USING MODEL-ELICITING ACTIVITIES TO INTRODUCE UPPER ELEMENTARY STUDENTS TO STATISTICAL REASONING AND MATHEMATICAL MODELING

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Abstract

Much has been written about the emphasis on models and modeling and certainly mathematical modeling is no new phenomenon in the world of mathematics. In fact, mathematical models certainly existed prior to Malthus' *Essay on the Principle of Population* (Malthus, 1798), but his essay is one of the first and still most well-known mathematical models. Due to the efforts of several prominent mathematics educators as early as the 1970s, mathematical modeling holds a place of prominence in K-12 mathematics. This fact was substantiated when it appeared as an emphasis in the content standard of algebra in the *Principles and Standards for School Mathematics* (NCTM, 2000) and it is currently an emphasis in the Common Core State Standards (2011). The term mathematical model has varied definitions.

Definition of a Mathematical Model

Many definitions of what constitutes the process of mathematical modeling have been offered. Adopting an operational definition is imperative to this and any other discussion of Model-eliciting Activities (MEAs) because creating mathematical models to explain circumstances and situations is the central focus of doing MEAs. It is further important to suggest that the definition of mathematical modeling is germane to K-12 students and is not the mathematical modeling done in industry and at the university level. Nevertheless, the mathematical models created at this age can be a major asset to successful formulation of mathematical models later in life.

Lesh et al. (2000) describe mathematical modeling as when, "students are asked to develop an explicit mathematical interpretation of situations" (p. 595). Lesh and colleagues further refer to this process as 'mathematizing' situations. In effect, when creating mathematical models students consider highly technical situations that may not be formally mathematized. However with MEAs, they are asked to mathematize data in an attempt to make sense of a novel situation. In using the term mathematized, one can consider situations in which mathematics has been applied to formalize the system. Mathematizing may also suggest, "making symbolic descriptions of meaningful situations" (p. 595). This process, Lesh states, is in opposition to what is done in most mathematics classrooms when students interpret pre-existing symbols and notations to solve a problem. In having students create meaning from their own symbolic representation, it could be hypothesized that meaningful learning (Ausubel, 1962) is promoted as opposed to imposing a system of symbols and notations on students.

History of Model-Eliciting Activities

Though he is certainly not the only individual promoting the use of mathematical models as a tool to facilitate mathematical learning, thinking, and assessment, Dr. Richard Lesh is often credited with promulgating the use of mathematical modeling (personal communication with

J. Middleton, 21 October, 2012) through a curricular approach referred to as Model-Eliciting Activities, hereafter referred to as MEAs. Initially, MEAs were known as Thought-Revealing Activities or Case Studies for Kids (Lesh et al., 2000), but they later came to be known by the more descript title of Model-Eliciting Activities (MEAs). The structure of the problems has not changed significantly since being initially created in the early 1970s, though the process for creating them has become more formal than it initially was. Formal creation today demands that the six design principles (Lesh et al., 2000) have been met.

Purpose of Model-Eliciting Activities

From their inception, Thought-revealing Activities, Case Studies for Kids, or MEAs, regardless the name, have been used primarily to investigate students' thinking. This is the foremost purpose of using MEAs in any setting. MEAs hold great potential in situations in which other assessment techniques fall short. In the mid to late 1970s, mathematics educators began to clamor for an investigation of students' mathematical processes rather than or in addition to merely investigating their mathematical products (Carpenter, Fennema, & Franke, 1996; von Glassersfeld, 1983). Lesh and colleagues quickly realized that it is difficult or impossible to systematically investigate the manner in which students think without an assessment tool designed to harvest such data. MEAs were therefore created in response to this necessity for researchers, teachers, and educational stakeholders, providing them the opportunity to conduct a close analysis of students' thinking while solving mathematical tasks. One may hypothesize that the time for such a tool has passed. However, with the ubiquity of national and state standardized assessments, arguably more prevalent than they have ever been (Bovaird, Geisinger, & Buckendahl, 2011), and with such assessments emphasis almost exclusively on mathematical products, a huge void is left in understanding *why* students come up with the answers that they do. It may thus be hypothesized that the necessity for MEAs is greater than it has ever been historically. After all, it may be speculated that MEAs provide a richer set of data than any other assessment tool in mathematics.

