the MEA, and the extent to which misconceptions might remain.

**MEA Scoring Rubric** – as an initial approach for assessing the students’ overall performance on the MEA, we initially developed an evaluation rubric based on four of the six MEA constructs: (1) **Generalizability**, (2) **Self Assessment/Testing**, (3) **Model Documentation**, and (4) **Effective Prototype**. Supporting elements have been delineated together with expectations for each solution-related principle. For example, we expanded the **Effective Prototype** principle to include refinement and elegance of the solution. Specifically:

- **Generalizability**: Assesses the degree to which the model is a working solution for the particular problem and other similar situations. Is the model robust; can it be easily “handed over” to other students to apply in similar situations?

- **Self-Assessment/Testing**: Assesses the extent to which the solution has been tested and reflects thought and procedural revision. Have nuances or special conditions in the data or problem been uncovered and accounted for in the procedure?

- **Model Documentation**: Evaluates the level of detail and explicitness in the written procedure. Clarity of expression, correct grammar, and ease of reading are also assessed. Have the assumptions that were made been clearly stated? Has all information specifically requested by the client been included?

- **Effective Prototype**: Measures the refinement and elegance of the solution procedure. Is the procedure based on thorough application of engineering concepts and principles? Have appropriate engineering ideas been used? Is the solution accurate and of high quality? Each dimension is graded on a 5-point Likert scale, indicating the degree to which the solution achieves or executes the principle. The scores across the four dimensions can be averaged to obtain an overall score. A score of a “1” on any given dimension indicates that the principle was clearly not achieved or executed in the solution. A score of “2” indicates some, but insufficient, achievement or execution. A “3” indicates sufficient, or adequate level of achievement and satisfaction of the base requirements. A score of a “4” indicates that the solution embodies the principle for the most part and that the solution has gone beyond the basic requirements; i.e., the team has achieved more than expected and has generally done a good job. In order to achieve a “5” on a given dimension, the principle must be executed in an outstanding manner as delineated in the rubric. The ethics component are scored using the Pittsburgh-Mines Ethics Assessment Rubric (P-MEAR) previously developed and validated [7]. Figure 3 shows a partial view of our rubric scoring sheet.
### Assessment of Learning Benefits

We would expect to see evidence of student learning through the use of MEAs. Specifically, as noted, we would expect that after each properly implemented MEA exercise, students’ (1) comprehension of the engineering concepts, (2) problem solving skills, (3) ethical reasoning ability, and (4) ability to work in teams should be enhanced.

During the past year (year two) and the current third year of the project we have been collecting data that should better enable us to ascertain the extent that these benefits may have accrued. To date, little empirical testing and assessment have occurred, especially in the engineering domain. It is clear that researchers need to objectively assess the assertion that MEAs result in improved student learning in engineering environments if MEAs are to be widely implemented.

To do this, we have collected data through a set of pilot classroom experiments. We created three MEAs that use three basic engineering statistics concepts - descriptive statistics, central limit theorem and hypothesis testing – identified by the instructors and course coordinator. Because the course (Engineering Statistics 1) was taught in three sections in Fall 2008, it provided an opportunity to test both our MEAs and assessment instruments. It also provided an opportunity to explore ways in which MEAs could/should be implemented in the classroom.

---

<table>
<thead>
<tr>
<th>Class:</th>
<th>Concepts Categories (Bold faced letters are for coding)</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Iteration (See Lesh, Adams, Hjalmars)</td>
<td>Types of iteration (Proof of) (See Hamilton 2006)</td>
<td>Versions (Wiki edits)</td>
<td></td>
</tr>
<tr>
<td>Express-test-revise</td>
<td>Drafts (Docs) (Preservation of good ideas) (count)</td>
<td>Difference between steps (Shifts in Work) (Bad ideas left behind) (yes/no)</td>
<td></td>
</tr>
<tr>
<td>Challenge to students (evidence through iteration) (Adams 2003: Transformative-processes in which new understandings were generated and synthesized into the design task) (yes/no)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Engineering Ethics Assessment</td>
<td>Recognition of dilemma</td>
<td>Rate 1 – 5 (Use PGH-Mines)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Information</td>
<td>Rate 1 - 5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Analysis</td>
<td>Rate 1 - 5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Perspective</td>
<td>Rate 1 - 5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Resolution</td>
<td>Rate 1 - 5</td>
<td></td>
</tr>
</tbody>
</table>
The experiment was designed so that all the students in each section would be assigned two of the three MEAs in order to neutralize any instructor effect. Thus, each MEA was assigned to two sections with the third section intentionally kept as the comparison group. The experimental design is given in Table 3.

