A Framework for Posing Open-Ended Engineering Problems: Model-Eliciting Activities

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Abstract - **Integrating more engineering contexts, introducing advanced engineering topics, addressing multiple ABET Criteria, and serving under-represented student populations in foundation engineering courses are some of the opportunities realized by the use of a new framework for developing real-world client-driven problems. These problems are called Model-Eliciting Activities (MEAs), and they are based on the models and modeling perspective developed in mathematics education. Through a NSF-HRD Gender Equity Project that has funded the development, use, and study of MEAs in undergraduate engineering courses for increasing women's interest in engineering, we have found that the MEA framework fosters significant change in the way engineering faculty think about their teaching and their students. In this paper, we will present the six principles that guide the development of an MEA, detail our motivation for using the MEA framework to construct open-ended problems, and discuss the opportunities and challenges to creating, implementing, and assessing MEAs.**

Index Terms – ABET criteria, engineering problem solving, mathematical modeling, open-ended problems

INTRODUCTION

Engineering faculty who teach undergraduate engineering courses are under immense pressure to address a wide variety educational goals that extend well beyond the traditional student learning of engineering science and design. The now familiar ABET Criterion 3 a though k has placed the responsibility squarely on the shoulders of every engineering faculty member to ensure that our graduates have abilities in the areas of teaming and communication and understandings in the areas of ethics, global and societal impact, and contemporary issues [1]. The expectation is that all of these topics will be integrated throughout an engineering curriculum with some fraction being addressed in every core course. Let us not forget that engineering faculty still need to facilitate students' learning of engineering science and design!

ABET is not the only influence on the educational goals that must be met in our undergraduate engineering courses. Retention, which often translates to future recruitment, of a diverse student population in engineering is a high national priority [2] and therefore an institutional priority. Creating learning environments that encourage and support the success of all students has become an educational goal.

The changing fields and practice of engineering are also influencing educational goals. Faculty are faced with having to find a balance between teaching fundamental concepts and emerging technologies.

For faculty teaching foundational courses there is an added burden of providing instruction that enables successful transition from high school to higher education. Educational goals can encompass remediation, study skills development, establishment of academic goals and expectations, development of problem solving skills, and introduction to the fields of engineering, to name a few.

What becomes clear is that engineering faculty need a framework for developing, implementing, and assessing open-ended problems that fulfill a variety of educational goals. In this paper, we present a description of Model Eliciting Activities (MEA), the six principles that guide the development of an MEA, detail our motivation for using the MEA framework and discuss the opportunities and challenges to creating, implementing, and assessing MEAs.

MODEL ELICITING ACTIVITIES

From a practical engineering faculty members' perspective, a Model Eliciting Activity (MEA) is an open-ended, real-world, client-driven problem. Such a description makes it very difficult to understand how an MEA can possibly be any different from the open-ended engineering problems that engineering faculty have assigned their students throughout the history of formal engineering education. Part of the problem lies in the emphasis engineering practice places on product, the solution to the problem. MEAs are not so much about product as they are about process, the development of higher order understandings that lead to solutions.

Why is process versus product orientation important? The authors contend that this is the difference between practicing engineering and educating future engineers. While a strong product orientation is important to the success of an engineering project or company, a strong process orientation is important in developing students' higher-order thinking skills. That is not to say that practicing engineers are not concerned with process, but that the attention to process is more often

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secondary to product and it is the product that is evaluated and rewarded.

Herein lies how MEAs are different. The open-ended problems that engineering faculty typically assign are product oriented. That is, emphasis is placed on the final solution and typically the evaluation of students' learning is based solely on the final product characteristics, which may or may not reveal anything about the process the student used to create the solution. First year students often have the idea that the product is the first solution that they can quickly identify and implement to a personally satisfying level. They do not employ a problem solving process in which they evaluate their solution against the client's needs. So they do not go through cycles of testing and revising. If instructors can see the process students use to solve a problem, they gain a better understanding of students' conceptual misunderstandings and inability to find the complexity of the problem that lead to circumvention of the problem solving process; they can create instructional interventions to promote improved learning of fundamental concepts and a problem solving process.

So let us redefine what an MEA is. An MEA is an activity that is both thought-revealing and model-eliciting [3]. MEAs require that students reveal how they are interpreting a mathematical situation through a purposeful documentation trail that promotes testing, refining, and extending their ways of thinking. These problems are model-eliciting because they require students to mathematize (e.g. quantify, organize, dimensionalize) the situation.