Description of Model-eliciting Activities

Unaware of such an approach and after learning about the many qualities of MEAs, many individuals are interested in learning what comprises an MEA. In short, an MEA is comprised of four central components: newspaper article, readiness or warm-up questions, data table or other mathematical information, and a problem statement (Chamberlin & Moon, 2005). Each component serves a valid purpose and is used to engage problem solvers in the task. The purpose of the newspaper article is to get students acquainted with the context of the problem. Mathematics educators have been criticized for not providing substantive context for many mathematical problem solving tasks. This claim is almost never heard when MEAs are implemented and it is averted by providing a very short, one page reading passage in the form of a newspaper article. This article requires approximately two to three minutes to read and it often provides information for the second component of an MEA. The second component of an MEA is the readiness or warm-up questions. These questions are designed to monitor students' comprehension of the newspaper article, a fairly superficial demand, as well as to force students to operationalize definitions, often a more cognitively demanding task. As an example, in the MEA entitled On-time Arrival (see the sample MEA in appendix A or visit: https://engineering.purdue.edu/ENE/Research/SGMM/CASESTUDIESKIDSWEB/ontimearrival.htm, students are purposefully asked to define the term on-time (this MEA could/should be revisited throughout the chapter as it provides insight on the discussion). Developers of this MEA specifically omitted the definition of on-time so that students would be faced with operationally defining what constitutes promptness in the airline industry. This is a typical responsibility of mathematicians as they solve problems and create mathematical models, but it may not often be an expectation of problem solvers in contrite textbook problems.

The third component to an MEA is often a data table or some other mathematical information that may be used to solve the problem. To revisit the example of On-time arrival, the data table consists of arrival data for one month from five fictitious airlines from which students are asked to identify the most on-time company. As a side-note, the most logical response to this problem, i.e. measures of central tendency, are not adequate to solve the problem given the way the data were created. Also, MEAs are considered well-structured because information to solve the problem is provided in the data set page. This is in opposition to something such as a Problem-based Learning (PBL) task which is ill-structured because students have to locate the data to solve the problem. Well-structured problems are often ones that can be solved in a timely manner, thus making MEAs even more attractive to teachers. The fourth component of an MEA is a problem statement. This is often a fairly concise demand, but the manner in which the problem statement is phrased is calculated and highly structured. To become intimately acquainted with MEAs, it is suggested that interested parties solve one such as On-time Arrival in appendix A.

Process of Solving Model-eliciting Activities

Still the question may remain, 'Why are MEAs different than myriad peer problem types?' MEAs possess specific qualities that ask students to engage in multiple iterations to solve the problem. This is the case because first attempts at solving MEAs are rarely successful. As a result, it is typical to see problem solvers engage in multiple iterations of the problem. The analogy has rarely been made, but solving an MEA is fairly similar to the engineering design process (Duncan, 2011; Hamilton, 2009). With the engineering design process, students are expected to design a product on paper, create a prototype of the product, test the product, identify shortcomings, and make revisions as needed. Invariably, nearly all parties familiar with the engineering design process make revisions to a less than perfect, mediocre, or nearly perfect product. Students solving MEAs engage in a nearly identical process. As students create mathematical models, the models need to work to solve the immediate problem. It is instrumental though that the mathematical models also work to solve additional problems that may contain a relatively similar data set. This speaks of the generalizability and the effective prototype principle that are components of design in each MEA. The process of creating and refining multiple iterations of the model has aptly been referred to as the process of, 'express, test, and revise' (Hamilton, Lesh, Lester, & Yoon, 2007) in an attempt to seek a highly refined mathematical model.

Design Components of Model-eliciting Activities

Given the many attributes of MEAs, it is not astonishing to learn that designing them is far from an insignificant process. In fact, designing MEAs is a rather time-consuming process that demands developers adhere to stringent design principles. Six design principles are used to create each MEA and they are the following: model-construction principle, reality principle, self-assessment principle, model documentation principle, model share-ability and reusablity principle, and effective prototype principle (delMas, Garfield, & Zieffler, 2009; Lesh et al., 2000). Interestingly, several of these design principles are intricately intertwined as will be illustrated in the forthcoming discussion and many are self-explanatory.

