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A Novel 3D+MEA Approach to Authentic Engineering Education for Teacher Professional Development: Design Principles and Outcomes

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teacher professional development, authenticity, model-eliciting activities, manipulatives

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A Novel 3D+MEA Approach to Authentic Engineering Education for Teacher Professional Development: Design Principles and Outcomes

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Abstract

This paper describes the design principles and implementation of a novel approach for a K–12 teacher professional development (PD) program. The approach integrates training focused on development of model eliciting activities (MEAs) within authentic engineering design tasks, collaborative 3D model design and fabrication, and inspirational site visits with access to active engineers to enhance understanding of current issues faced by NASA aerospace researchers. Throughout the training, participants collaborated with program staff including engineering, 3D graphics, education, and MEA specialists to develop research-related MEAs with accompanying 3D-printed manipulatives. The purpose of this article is to provide a framework for engineering education teacher PD in authentic contexts and examine teachers' experience of the program, including comfort with and knowledge of integrated science, technology, engineering, and mathematics (STEM) instructional strategies. Pre–post survey results show high levels of satisfaction with the workshop and significant gains in integrated STEM understanding and comfort. Potential barriers to curriculum implementation include lack of a 3D printer and time. We provide a list of lessons learned from the PD development and implementation along with recommendations for developing similar PD programs.

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Science, technology, engineering, and mathematics (STEM) education emphasizes the integration of abstract concepts from science and mathematics with concrete applications of engineering and technology. The National Academy of Engineering and National Research Council (NAE & NRC, 2014) defined integrated STEM as the “cohesion of central concepts across the mathematics and science representations, engineering objects, design and construction activities, and social structures in the classroom” (p. 58). Students and teachers that use truly integrated STEM curriculum are challenged to move beyond teacher-focused curriculum and adopt student-centered curriculum that incorporates real-world challenges as context for academic exploration and engagement. As teachers migrate from more familiar educational strategies toward those that empower students to create their own methods for learning, it is important to develop and deliver professional development (PD) opportunities that provide training on tested methods of implementation.

Engineering in K–12 has increasingly been adopted as a means of integrating STEM and is becoming more prevalent across the United States (NAE & NRC, 2009). In particular, the Next Generation Science Standards (NGSS), adopted by

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18 states and the District of Columbia (National Science Teachers Association, 2017), incorporate a set of science and engineering practices, based on an analysis of the practices in which actual scientists and engineers engage (NRC, 2012). Students must learn the disciplinary core ideas in the context of these science and engineering practices. Carr, Bennett, and Strobel (2012) reported that at least 41 states have adopted or proposed K–12 engineering standards. Furthermore, while it is predicted that STEM occupations in the United States will only continue to grow, it is also the case that occupations that require STEM knowledge and skills are more pervasive than those in just science and engineering fields (National Science Board, 2015). Despite the recent focus on integrated STEM and engineering, there is a lack of vision and framework on supporting their implementation (Carr et al., 2012; NAE, 2010). Moreover, studies indicate that teachers continue to teach science and mathematics in isolation, and grapple with barriers of insufficient content knowledge to integrate disciplines, inadequate instructional time, and limited access to or awareness of curricular resources that blend disciplines (Abell, 2007; McBride, 1991; NAE & NRC, 2014). Teachers may also lack student-centered pedagogical skills and experience that are necessary for facilitating engineering in the classroom (Singer, Ross, & Jackson-Lee, 2016). Not surprisingly, teacher PD and training in integrated STEM, and particularly in engineering education, has also been sparse (NAE & NRC, 2009).

Reimers, Farmer, and Klein-Gardner (2015) argued that PD for teachers of engineering requires a unique framework. To this end, Farmer, Klein-Gardner, and Nadelson (2014) developed a set of standards for the preparation and PD for teachers of engineering. These standards cover engineering content and practices, pedagogical content knowledge in engineering, engineering as a context for learning in other non-engineering subjects, identification of appropriate curriculum and assessment methods, and alignment to research, standards, and educational practices in current education research. Teacher PD encompassing one or more of these standards has shown positive effects on teacher and student outcomes (Reimers et al., 2015). Engineering provides a means of integrating STEM disciplines in a realistic, authentic context, increasing students' mathematics and science content knowledge, and increasing their interest in STEM fields (Bethke Wendell & Rogers, 2013; Hirsch, Berliner-Heyman, & Cusack, 2017; Lachapelle, Phadnis, Jocz, & Cunningham, 2012). However, opportunities for working on authentic STEM problems that might lead to the development of interest, experience, and STEM skills in K–12 have been limited. Teacher knowledge about integrated STEM and the implementation of authentic curricular activities that support STEM-related skills and practices are necessary to effectively implement the standards and support STEM knowledge and interest in K–12. The presented method is one

example of how this authentic integrated STEM approach may be implemented for teacher PD.