EXAMPLE OF AN MEA: NANO ROUGHNESS

To better understand the principles of MEA design, we first present a brief description of a specific MEA. *Nano Roughness* was designed and implemented in Fall 2003. The problem was developed to provide first-year engineering students with a hands-on experience with relevant scientific and mathematical concepts used in nanoscale technologies and research. It was implemented in an engineering problem solving and computer tools course in which students learn to develop a logical problem solving process for fundamental and open-ended engineering problems. Reference [4] describes the development of this problem.

Pre-Lab Component

Most MEAs have a background reading to introduce the context of the problem. As the content and context of this problem was unfamiliar to most students, a pre-lab reading was assigned so that students had time to absorb information about the purpose and functionality of an Atomic Force Microscope (AFM).

Laboratory Component

To orient the students towards the concept of roughness, students individually answered the following questions

- How do you define roughness?
- What procedure might you use to measure the roughness of the pavement on a road?
- Give an example of something for which degree of roughness matters. For your example, why does the degree of roughness matter? How might you measure the roughness (or lack of roughness) of this object?

The students then read a profile about a company that develops coatings for orthopedic and biomedical implants.

The team activity required students to develop a procedure to measure roughness given AFM images of three different samples of gold. The motivation for developing the procedure is established by using a realistic context in which a company specializing in biomedical applications of nanotechnology wishes to start producing synthetic diamond coatings for joint replacements. The company intends to extend its experience with gold coatings for artery stents to this new application. Student teams of four are required to establish a procedure for measuring the roughness of gold samples that could be applied to diamond samples. The students then apply the procedure to three different samples of gold and develop a list of additional information they need to improve their procedure. The team must write a memo to the company describing their procedure and its application to the sample AFM images and listing the additional information needed to improve their procedure.

Homework Component

In a follow-up homework assignment, students learn about the average maximum profile (AMP) method. This is one of many techniques used to quantify roughness using AFM images. A line is drawn across the image and a height profile is generated. The AMP is the average of the difference between the heights of the ten highest peaks and the ten deepest valleys. In this model-exploration task, student teams were asked to compare their method to the AMP method by: (1) discussing the similarities and differences between the methods, (2) using both methods to quantify roughness for three images, and (3) indicating the ways the AMP method lends itself to the development of a software tool.

Project Component

While not officially part of the MEA, the *Nano Roughness* problem continued into a model-adaptation phase. Students use MATLAB, a computational tool and interpreted programming language used by engineers, to develop a software tool to generate an AFM image from a data file containing a listing of height measurements made at (x,y) locations across a sample surface and implement the AMP and other roughness measures. This project allows students to put into practice their knowledge of flow charting, user-defined functions, repetition and flow control structures, 2-dimensional array manipulations, and reliability considerations (statistics).

SIX PRINCIPLES OF MEA DESIGN

There are six principles that guide the development of a Model-Eliciting Activity [5-6]. Each principle described below is accompanied by a discussion of how the principle relates to the creation of open-ended engineering problems focused on process.

1. Model-Construction Principle

The Model-Construction Principles ensures that the activity requires the construction of an explicit description, explanation, or procedure for a mathematically significant situation. Engineering problems by-and-large are mathematically significant. A word of caution - the tendency is to think of a mathematical model as being an equation, period. Here a mathematical model rarely refers to equations but rather refers to descriptions, explanations, and procedures that may or may not require the use of prescribed relationships. Another tendency is to get hung-up on the existence of established procedures or the idea that there is one "right" way of doing something. There is supposed to be an amount of discovery associated with an MEA, so taking a step back from the current body of knowledge on a topic allows students to create that knowledge for themselves. If necessary, there can be a debriefing of the problem through which students can compare and contrast their ways of thinking to actual engineering practice.

In the *Nano Roughness* MEA, the students need to develop a procedure for quantifying roughness using AFM images. The fact that there are a number of established methods for quantifying roughness from AFM data ensured the creation of a very open-ended problem that is mathematically significant. Methods found in reference [7] were used to create the follow-up homework and project components. In the homework, student teams quantitatively and qualitatively compared their procedure to the AMP method. In the project, student teams created a MATLAB program to perform the AMP and other methods for quantifying roughness using AFM generated data sets.