Model-construction principle. The model-construction principle illustrates the fact that most of the principles are self-explanatory. With the model-construction principle, it is stated that problem-solvers need to create a mathematical model to solve the problem. There are two parts to this principle though. The first component is that the model needs to be able to explain, "patterns and rules governing the relationships between the numbers" (delMas, Garfield & Zieffler, 2009) in the data. The second part is that the model needs to be able to be used in subsequent situations. These subsequent situations are ones in which problem solvers identify a fairly similar mathematical situation. The mathematical model therefore needs to be able to work on the immediate situation and on future, similar situations. This component of the first principle, i.e. the model-construction principle, is not unlike the model-reusability principle. In each instance, problem-solvers need to be able to create something that has generalizability.

Reality principle. The reality principle may be the exception to the rule that the six design principles are self-explanatory. It might seem obvious that the reality principle demands that the problems are incredibly lifelike or ones which the problem solver(s) would encounter on an everyday basis. This is not exactly an accurate statement however. The reality principle stipulates that the problem must be, "meaningful and relevant to students" (delMas, Garfield & Zieffler, 2009). This is the point at which the Lesh and colleague MEA developers and the Garfield MEA developers differ slightly. Lesh and colleagues are notorious for creating data and mathematical situations that very closely mimic real-life situations and Garfield and colleagues place a high priority on identifying actual data that has kept its integrity or has only slightly been modified. It is important to note that developers of MEAs under the direction of Lesh expended great efforts in making the data incredibly realistic so in many instances it is not possible to ascertain the authenticity of data in Lesh-created MEAs. As an example, when the MEA entitled *Summer Camps* was developed, an MEA that had data on a summer track and field camp, an expert in track and field and elementary education (the first author) utilized his expertise as a collegiate track assistant coach to use authentic data for young students. The single connecting component that Lesh and Garfield hold in common regarding the reality principle is that the solution must be meaningful and real to problem solvers. Lesh, in fact places such a priority on meaningfulness in model creation that he has been known to also call this principle the meaningfulness principle. As a final note, Garfield seeks accurate, untouched data in as many situations as possible because she uses her MEAs with predominately college undergraduates in statistics courses. MEAs created by Lesh and colleagues have documented use in grades 3-graduate work including freshmen engineering courses.

Self-assessment principle. The self-assessment principle certainly is as the name suggests. When completing, and when finished with the final product, problem-solvers should be able to self-assess their products with a high degree of accuracy. In many, i.e. non-MEA, mathematical situations in grades K-12, this is not the case. This is reason that classrooms that utilize the direct-instruction, guided practice, and independent seatwork paradigm often have lines of 10-15 students at the teacher's desk inquiring as to whether their answers are correct. This issue is predicated on the fact that students have no idea whether or not their response is correct or even logical. The notion of students being able to identify whether their response is logical is something that is outlined in the *Principles and Standards for School Mathematics* (NCTM, 2000). Further, it is interesting that students can solve highly complex problems and identify the accuracy of their mathematical model, but with ostensibly mundane, algorithmically-driven mathematical exercises such as dividing fractions, students are not always able to carefully assess responses. In fact, it may be the case that with algorithmically-driven problems students have little idea if their answers make sense. It would seem counterintuitive that students could accurately self-assess in more cognitively complex mathematical situations relative to situations in which cognitive demand is low, but given design features of MEAs, this is the case.

Model-documentation principle. The model-documentation principle simply states that problem solvers must be able to carefully document and reveal their mathematical model during the process of solving the problem. This is no small task for students because it demands technical writing which may not often be explicated and practiced in many schools. In specific, students need to be able to re-create their thinking process in great detail so that others could replicate their model if desired. Carefully documenting the model created enables students the opportunity to explain their mathematical model to peers with great aplomb.