Background

Integration of Engineering Principles and Science Education Standards

The NGSS, developed using the *Framework for K–12 Science Education* from the NRC (2012), incorporate scientific and engineering practices, crosscutting concepts, and disciplinary core ideas to form the basis of the education standards contained in the NGSS:

- Asking questions (for science) and defining problems (for engineering).
- Developing and using models.
- Planning and carrying out investigations.
- Analyzing and interpreting data.
- Using mathematics and computational thinking.
- Constructing explanations (for science) and designing solutions (for engineering).
- Engaging in argument from evidence.
- Obtaining, evaluating, and communicating information.

The practices describe both behaviors that scientists apply as they investigate and build models and theories about the natural world and the key set of engineering practices that engineers use as they design and build models and systems (NRC, 2012). Notably, the disciplines covered by the NGSS include physical science, life science, Earth and space science, as well as the novel combination of engineering, technology, and applications of science collectively to form a fourth discipline. With this level of integration of engineering incorporated into national-level standards, it is clear that there is a recognized need and urgency to elevate the integration of practical, solution-driven approaches with a more traditional academic understanding of science and mathematics topics.

Irwin, Pearce, Anzolone, and Oppliger (2014) noted that “The goal of science is to construct theories about the natural world where the goal of engineering design is to find solutions to problems that can be manifested in a physical product, plan, or mechanical device” (p. 2). They also mentioned that practices relevant for high school students would include engineering projects that involve construction, product testing, and design of objects, tools, processes, or systems (Irwin et al., 2014). Further, in order to address more fully the concerns of the NGSS (i.e., integration of engineering with math and science), PD should be created and offered for teachers who lack a background in engineering and who lack experience with integrating engineering education concepts into STEM. The shortage of availability of such training may prevent successful implementation of the vision guiding the NGSS (Irwin et al., 2014).

Teacher Professional Development in Engineering Education

There are many different models of teacher PD programs in engineering education (NAE & NRC, 2009), varying in scope, target audience, curriculum, and trainers. Professional development that adheres to one or more of the Standards for Professional Development for Teachers of Engineering (Farmer et al., 2014) has shown positive outcomes in the research literature (Reimers et al., 2015).

One type of PD approach places teachers in authentic research environments. An example of an immersive research experience for teachers is the National Science Foundation's Research Experiences for Teachers in Engineering and Computer Science, which funds projects that place teachers in research laboratories so that teachers can translate their experience into classroom activities. These experiences are often several weeks in length and focus heavily on participating as a researcher in the laboratory (e.g., Hsieh, 2015; Ragusa & Mataric, 2016). Programs that immerse teachers in research have shown positive results overall including improved science teaching self-efficacy (Ragus & Mataric, 2016), increased content knowledge of their particular research area (Westerlund, Garcia, Koke, Taylor, & Mason, 2002), and increased competence in teaching engineering or the engineering design process (Billiar et al., 2016).

Another feature of successful teacher PD is a participatory design approach to develop or learn about curriculum. Participatory design approaches seek the input of users in development and design (Carroll, Chin, Rosson, & Neale, 2000). Recently, the participatory approach of co-designing curriculum has been used for enhancing outcomes of teacher PD (Kyza & Nicolaidou, 2016; Voogt et al., 2011). In this process, teachers "create new or adapt existing curriculum materials in collaboration with each other, and often with experts such as educational design experts, educational researchers, and domain experts" (Voogt et al., 2011, p. 1236). A co-design approach to developing reform-based curriculum can utilize teachers' valuable classroom experience and knowledge in addition to giving them ownership over the creation of lessons and reform teaching methods (Bjögvinsson, Ehn, & Hillgren, 2012; Kyza & Nicolaidou, 2016). Finally, the process of curriculum design as teacher PD has been shown as an effective approach to teachers' learning; for example, outcomes include increased content knowledge and motivation to deepen their knowledge (Kyza & Georgiou, 2014).

Model-Eliciting Activities

Model-eliciting activities (MEAs) are modeling problems that require students to apply science and math concepts and practices while using a model-development process (Diefes-Dux, Hjalmarson, Miller, & Lesh, 2008)

that parallels a simplified engineering design process commonly found in K–12 curricula (Cunningham, 2007). Students design and test a mathematical model that demonstrates, explains, or illustrates their problem-solving process. MEAs have been used as a tool to help students become better problem-solvers (Shuman & Besterfield-Sacre, 2009) and have also enabled students' content knowledge gains, teamwork and communication skills, modeling skills, and engagement (Diefes-Dux et al., 2008; Lesh & Yoon, 2004). By following the models-and-modeling perspective that "assumes that solving concrete, situated problems is easier than abstract, decontextualized problems" (Diefes-Dux & Salim, 2012, p. 315), MEAs present a variety of contexts for developing a model that can be applied to other situations and extend the original problem context.