2. Reality Principle

The Reality Principle requires that the activity be posed in a realistic context and designed so that students can interpret the activity meaningfully from their different levels of mathematical ability and general knowledge. This principle encourages the use of an authentic engineering context in which a client has a need for a solution. This principle also promotes consideration of students' academic backgrounds and personal experiences.

The client in *Nano Roughness* is a company that produces coatings for biomedical applications. This client needs a procedure for quantifying surface roughness of a new product line. It was expected that students would apply algebra, dimensions, and units, and perhaps even statistics, to this problem. Few students have been exposed to nanotechnology in high school. Therefore, a pre-lab reading was assigned to provide background on AFM. In addition, it was not known whether students would have been exposed to the concepts of roughness and measuring roughness. So, warm-up questions were used to introduce these concepts at the beginning of the MEA.

3. Self-Assessment Principle

The Self-Assessment Principle ensures that the activity contains criteria the students can identify and use to test and revise their current ways of thinking. Often the problem provides sample data that students can use to test and revise their mathematical model.

The AFM images in the *Nano Roughness* MEA provide students with the data to test and revise their procedure for quantifying roughness. The idea is that as students apply their procedure to a number of different AFM images, they notice and account for new pieces of information. The three images the students had to work with were vastly different. Each image was scaled differently. Student teams had to decide whether or not to account for these scale differences. In addition, two images had very evenly dispersed peaks and valleys, but one had small peaks and one had larger peaks. The third image had very large but incidental peaks. Student teams had to reconsider their definition of roughness. Do a few really large peaks make a surface more rough than many smaller peaks?

4. Model-Documentation Principle

The Model-Documentation Principle requires students create some form of documentation that will reveal explicitly how they are thinking about the problem situation. Efforts are made to make the documentation trail seem a natural part of the problem solving activity, rather than additional work. In many MEAs, the documentation has taken the form of a memo to the client. This principle yields information for instructors about students' conceptual understandings and provides the materials for assessment of student learning.

In the *Nano Roughness* problem, students were required to write a memo to the client describing their method for measuring roughness from AFM images. The students were also to include a description of how their procedure could be applied to the given AFM images. Students' mathematical interpretation of the problem, their definition of roughness and their thinking about the issue of scale, or their lack of consideration of these issues, is evident through their writing of the memo.

5. Construct Share-Ability and Re-Usability Principle

Often termed the Generalizability Principle, this principle requires students produce solutions that are shareable with others and modifiable for other situations. This means that the students must be able to hand their mathematical model over to the client and the client should be able to use the model. Further, the students should be able to easily adapt the model to a similar problem situation. Creating a re-usable, or general, solution is one of the more difficult tasks for students. Students have a tendency to create a highly specialized solution that only works for the test data they are provided.

Proving a number of test cases that are significantly different or guiding students in creating appropriate test cases can help students understand the value of creating a general solution to the problem.

This principle also fosters communication at a number of points in time and between a number of individuals (e.g. within teams, between teams, and with the client). In part, share-ability is focused on getting students to articulate their current ways of thinking as another means of receiving feedback that will lead to revising their ways of thinking.

In the *Nano Roughness* MEA, the students are directed to create a procedure for the client and then share the procedure with the client though the memo. The procedure is intended to be re-usable by the client, who will apply it in the future to unknown diamond coating samples. The students must demonstrate that it is general by using it to quantify the roughness of each AFM image they are provided.

6. Effective Prototype Principle

Finally, the Effective Prototype Principle ensures that the model produced will be as simple as possible yet still mathematically significant. The aim is for students to create a model that is simple to implement but based on sound application of science principles. Prompts that push students to revisit their model need to be included in the problem statement.

At the conclusion of the *Nano Roughness* MEA, the students are asked to list additional information that they would need to improve their procedure. This prompt encourages students to evaluate the quality of their procedure one last time. This can lead to a simplified or more reliable mathematical model.

Initial Motivation

One of our initial motivations for using MEAs in a first-year engineering course was to provide a learning environment tailored to a more diverse population than typical engineering course experiences as they allow students with different backgrounds and values to emerge as talented. An MEA can be used to create an environment in which the practice of engineering is emphasized rather than just mathematics and engineering content. The focus is diverted from the use of prescribed equations and algorithms in situations devoid of real-world context to the use of a broader spectrum of skills required for effective engineering problem solving. Further, problems that involve team interaction and contexts with a societal link are known to engage women. Our research focus has been on the potential for MEAs to improve the interest and persistence of under-represented students, particularly women, in engineering [8].