<table>
<thead>
<tr>
<th>Section</th>
<th>MEA 1</th>
<th>MEA 2</th>
<th>MEA 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Assigned</td>
<td>Assigned</td>
<td>Not Assigned</td>
</tr>
<tr>
<td>2</td>
<td>Assigned</td>
<td>Not Assigned</td>
<td>Assigned</td>
</tr>
<tr>
<td>3</td>
<td>Not Assigned</td>
<td>Assigned</td>
<td>Assigned</td>
</tr>
</tbody>
</table>

The MEA construction principles are designed to encourage student solutions to be both creative and diverse. Thus assessing learning and improved problem solving skills due to the MEA is not an easy task. We initially measured improved learning by including targeted exam questions related to the concepts embedded in each of the MEAs. Students were asked to answer a single conceptual question that addressed the concept of interest. We expected that the students who answered the questions would get a higher grade in general, if they were assigned an MEA related to that concept. The result was a data set involving 124 students, each of whom addressed two MEAs, and was tested on three concepts.

Since we expected that after resolving a MEA, a student’s comprehension of the engineering concepts of interest should be enhanced compared to another student who did not resolve that MEA. Thus we wished to test the following hypothesis:

\[ H_1: \text{An engineering student’s understanding of a given concept will be improved after solving an MEA built around that concept, compared to another student who did not resolve that same MEA.} \]

We tested this hypothesis using ANOVA for each assigned MEA with the test scores as the dependent variable. Here we have used the data from test scores as a proxy measure of learning. The distribution of the scores appeared to be normal. If a student addressed the MEA, compared to another student who didn’t, we would expect the score to be higher on average. The general linear model to test the hypothesis is given in Equation 1.

\[(\text{Question Score}) = \beta_0 + \beta_1 (\text{MEA Dummy}) + \epsilon \quad (1)\]

In Equation 1, MEA Dummy is a binary variable that takes the value 1 if student addressed the MEA related to concept of the question and 0 otherwise.

We found that for two out of the three questions there was a significant improvement in learning for the students who addressed the MEA (question 1, \(\beta_1 = 0.66, \ p - \text{value} < 0.1\) and question 2, \(\beta_1 = 1.69, \ p - \text{value} < 0.1\)). For question three, the results failed to show a significant difference. \(R^2\) values were around 0.5, but since the data is categorical, we did not expect it to be higher. In summary, for two out of three cases we tested, we were able to show that the MEAs did provide...
a relative improvement in learning compared to students who did not have the MEA, indicating that there is some support for MEAs as a learning enhancement tool.

Based on our experiences during the second year, we have revised the experiment for the third year. Now, we have used the MEAs in only one of the three introductory engineering statistics courses, but with a trained instructor. The other two sections served as comparison groups. To determine the efficacy of the MEAs we developed a concept inventory (based on the Statistics Concept Inventory developed by Reed-Rhodes [8]). This was given to students in all three sections so that we could determine effect size; we also used our reflection tool with the experimental section. A second experiment was conducted using two sections of an engineering economics course taught by the same instructor. In the experimental section she introduced a series of three MEAs; in the comparison section, no MEAs were used. Again, pre and post concept inventories were administered to determine effect size. Finally, in a third experiment, the “Wet Suit” MEA developed by Moore and Miller [9] was used in a junior Bioengineering Transport Phenomena which included a five-week heat transfer module. The thermal sciences concept inventory was used here pre- and post-test. Although there was no comparison group, the same MEA was used in two senior level thermodynamics sections at the Colorado School of Mines with pre- and post-test concept inventory data again collected.