Following the framework of an authentic engineering task, students working on an MEA are grouped in teams to solve problems for hypothetical clients that ask the students for help in a problem statement (often in the form of a letter). The students are provided information and data to analyze while evaluating tradeoffs and calculating an optimal solution to the open-ended problem. The student teams use a model development process that is similar to engineering design processes. The product of the activity is not the answer itself, but rather the documented method, or procedure that the team used to find the answer, thus revealing how the students were thinking about the problem. In this student-driven learning environment, teachers serve as facilitators and provide coaching and prompting to challenge the teams to think deeper and explore alternative solutions and procedures. Through team-based argumentation, discussion surrounding data, and working with models, students find themselves immersed in relevant contexts that require an applied understanding of STEM content. By incorporating this type of curriculum that requires a process model as a solution, teachers can better develop and assess their students' critical thinking and higher-level thinking skills (Diefes-Dux & Salim, 2012). Similar to an engineering problem, MEAs often have a wide array of possible answers, much discussion over the "best" solution, and, finally, generation of a method or process determining an eventual selection.

Although originally developed for K–12 mathematics, MEAs have been increasingly used in undergraduate engineering (Moore & Hjalmarson, 2010; Shuman, Besterfield-Sacre, Yildirim, Bursic, & Vidic, 2011; Zawojewski, Hjalmarson, Bowman, & Lesh, 2008) and K–12 science classrooms (Purzer, Duncan-Wiles, & Strobel, 2013; Razzouk, Dyehouse, Santone, & Carr, 2014; Reid & Floyd, 2007; Tazaz et al., 2013). There are currently over 550 peer- and expert-reviewed MEAs on CPALMS (Florida's official Web-based platform for the standards; see www.cpalms.org), which are used by K–12 teachers in Florida and nationwide.

Three-Dimensional Physical Models in Education

The use of physical models for teaching concepts is embedded in human culture and society and includes everything from simple manual gestures (e.g., using a hand to show the flight path of an aircraft) to full-scale prototypes of complex machines. Visual and tactile models are useful for education via communication or visualization of science concepts, objects, and phenomena that are normally difficult to perceive (Cook, 2006). In engineering, where physical objects are often the answer to a problem, models are highly valuable in the iterative design process to ensure a common understanding as the process moves ahead. Physical models are able to present difficult concepts in a visual and tangible way, allowing individuals or teams a chance to work through their challenges with the benefit of hands-on media. While models have long been a part of a broader set of educational tools, the rise of consumer-grade additive manufacturing technology brings with it new approaches for custom media as well as a context for rapid prototyping and on-demand educational manufacturing.

In recent years, 3D printing has moved from the engineering laboratories of major corporations into schools and such venues as online stores and big-box hardware stores. The mass availability and high-volume production of 3D printers have driven costs for the creation of small physical models down to very affordable levels and thus presented an opportunity for educators to become involved in aspects of engineering to a degree that was less feasible just a few short years ago. In addition to more common materials like ABS and PLA plastic, some 3D printers are capable of using other inexpensive media like clay, and are poised to impact not only STEM education, but also the arts, as creators from a variety of interests gain technical capabilities to produce models using 3D printers.

Although physical models for learning are not new, the precision and accuracy available through 3D printing, paired with the relatively low cost, are worth exploring for its impact on STEM education. In the simplest form, students have the opportunity to visualize new concepts or have access to artifacts that would otherwise be viewed on a 2D screen (e.g., the Smithsonian X 3D project; Smithsonian Institution, 2017). Additionally, students can compare and test printed objects as a means of data collection and analysis (e.g., comparing shapes and tread patterns on tires). Finally, 3D printing can allow students to design, test, and redesign their own physical models, particularly with the use of free user-friendly sites like Tinkercad (<https://www.tinkercad.com/>).

3D+Model-Eliciting Activities

MEAs are one framework for curriculum that use engineering as an integrative context for real-world STEM applications. 3D-printed objects can extend the traditional

“minds-on” MEA to the use of physical models as well as mathematical models, providing additional opportunities for engagement and modeling in STEM. Here, the term “3D+MEA” is used to represent MEAs that are intended to be used with 3D physical models, whether 3D-printed, molded, or manufactured using some other method.