A second motivation for using MEAs was the Reality Principle, which encourages the use of real-world engineering contexts. We were interested in engaging our first-year students in the practice of engineering and exposing them to a variety of contexts which require engineering solutions. Our purpose was threefold. First, first-year students have a very narrow vision of engineering; we wanted our students to have a broader perspective of the engineering disciplines and engineering's role in society. Second, we wanted to provide our students with more realistic engineering experiences in their first-year. Third, we wanted students to begin to develop engineering problem solving skills. MEAs have provided a vehicle for inclusion of more engineering in the first-year by enabling problems to be built around accessible engineering contexts that foster students' higher level learning of the mathematics, science, engineering, and technology content being taught in the course.

Our third motivation for using MEAs was the emphasis on student teams. Problems designed for first-year students that truly require multiple perspectives and team effort had been difficult to find or construct. If an MEA adheres to the six principles, adequate problem complexity, and thus the need for team interaction, is achieved.

Realized Opportunities

As stated earlier, use of the MEA principles to create open-ended engineering problems presents opportunities to address a variety of educational goals. First, consider the opportunities to address the ABET Criterion 3 a through k. Table I summarizes which criteria are addressed by the *Nano Roughness* MEA. It is acknowledged that the degree to which a single MEA can address each criteria varies according to the content, context, and implementation of the problem. Due to the nature and goals of our first-year engineering problem solving course, the MEAs we have developed and implemented emphasize (a) the application of mathematics, (b) analysis and interpretation of data, (d) teaming, (e) engineering problem solving, and (k) application of computer tools. The contexts we have chosen have allowed us to touch on (f) the engineering profession and ethics, (g) communication, (h) global and societal context, and (j) contemporary issues. Engineering courses with different learning objectives may elect to emphasize or de-emphasize different criteria.

MEAs hold great potential for changing the way faculty think about their teaching and their students. Engineering faculty working with or on the MEA development team have changed and continue to change their notions about what it means for a problem to be open-ended, client-driven, and realistic. They have had to consider the following kinds of questions:

- What is the nature of typical problem-solving situations where mathematics, science, and technology are needed for success in engineering?
- What kinds of "mathematical/scientific thinking" (conceptualization, computation, or communication) are emphasized in these situations?
- Which "big ideas" and achievements provide the most powerful foundations for success beyond school?
- What does it mean to "understand" relevant constructs and conceptual systems?
- How do these competencies develop as students make the transition from novices to experts?

TABLE I
ABET CRITERIA ADDRESSED BY THE *NANO ROUGHNESS* MEA

ABET Criterion 3 a-k	Level	Comments
(a) an ability to apply knowledge of mathematics, science, and engineering	High	Students must draw on their knowledge of algebra, dimensions, and units. Statistics might also be applied.
(b) an ability to design and conduct experiments, as well as to analyze and interpret data	Low	While this MEA is not experimental in nature, student need to be able to interpret the AFM images, making decisions about what it means to have a rough surface
(c) an ability to design a system, component, or process to meet desired needs	Potential	While not a classical engineering design problem, students are in essence designing a procedure. Reformulation of the project component would allow the engineering design process to be highlighted.
(d) an ability to function on multi-disciplinary teams	High	The development of team interaction skills is fostered as student teams create their procedure and work through the homework and project components.
(e) an ability to identify, formulate, and solve engineering problems	High	Students need to interpret the client's needs to better define and solve the problem. The engineering problem solving method can be highlighted through this problem.
(f) an understanding of professional and ethical responsibility	Potential	While not emphasized in the problem as written, one could envision a debriefing focused on the impact of creating a faulty or unreliable procedure.
(g) an ability to communicate effectively	Low	Students practice their written communication skills through the writing of the memo to the client.
(h) the broad education necessary to understand the impact of engineering solutions in a global and societal context	Low	This MEA provides some exposure to the use of nanotechnology in a biomedical application.
(i) a recognition of the need for, and an ability to engage in life-long learning	Potential	It was our hope through the NSF NUE project to inspire students to pursue further coursework in nanotechnology though this exposure
(j) a knowledge of contemporary issues	Low	This problem introduces nanotechnology and biomedical engineering - both high profile and emerging engineering fields.
(k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice	Potential	The MEA builds up to a project component in which the students use MATLAB to program various roughness measurement methods.