THE RESULTS FROM ALL OF THESE EXPERIMENTS WILL BE INCLUDED IN THE FINAL VERSION OF THIS PAPER. DATA IS CURRENTLY BEING ANALYZED

Using PDA Data to Assess the MEA Problem Solving Process

Technology is playing an important role in today’s engineering education. In recent years there has been a phenomenal growth in the variety of technological devices introduced into the classroom, including such mobile ones as Personal Digital Assistants (PDAs). Increasingly, faculty and students are making use of these devices. These tools have been primarily used to assist in instruction. Thus research related to use of such tools is limited to teaching scenarios.

We are investigating how the new technology tools, in particular PDAs, can be used in assessing the problem solving process, especially in conjunction with reflective surveys. As noted, we have used PDAs to record the problem solving process, providing a data set that enables us to begin to analyze that process. We have investigated how students go about teaming, iterate during the process, tasks they choose to focus on [4] and are now investigating the relationship between these process characteristics and problem solving outcomes as measured by change in thinking, grade, and ethical reasoning obtained through the use of reflective statements.

Our pilot data suggests that there is a relationship between the process measured by the PDAs and the problem solving outcomes. We first analyzed the process in terms of the teaming style. We grouped teams into three types based on the extent of functioning as a team or individual when student work in teams, they have higher grades. Working in teams as opposed to subgroups or individuals have a clear advantage in solving modeling problems. The results indicate that the solution process of our engineering students is mostly linear; i.e., the students work on a single task at a time and do not go back to it once they feel that they have completed the step. This result suggests that iteration in problem solving process may be much less frequent in the engineering student problem solving process than originally thought.
Finally, we investigated the time that students seem to allocate to different phases of modeling problem solving (namely, the initiation, problem solving and finishing phases). Based on which phase students allocate the most time, we find that allocating more time to the problem initiation pays off, in other words, students who spend more time to the understanding the problem and searching for a solution seem to have a better grade.

Determining the Cognitive Factors that Affect the Development of Modeling Ability
A major overall goal is to investigate the impact of cognitive factors in development of students’ modeling ability [10]. To do this, we are now investigating the impact of self-efficacy, metacognition and epistemological beliefs, as well as previous experience, and such other factors as GPA, gender and age. In doing this, we are assuming that problem solving is a subset of modeling. We are investigating modeling practice in engineering education with the help of a rich literature on problem solving. To highlight the dimensions of competence in engineering modeling, we will be contrasting the performance of more experienced senior engineering students with that of new or novice engineering students (sophomores). The four main questions we are investigating are:

- What are the identifying characteristics of weak / strong engineering modeling strategies?
- What is the extent of shift that occurs in engineering students’ modeling skills with a single course (within semester), with a year (within two semesters), and within a few years (within domain education period of sophomore to senior years, or 5-6 semesters)?
- For those engineering students where we can observe a shift in modeling, what are significant process variables that contribute to the shift? How does the enhanced domain knowledge, gaining modeling experience and cognitive, affective and demographic background of student potentially contribute to this shift?
- How do the learning styles of students and the teaching style of the faculty contribute to this learning shift?

By answering these questions, we hope to better characterize the dimensions of modeling competence not only by what more experienced students do correctly, but also by better explaining the engineering modeling competencies, and ultimately, understanding the strategies of experienced modelers in order to develop instructional aides for novice students.

Conclusion
To date, we have developed and implemented MEAs with the aim of enhancing conceptual understanding and problem solving skills of engineering students. We have collected data from these implementations with the aim of validating such benefits. This research was initiated in 2007 at University of Pittsburgh Swanson School of Engineering under funding from an NSF CCLI Type 3 grant together with six other university partners.

We have developed and tested eleven new MEAs in addition to adapting and implementing seven more developed by our colleagues. These have been implemented primarily in industrial engineering courses including a pilot engineering course that was devoted to using MEAs as a mechanism for teaching problem solving. We have introduced an ethical component into the majority of the MEAs that we developed, and have designated these as E-MEA.
In addition, we have collected data about the MEA solutions using six specific tools: PDAs, Wikis, reflection tools, student reports, MEA Grading Rubric and test scores. We are currently using this data to investigate the benefits of MEAs as a learning tool and as a supplement to the instructor. Our plan is to investigate the effectiveness of MEAs and document the benefits in conceptual learning, problem solving and ethical reasoning. We also plan to analyze the problem solving patterns observed when student teams work through an MEA exercise.

Acknowledgement
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