In an educational setting, it is not feasible to expect all students and teachers to become at once designers, modelers, fabricators, and engineers; yet there exist multiple avenues for adoption of 3D printing technologies to create learning experiences designed to overcome visualization challenges, enhance spatial problem solving, or promote learning through iterative design. Tillinghast et al. (2014) noted two forms of integration for bringing 3D printing into a classroom: active and passive. Active integration includes involving students in the design process to assist in creating the model and related curriculum. This form involves training on multiple aspects of the 3D modeling and printing process where learning encompasses the technical skills necessary to produce a 3D-printed model. Passive integration relies on more traditional education techniques, but with the additional aid from a 3D model developed prior to a lesson. Students benefit in both cases, but passive integration of 3D printing bypasses the student-as-designer opportunity and favors the interaction of the student with the model to address core topics from STEM disciplines. Finally, teachers who develop 3D+MEAs can benefit from collaborating with a skilled modeler to develop a 3D model for an MEA rooted in authentic engineering problems.

Authentic Engineering Experiences

Strobel, Wang, Weber, and Dyehouse (2013) defined authenticity in learning environments as follows: “Authentic problems are problems, which primary purpose and source of existence is not to teach or provide a learning situation; The primary purpose and source should be a need, a practice, a task, a quest and a thirst existing in a context outside of schooling and educational purposes” (p. 151). Four types of authenticity were characterized in engineering education: context authenticity, task authenticity, impact authenticity, and personal/value authenticity. To have context authenticity, a problem must resemble something that might be encountered in a real-world context. Examples of context authenticity include providing students with patient data (real or simulated) in medical school or providing students with real sea ice data to analyze in a math or science classroom. Task authenticity refers to activities that are similar to those undertaken in the real world, such as scientific inquiry or chemical analysis. Students using the engineering design process to find an optimal solution to an open-ended problem is one example of task authenticity. Impact authenticity means that the products students create are used in out-of-school situations.

One example of impact authenticity is students collecting and analyzing data about the numbers of students eating lunch at a given time, which the school then uses to adjust the lunchroom schedule. Finally, personal/value authenticity refers to projects that hold value for students' own lives or that are personally relevant. This type of authenticity is often found when students work on projects that satisfy personal or community needs, such as studying the biodiversity in a nearby forest. Immersion in real-world experiences or research activities is one method of creating an authentic engineering experience. MEAs can be designed to include one or more features of authenticity.

One of the principles underlying the design of MEAs is the reality principle, which requires an "authentic engineering situation" (Diefes-Dux & Salim, 2012, p. 316) to guide the real-world, context-driven approach of this type of problem. To the extent possible then, it is important to provide MEA developers with the expertise that can only come from experience in real-world engineering problems. While teachers and others who may require PD to develop MEAs may not themselves be engineers, it is possible to embed engineers in teacher PD and embed teachers in engineering laboratories for collaborative interaction and discussion to arrive at realistic problems faced by engineers today.

To address the need for high-quality PD in integrated STEM, we designed and delivered a PD experience centered around authentic engineering. In this article, we describe the design principles and implementation of a PD workshop for teachers where engineer-teacher interactions guided development of MEAs enhanced with 3D physical models developed and printed on-site. We aimed to create an authentic engineering experience for teachers and eventually for the students who will use the curriculum. The research questions for this study are:

- What are teachers' views of and reactions to the PD program?
- What is the effect of the PD program on teachers' understanding of integrated STEM via MEAs?
- What is the effect of the PD program on teachers' comfort with integrated STEM instructional strategies and 3D technologies?
- What are the effects of the PD program on teachers' attitudes toward the importance of integrated STEM and their teaching and understanding of STEM content?

Professional Development Overview

Workshop goals and design features

The primary goals for the PD were to:

- Increase teachers' knowledge of integrated STEM, including 3D+MEAs
- Provide learning opportunities in curriculum design for 3D+MEAs and MEAs
- Increase teachers' comfort with integrated STEM

To address these goals, the PD program encompassed several research-based design features to provide an authentic learning experience. These design features were: (a) at least 40 face-to-face contact hours, (b) exposure to real-world engineering problems, (c) access to expertise in engineering, 3D modeling, and integrated STEM curriculum/pedagogy, (d) curriculum development, and (e) peer curriculum development teams. The PD also encompassed features related to each of the Standards for Preparation and Professional Development for Teachers of Engineering (Farmer et al., 2014).

Interaction and feedback from content experts took place throughout the workshop, allowing groups of teachers to develop scientifically accurate curriculum, get feedback on their ideas, and take part in an iterative lesson review process via a participatory curriculum design approach.