Model share-ability and reusability principle. Some of the model share-ability and reusability principle was already discussed in the model-construction, model-documentation, and the reality principle. However, with this principle, the creation of a model that enables problem solvers the opportunity to use the model in a similar situation, i.e. reusability, and to easily share it with peers is of primary importance. It is not uncommon for teachers of mathematics to explain a procedure to students and not to explicate future situations in which it can be used. When creating MEAs, developers have already considered this issue because problems are written with a specific emphasis on relating to future situations. As an example, at the turn of the millennium (i.e. 1999/2000), many problems were written in which problem solvers were asked to create a rating system for activities such as making athletic teams at school, judging a summer reading or a paper airplane flying contest, etc. The data in the aforementioned rating MEAs was realistic and meaningful to students and just as significant, the models created were ones that could be used repeatedly in mathematics class and in real-life.

Effective prototype principle. Naturally, with the effective prototype principle, developers have been asked to create problems that demand an effective model for a successful solution. This principle links closely with the self-assessment principle and it substantiates the claim that students are involved in the process of express, test, and revise, because many first iterations of mathematical models work to a degree, but they are not highly refined products. The effective prototype principle stipulates that the model is one that is efficient, concise, and easy to interpret.

Once an individual has designed several, e.g. four to five, MEAs, the process of developing them with all six design principles becomes almost second nature. Moreover, as the previous comments reflect, often one principle has an effect on another principle so by controlling a few factors in the design process, meeting all six principles can occur. It is important to note that all MEAs that are field-tested and highly respected meet all six principles. With the advent of the internet, many MEAs have been created and there is no guarantee that all MEAs meet all six design principles. The MEA resources listed at the end of this chapter are strong examples of MEAs that have been developed with the six design principles in mind. Given the highly specific nature of designing MEAs and the other discussion points, one may contemplate what implications exist for using MEAs.

Value of Using Model-eliciting Activities

The value of MEAs has consistently been attacked citing three concerns. First, flexible time for teachers in the classroom has been almost completely eliminated given increasing demands from overcrowded curricula. Second, MEAs require a fair amount of time to implement, assess, and for students to debrief on solutions. Third, MEAs may not directly translate to higher performances on state and national standardized assessments. One simple response suffices for all of these criticisms and that is, ‘As a stakeholder in the education process, e.g. a teacher, do you want to facilitate actual learning or does merely engaging in the tedium of direct instruction satisfy your definition of student learning?’ One facet of MEAs that is attractive to most individuals seeking authentically engaging and mathematically worthwhile activities is the claim by Lesh and colleagues (2000) that when students solve MEAs, they are engaging in pre-college level mathematics. This claim is substantiated by the fact that MEA solvers engage in real-world problem solving demands while doing highly open-ended activities. Further, this claim often precipitates the question of what actually should be done in the K-12 classroom to prepare students to succeed mathematically in the outside world and in the university world. The expectations of completing an MEA are highly realistic and students are expected to function as autonomous groups, making mathematical modeling an achievable curricular demand in the K-12 mathematics setting.

Promising Uses of Model-eliciting Activities

MEAs appear to hold promise in accomplishing at least four objectives. First, data supports their use in conducting a fine-grain analysis of how students think (Chamberlin, 2004; Chamberlin, 2002a). From her (Michelle Chamberlin's, 2004) dissertation a product referred to as *Ways of Thinking* sheets was developed. These sheets are a systematic manner in which teachers can carefully analyze students processes as they complete MEAs. Further, MEAs are a breath of fresh air when one considers the current status of state and national standardized tests and what they are designed to do (i.e. look merely at mathematical products and relatively simplistic regurgitation of mathematical procedures and algorithms). Second, MEAs hold promise for engaging students of various capabilities (Chamberlin, 2002b). This is not to suggest that MEAs are a panacea for lack of engagement with every single primary and secondary student. However, they have been shown to be useful with students requiring remediation, general population students, and students of advanced capabilities all within the same study (Chamberlin, 2002b). It is hypothesized that inherent qualities of MEAs, namely that they have multiple entry points, is responsible for engaging students of various academic and intellectual abilities.