PAST & CURRENT CHALLENGES

There are a number of challenges to successfully developing and implementing MEAs. Initially, integrating MEAs into an already packed curriculum can be difficult. A typical MEA takes about an hour of classroom time. Therefore, a balance must be struck between content coverage and development of a broader range of skills and higher level learning. However, by targeting the Model-Construction Principle toward the mathematics, science, or engineering concepts being covered in the course, course content need not be overly compromised.

When MEAs are implemented by instructors not on the development team, training is required. In our case, MEAs are done in a computer lab led by a graduate and upper-division undergraduate teaching assistant (TA) pair. As these problems are significantly different from the problems TAs have experienced in their own coursework, appropriate TA training is needed to provide them with the tools and understandings to support student learning during an MEA. We provide the teaching assistants with instruction on the six principles of MEA design, expectations for student learning and engagement in an MEA, expectations of instructors during an MEA, and techniques for facilitating student teaming. We also engage TAs in the MEA development process. They work each MEA during their weekly meetings and provide feedback on the problem and the grading criteria.

Assessing student work on an MEA continues to be a challenge for us, primarily due to the number of students enrolled in our first-year course. The issue is that the more open-ended a problem is, the more subjective the grading becomes. Managing for consist grading is less of an issue in a course with a low enrollment where a faculty member may be more intimately involved in the grading; it is a huge challenge in a large course where the grading is done by teaching assistants. The later situation limits the nature of the assessment of student learning. For instance, we do not have the resources (e.g. TA time) to assess a student's memo in such a way as to truly facilitate development of communication skills. Even assessing quality of students' solutions can be problematic.

A grading rubric for the *Nano Roughness* problem is shown in Table II. This grading rubric was not provided to the students prior to the submission of their work as we did not want students to be guided by a rubric to an adequate solution. One of the aims of an MEA is for students to figure out the complexity of the problem and decide when they have a complete solution (i.e. met the client's needs). Unfortunately, this grading rubric is essentially a check on whether students completed the things they were told to do in the problem. An attempt is made to assess the quality of students' work as we look at the degree to which they have met the client's needs. While the authors agree that the grading rubric is not adequate for providing students feedback on the many learning objectives students are trying to achieve, it does do one thing well. It does not dictate or presume a single "right" solution strategy to the problem. This is strategic; the intent is to draw students' attention away from trying to rely on rote use of equations and algorithms and turning them on to interpreting significant, powerful, interesting, and useful constructs. We are in the process of developing grading rubrics that better access students' learning as a result participation in an MEA.

TABLE II
GRADING RUBRIC FOR *NANO ROUGHNESS* MEA

Criteria	**Yes**[a]	**Sort of**[b]	**No**[c]
Point Value	**1**	**0.5**	**0**
Individual Contribution (3 points total)			
Roughness definition (1 point)			
Procedure for measuring roughness of pavement (1 point)			
Roughness example and measurement (1 point)			
Team Contribution (7 points total)			
Roughness measurement procedure (technique) (2 points)			
Analysis/Interpretation of the result from the application of the procedure (2 points)			
Listed information (at least 2 items) needed to improve procedure (2 points)			
Memo directed at the client and easy to follow (1 point)			

[a] Clear, concise, and useful for the client and/or generalizable to similar situations
[b] Requires minor editing/additions/rework to meet the client's needs
[c] Is non-existent or requires redirection or major editing to meet the client's needs

Finally, development of an MEA takes time - with numerous cycles of testing and revising before implementation in the classroom [4]. A portion of the time factor relates to initial and continuous education of the faculty and graduate students writing the problems about MEA principles and the educational benefits of using MEAs in the classroom. As more faculty learn about MEAs, we envision that taking a more *models and modeling* perspective in open-ended problem development will become part of the engineering education culture. This should, over time, reduce the learning curve. Another significant time factor is idea generation for and development of engineering contexts. We are in the process of growing the engineering community that is engaged in or aware of MEA development. The aim is to engage more engineering faculty in sharing their practice and research through MEA development. The desired result is a bank of MEA problems that are shareable and re-usable across the engineering education community.

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