Through participation in the workshop, teachers took the role of students while the facilitators modeled the type of instruction that is expected in the classroom. The workshop integrated scientific and engineering practices (see Table 1) recommended in the *Framework for K-12 Science Education* developed by the NRC (2012) to address these design features.

The workshop was structured to allow small teams of educators to collaborate among themselves, with training staff, and with NASA engineers to devise a novel MEA and corresponding 3D model. Each team was able to leverage their site visit experiences to form the basis of an activity designed for classroom implementation. Further collaboration within the larger group, including staff with 3D design and modeling expertise, allowed participant groups to develop 3D models central to the overall situation explained in the MEA. Using these design features, this PD program aimed to provide a high-quality PD experience to meet the need for teachers who are able to integrate STEM effectively into their classrooms.

Program overview

This PD took place at the NASA Kennedy Space Center Educator Resource Center in Cape Canaveral, Florida. This site was chosen for its rich history in advancing U.S. aerospace programs, access to a wide variety of creative engineers and scientists, commitment to advancing STEM education and teacher PD, and relatively central location in Florida.

The primary facilitators included two MEA content experts (one of whom had expertise in instructional design), one engineer/MEA content expert, one science content and 3D graphics expert, and one 3D modeler. Additionally, one facilitator from NASA Education was present and able to contribute additional engineering expertise.

The PD experience included 41 direct contact hours plus several additional lesson review and feedback cycles with the facilitators after the workshop, which varied by

Table 1
NGSS science and engineering practices appearing in this training.

Practice	Workshop training	Student expectations
Asking questions (for science) and defining problems (for engineering)	Site visits to learn how engineers are asking questions, refining questions, conducting research, and testing models to drive progress in their field.	Students use a model design process similar to the engineering design process to determine the problem context and scope.
Developing and using models	Educators work closely with engineers and 3D-printing experts to design, refine, model, print, and test 3D models related to aerospace research.	Students use 3D models to generate information to help answer real-world challenges posed within the activity; students develop mathematical models as part of the MEA framework.
Planning and carrying out investigations	Educators create tasks within their MEAs and use their custom models to answer questions posed within the lesson activities as part of testing their 3D models.	Students carry out investigations through testing their models (process and 3D).
Analyzing and interpreting data	Educators translate real-world data into information appropriate for their students; they analyze the data to ensure open-endedness.	Students analyze the data to come to an optimal solution; they go through cycles of testing and revision.
Using mathematics and computational thinking	To create an MEA, educators must think about the problem from the student's perspective by finding, integrating, and testing data to form an open-ended problem.	Students analyze the data using multiple methods including seeking patterns, finding relationships, identifying variables, and creating algorithms to come up with a process that works for a variety of similar situations.
Constructing explanations (for science) and designing solutions (for engineering)	This workshop focused on engineering challenges as a primary context for describing and/or solving problems with 3D models derived from aerospace research situations.	Students use a model design process to determine a solution; they interpret effectiveness of the solution based on the client's needs.
Engaging in argument from evidence	Educators negotiate with their team members in selecting a topic, develop the lesson content based on real data, and justify their decisions for design with modelers, curriculum reviewers, and experts.	Students use data to make decisions; they justify their arguments based on evidence.
Obtaining, evaluating, and communicating information	Participants translate what was learned at their site visits to an age-appropriate 3D+MEA.	Students may obtain data through testing 3D models, evaluating information provided to them in the problem, and communicating within their team and to the client about their process.

participant depending on the kinds of revisions needed. An hour-long webinar took place before the workshop to provide participants with an overview of what to expect at the workshop and to provide general information about MEAs and 3D printing. Each team of two to three teacher-participants was expected to complete one 3D+MEA by the end of the training week. Following the training, each individual participant was expected to develop two additional MEAs (with optional 3D components), due several weeks after the workshop. The goal was to make the lessons available to more teachers by publishing the MEAs and 3D+MEAs on CPALMS (www.cpalms.org) and MyStemKits.com. All of the MEAs were expected to incorporate an aerospace research and engineering context related to observations from research laboratory tours at NASA Kennedy Space Center (NASA KSC).

During site visits to four NASA KSC laboratories, teachers gathered detailed notes on current programs and research being conducted in a variety of areas including automated extraterrestrial fabrication, space hardware design, controlled environment agriculture, and advanced manufacturing. During the tours, teachers were tasked with brainstorming ideas for a reality-based aerospace-themed MEA that also aligned to Florida's education standards for mathematics and/or science. Teachers interacted with resident scientists and engineers to formulate

ideas for MEAs that could integrate concepts from contemporary research.