Given the fact that they may be used with students of various capabilities, it may not be surprising to learn that MEAs appear to possess some promising features with respect to identifying a wide range of capable students including students of mathematical promise. Many identification procedures in the world of gifted education have no problem identifying the *prototypical* gifted student. This is often accomplished by using a group of data sources such as, but not limited to, intelligence quotient (IQ) tests, academic performance in school, and a work sample or parent, teacher, or peer-nomination. However, what about students that are atypical demographically from the vast majority of students identified? Is it safe to assume that current identification procedures are flawless and if not, is there any tool or instrument that is mathematics-specific? Contrary to the previous implications, the use of MEAs in identifying a wider range of capabilities has not been formally studied. Instead, anecdotal data from teachers suggest great promise. The use of MEAs as an assessment tool is consistent with its initial purpose, i.e. to carefully look at how students think. A fourth implication for using MEAs is that they appear to be promising in identifying and facilitating development of creatively gifted students (Coxbill & Chamberlin, unpublished manuscript). Creatively gifted students (Krutetskii, 1976) comprise a population that is often minimized if not altogether neglected. This is likely the case for at least one to several reasons. First, classroom teachers may not have received any training with respect to the concept of creativity in mathematics. Second, as a result of their unfamiliarity in addressing needs of creatively gifted students, teachers have little insight with respect to how to identify them. Third, time simply does not exist to investigate such students given already overcrowded curricula in mathematics and other subjects. The process of developing creatively gifted mathematics students with MEAs is a research endeavor that is in its infancy, but is being investigated by several researchers including Eric Mann at Purdue University (personal communication with E. Mann, 24 January 2012) Scott Chamberlin, and Emmy Coxbill at the University of Wyoming.

Conclusion

Given the positive comments about MEAs it is strange to think that educators have not fully embraced them. This may be the case for the following reasons. First, despite incredible efforts on behalf of individuals that promote MEAs, they have not received widespread recognition as they deserve. Second, they are considered to be too out of the mainstream and they do demand preparation and a fair degree of self-efficacy to implement. This hypothesis may frighten some prospective users because a strong conceptual understanding of mathematics is of great importance in implementing such problems. Third, MEAs are at this point a supplementary curriculum. They are not a stand-alone curriculum and administrators and teachers that adopt a new curriculum may desire one-stop shopping so that they do not need to supplement calendar days in the school year. Finally, and this sad point cannot be neglected with the (over)-emphasis on state and national standardized assessments, they have not been correlated with such assessments. Consequently, some administrators may be concerned that MEAs promote true conceptual understanding in mathematics, but they may not immediately translate to high standardized assessment scores given the respective emphases of MEAs and standardized assessments.

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Resources

Internet sites

- Carleton College Science Education Resource Center: http://serc.carleton.edu/sp/library/mea/examples.html
- Indiana University Center for Research on Learning and Technology: http://crlt.indiana.edu/research/csk.html
- Purdue University College of Engineering: https://engineering.purdue.edu/ENE/Research/SGMM/CASESTUDIESKIDSWEB/casestudies/phone/CASESTUDIESKIDSWEB
- Purdue University College of Engineering: https://engineering.purdue.edu/ENE/Research/SGMM/CASESTUDIESKIDSWEB/index.htm
- University of Minnesota Department of Statistics: http://www.tc.umn.edu/~catalst/materials

Books

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APPENDIX A

Newspaper Article: The Challenges of Flying

Chicago, Illinois - With 180,000 people flying in and out of O'Hare International Airport in Chicago each day, nearly 70 million people per year, O'Hare is one of the busiest airports in the world. Being this busy has advantages for passengers. For instance, if one's flight gets cancelled, one has a very good chance of finding another flight. Also, O'Hare has flights to virtually every other airport in the world.

However, along with these advantages come some disadvantages for the passengers. It can be difficult to get to one's gate, to park one's car, to pick up one's baggage, and to check in when you have to compete with thousands of other people each day. Despite these disadvantages, people keep coming back to the airport and passengers have even rated the airport as their favorite airport in the world (on an internet survey). On the survey, passengers provided numerous reasons for their like of O'Hare airport. A popular reason was that all of the airlines at O'Hare try to stay on schedule. Staying on schedule is very important, because one or two little disturbances can offset the entire airport schedule.