Following the research tours, groups of teachers were tasked with developing a unique MEA that integrated their interests and experiences from the tour, an original concept for a 3D model to accompany the MEA, and a realistic aerospace engineering context. Teachers were grouped based on the similarity of their topic preferences. Expert MEA facilitators led the training that began on Day 2 of the workshop. During this portion of the training, teachers were introduced to MEAs, learned MEA teaching and implementation strategies, discussed the six principles of MEA design, and began developing MEAs through an iterative cycle of writing and feedback. A backwards design approach (Wiggins & McTighe, 1998) was used to guide MEA development, which starts with the desired results of teaching and ends with the teaching activities, ensuring close alignment to selected standards.

With feedback from the facilitators, the teams brainstormed and developed their models and lessons during the rest of the week. During this time, teachers were able to implement an iterative design methodology to design, test, print, update, reprint, and retest their 3D models. NASA engineers, scientists, and 3D designers were introduced throughout the week to describe their work, meet with, and mentor the teachers during their development activities.

Table 2
Schedule of workshop activities.

Day	Activities
Monday	Welcome/logistics, NASA tours (4 total) with Q&A throughout, debrief
Tuesday	MEA overview, 3D printing for K-12 overview, brainstorm topic ideas
Wednesday	Small group writing sessions, NASA 3D modeling presentation
Thursday	NASA engineer presentation, small-group writing sessions
Friday	Small-group writing sessions, evaluation, debrief

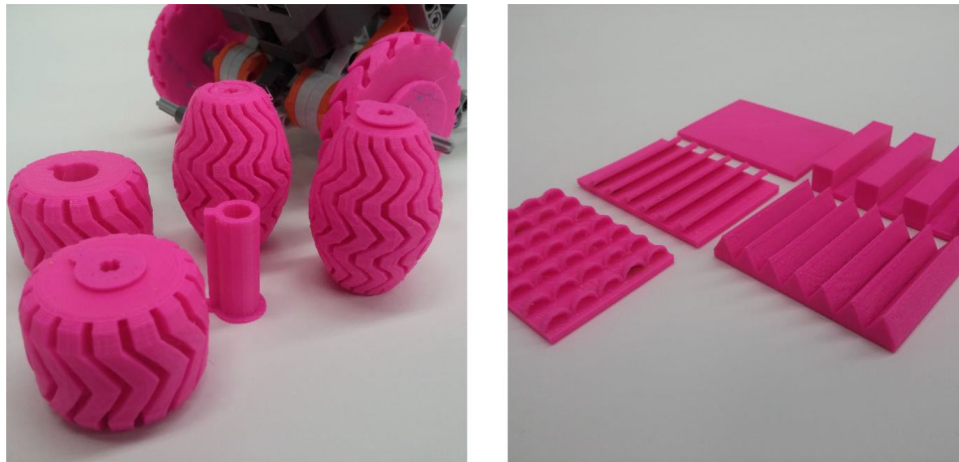


Figure 1. Research-inspired 3D printed models. Left: Rover tread patterns to address a variety of terrain types and regolith composition. Right: Atmospheric microbe sample collectors.

Table 2 provides a broad overview of the schedule of workshop activities during the week.

Example lesson concepts

Participants of this workshop were tasked with developing 3D+MEAs related to current aerospace research at NASA KSC. At the end of the workshop, the participants had produced 8 original 3D+MEAs. Following the workshop, participants produced an additional 19 aerospace-themed MEAs. Research contexts covered in the final set of 3D+MEAs included: rover wheel tread design, solar panel dust removal, packing a module for shipping resources to the international space station, atmospheric microbe collection, astronaut bone density, rocket fin design, space allocation in food production chambers, and regolith brick geometry.

As part of their 3D+MEA writing, participants were tasked with developing 3D model concepts to be designed and printed in collaboration with an on-site 3D modeler. Each model corresponded to an MEA as well as a research context experienced in some way while touring NASA research facilities. Figure 1 contains two examples of models produced during the training. This blended experience in engineering practices, 3D model development, and MEA training and development led to a very focused week of 3D+MEA teacher PD.

Methods

Participants

Participants in this study were nineteen science and/or mathematics educators who participated in the PD program. Participants were purposefully selected for this PD. Ten of the participants were from one Florida county that was selected because of their administrators' motivation and resources to integrate 3D printing technologies in their schools. Ten of that district's schools, many of which are Title I schools with a high proportion of students living in poverty, received 3D printers through a "Donors Choose" program. We invited educators from this county to ensure that these participants had the initial motivation and resources to be effective in the classroom. Selected by district leaders, initially 16 participants from this county signed up to participate; 6 did not participate, due to attrition.