Travelers typically have three main concerns when flying to their destination. First and foremost, they are concerned with safety. When asked, most passengers say that they would not mind being a few minutes late to ensure that they arrive at their destination safely and without incident. After safety, the passengers' second most common concern is whether the flight takes off and arrives on time. Third, they want their baggage to be shipped to the correct destination and to also arrive on time.

O'Hare does a fantastic job of making sure the planes arrive and leave on time; however, many things can impact this timing. Those that travel regularly can make a pretty calculated guess as to whether their flights will arrive on time. This timing is contingent on several factors.

First, the origin of the flight impacts the plane's chance of arriving on-time. For example, planes rarely leave late from San Diego, California due to San Diego's great weather, but they frequently leave San Francisco late due to weather conditions such as fog. Veteran travelers often try to avoid flights that leave San Francisco to come to O'Hare. Second, the on-time arrival is based on the flight's destination. For example, sometimes a destination takes a plane into a very busy airport that may be too small for the amount of daily air traffic. In this case, a gate may not always be ready for the plane to pull up to and unload the passengers. Thus, the plane will have to wait. Similarly, an understaffed maintenance department may impact the company's ability to fix planes on a timely basis. Third, the on-time arrival may be dependent on the company. Some airlines are known for being consistently on-time, while other airlines are known for not being on-time.

For some travelers, arriving on-time is not an issue, because they are not in a hurry. For example, a family flying from Pittsburgh to Orlando in order to visit Disney World may not be too concerned if they arrive 15 to 30 minutes late. However, business travelers may miss important meetings if their flights arrive late.

Readiness Questions

1. Where is one of the busiest airports in the world?

2. What do you believe might be another busy airport?

3. Why would arriving on time be important to some travelers and not as important to other travelers?

4. List one thing cited in the article that may cause a plane to be late.

5. Can you think of others reasons for a plane to be late that are not mentioned in the article?

INFORMATION

In June, Ridgewood High School's Spanish club is going on a study abroad trip to Venezuela, and they have hired your class to help them select which airline to fly. Last year the Spanish club had a miserable experience when traveling to Barcelona. Their connecting flight to Reykjavik, Iceland was late, so they missed their next flight to Barcelona. The entire class had to stay overnight in the airport.

This year the class has decided to take a more systematic approach to choosing an airline. So far, the class has identified five airlines with economical fares that fly from O'Hare Airport to Venezuela, but they are still in the process of identifying more airlines that fly to Venezuela. Most of the flights have a connecting flight in Mexico City. They are hoping to find the airline that has the smallest chance of departing late from O'Hare so that they are less likely to arrive late in Mexico City. They don't want to miss their one connecting flight to Venezuela this year!

Problem Statement

In the preceding table, you will find information about departure times for flights on the five airlines that the Spanish Club has identified thus far. The departure times are for flights leaving from O'Hare Airport and scheduled to arrive in Mexico City. Rank the five airlines in terms of most likely to be on time to least likely to be on time for departing from O'Hare Airport. As you rank the airlines, keep track of your process. Describe your process in a letter to the Spanish Club so that they may use a similar process to rank the additional airlines that they may identify at a later time.

Number of Minutes Late for Flights Departing from O'Hare Airport

Sky Voyage Airline	Central American Airlines	Mexico Express	Sudamerica Internacional	Southeast Airline
5	15	9	0	0
0	9	5	25	5
20	4	5	0	0
5	0	5	9	9
0	0	125	0	40
6	14	10	0	0
0	20	5	4	5
0	15	10	0	25
15	16	0	35	10
0	0	4	0	30
0	0	10	0	12
7	15	10	10	0
0	10	10	5	0
5	10	9	55	10
40	25	7	0	9
4	5	12	0	5
0	20	5	0	0
0	15	0	17	27
0	11	10	5	11
0	12	7	0	0
3	0	13	65	30
60	5	0	5	5
5	0	0	0	0
0	30	10	0	4
7	4	5	2	40
0	5	4	0	0
0	10	6	0	15
123	10	5	75	0
0	25	7	0	6
5	4	5	0	9