We also invited several educators from a second county to participate. While these participants did not have 3D printers in their schools, they were former high-performing participants of a prior PD program focused on original MEA development. We anticipated that the inclusion of these teachers would strengthen the 3D+MEA lesson plans that would result from this PD program as these teachers had prior experience with MEAs and writing lessons for

Table 3
Participant demographic information.

Demographic	Category	Number	Percent (%)
Sex	Male	6	31.6
	Female	13	68.4
	Total	19	100
Race/ethnicity	Black	3	15.8
	White	8	42.1
	Hispanic/Latino	6	31.6
	Multiracial	1	5.3
	No response	1	5.3
	Total	19	100
Education	Bachelors	9	47.4
	Masters	7	36.8
	Doctorate	1	5.3
	No response	2	10.5
	Total	19	100
Years teaching	Less than 5	3	15.8
	6 to 10	9	36.8
	11 or more	6	26.3
	No response	1	5.3
	Total	19	100

publication on CPALMS. There were a total of five prior PD participants.

Finally, four NASA KSC education specialists participated in the workshop. NASA education specialists are educators who work to promote NASA's outreach mission to K–12. These specialists were interested in better understanding how 3D printing technologies and MEAs could be used to further aerospace education.

Table 3 displays the demographic information of the 19 total workshop participants. Most participants were female (68.4%) and White (42.1%). There were 31.6% Hispanic/Latino participants, 15.8% Black participants, and 5.3% participants of multiracial backgrounds. Most of the participants held a bachelor's degree (47.4%), while 36.8% held a master's degree, and 5.3% held a doctoral degree. Finally, most of the participants had six or more years of teaching experience (63.1%).

Eleven (57.9%) of the teachers reported that they taught at a Title 1 school. There was one elementary school teacher (grades K–5), twelve middle school teachers (grades 6 to 8), two high school teachers (grades 9–12), and four NASA education specialists (K–12). At the middle and high school level, teachers taught a mix of science and math subjects.

Research Design and Data Analysis

A quasi-experimental approach (no control group, pre-post test design) was employed to measure the effectiveness of program activities (Shadish, Cook, & Campbell, 2002). Both quantitative and qualitative methods were used

to analyze the data. For quantitative data, the analysis strategy was a comparison of pre- to post-survey gains using a Wilcoxon signed-rank test, which is a nonparametric version of the paired samples *t*-test. We report descriptive statistics, including the median, the *z*-value, and the *p*-value. If a participant did not complete both the pre- and the post-survey subscale, they were omitted from that analysis.

Open-ended survey questions were analyzed using qualitative content analysis, defined as “a research method for the subjective interpretation of the content of text data through the systematic classification process of coding and identifying themes or patterns” (Hsieh & Shannon, 2005) using an inductive category development approach (Mayring, 2000) in an iterative coding process. Units of analysis were idea “chunks” that could consist of a word, sentence, or paragraph. First, key concepts or variables were identified as initial coding categories and new codes were developed for those that did not fit (Hsieh & Shannon, 2005). Axial coding was then used to develop categories around the core, while selective coding was used to develop any connections between the discrete categories. The qualitative data were then summarized with descriptive statistics (e.g., Namey, Guest, Thairu, & Johnson, 2008). Inter-coder reliability was checked through a second rater who rated 25% of each of the responses for each open-ended item. Agreement was high at 91%.

Measures

The pre- and post-survey included several subsections to assess teachers' knowledge, attitudes, and motivations/

experiences regarding the workshop. The pre-survey also included demographic questions.

Workshop survey

The pre- and post-survey contained several items asking teachers about the workshop. The pre-survey contained nine Likert-type items (1 = strongly disagree, 4 = strongly agree) and seven open-ended items focused on teachers' motivations and interests in the workshop. The post-survey contained nine items that focused on teachers' understanding and plans for implementing MEAs and 3D+MEAs in their classroom (1 = strongly disagree, 4 = strongly agree). Additionally, eight items focused on teachers' opinions of the value of each component of the workshop (1 = little to no value, 4 = great value). Two items asked teachers to rate their satisfaction with the facilitators and to rate their overall experience in the workshop. There were two open-ended questions pertaining to these items; one asked teachers to list any suggestions for improving the quality of the workshop topics and the second question asked teachers to explain their reasons for their overall workshop satisfaction rating. The post-survey also contained three open-ended questions asking teachers to describe the barriers to implementing MEAs, the barriers to implementing 3D+MEAs, and the potential benefits of implementing 3D+MEAs.

MEA Understanding scale

The MEA Understanding scale consisted of 17 items designed to assess participants' self-reported understanding about MEAs. Teachers were asked to rate their level of agreement on a scale defined as follows: 1, strongly disagree; 2, moderately disagree; 3, disagree slightly more than agree; 4, agree slightly more than disagree; 5, moderately agree; 6, strongly agree. Exploratory factor analysis took place to determine dimensionality of the MEA understanding construct. After this process, the items were divided into the following subscales: MEA Theory (pre-survey $\alpha = 0.89$, post-survey $\alpha = 0.52$), MEA Construction (pre-survey $\alpha = 0.95$, post-survey $\alpha = 0.72$), MEA Implementation and Practices (pre-survey $\alpha = 0.94$, post-survey $\alpha = 0.84$), and MEA Identification and Composition (pre-survey $\alpha = 0.82$, post-survey $\alpha = 0.65$). The MEA Theory subscale consisted of items that focused on an understanding of the principles of MEAs. The MEA Construction subscale assessed how much teachers know about how to write a quality MEA. Next, the MEA Implementation and Practices subscale measured teachers' understanding of MEA implementation. Finally, the MEA Identification and Composition subscale assessed teachers' knowledge about developing an MEA.

MEA Comfort scale

The MEA Comfort scale contained 15 Likert-type questions on a four-point scale designed to measure

teachers' comfort with MEAs. The scale was defined as the following: 1, I don't really understand what this means and don't know how to do it; 2, I feel somewhat comfortable doing this, but I need more information and/or practice; 3, I understand what this means and feel comfortable/competent doing it; 4, I thoroughly understand what this means and feel adept at doing it. Exploratory factor analysis took place to determine the dimensionality of the MEA Comfort construct. After this process, the items were divided into the following scales: MEA Implementation (pre-survey $\alpha = 0.93$, post-survey $\alpha = 0.88$), General Teaching Strategies (pre-survey $\alpha = 0.78$, post-survey $\alpha = 0.64$), and 3D Technologies (pre-survey $\alpha = 0.97$, post-survey $\alpha = 0.79$). The MEA Implementation subscale assessed teachers' comfort with various facets of MEA classroom implementation; the General Teaching Strategies subscale measured teaching strategies that not only pertained to MEAs, but to other classroom lessons as well; and the 3D Technologies subscale contained items pertaining to teachers' comfort with implementing and writing lessons that include 3D technologies.

Design Engineering Technology instrument

The pre- and post-survey also included items from the Design Engineering Technology instrument (DET; Yasar Baker, Robinson-Kurpius, Krause, & Roberts, 2006). The DET was developed to assess K-12 teachers' perceptions of engineering and their familiarity with teaching design, engineering, and technology. The survey consists of self-report items on a five-point scale (1, not at all; 5, very much) with four subscales: importance of DET, familiarity with DET, stereotypical characteristics of engineers, and barriers in integrating DET. Hong, Purzer, and Cardella (2011) found acceptable to high reliability for the overall instrument and for each subscale as well as evidence for validity. We selected items from the DET scale based on their alignment with the goals and content of the PD training.

Competence and understanding

Finally, the pre- and post-survey contained items that measured teachers' perceptions about their competence in teaching and understanding STEM content. Teachers were asked to rate their response on a scale from one to ten and then briefly explain why they chose that ranking. Cronbach's α for the pre-survey was 0.835 and α for the post-survey was 0.752.

Table 4 shows the scales and subscales of the survey.

Teachers completed the pre-survey before the pre-workshop webinar took place in the summer of 2014. The post-survey was completed in the last hour of the on-site workshop. The Qualtrics survey system was used to administer both pre- and post-surveys.

Table 4
Survey scales and subscales.

Scale and subscale	No. items	Sample item
Pre-workshop items	9	I am planning to implement an MEA in my classroom
Post-workshop items	19	This workshop is a worthwhile PD activity
MEA Understanding		
a) MEA Theory	4	I understand the construct documentation principle
b) MEA Construction	2	I understand what information needs to be included when writing an MEA problem statement
c) MEA Implementation and Practices	6	I understand when I should intervene when students are working on an MEA
d) MEA Identification and Composition	5	The procedure, or method, is the focus of an MEA solution
MEA Comfort		Please indicate your level of knowledge:
a) MEA Implementation	7	Assessing students' work on an MEA
b) General Teaching Strategies	6	Asking questions that make students consider their ideas or strategies without leading them to a particular solution or method
c) 3D Technologies	2	Writing a lesson with a 3D printing component
Design Engineering Technology (DET)		
a) Importance of DET	4	How confident do you feel about integrating more design/engineering/technology into your curriculum?
Competence in Teaching and Understanding STEM Content	4	How confident are you in teaching integrated STEM in a classroom as compared to your major content area?

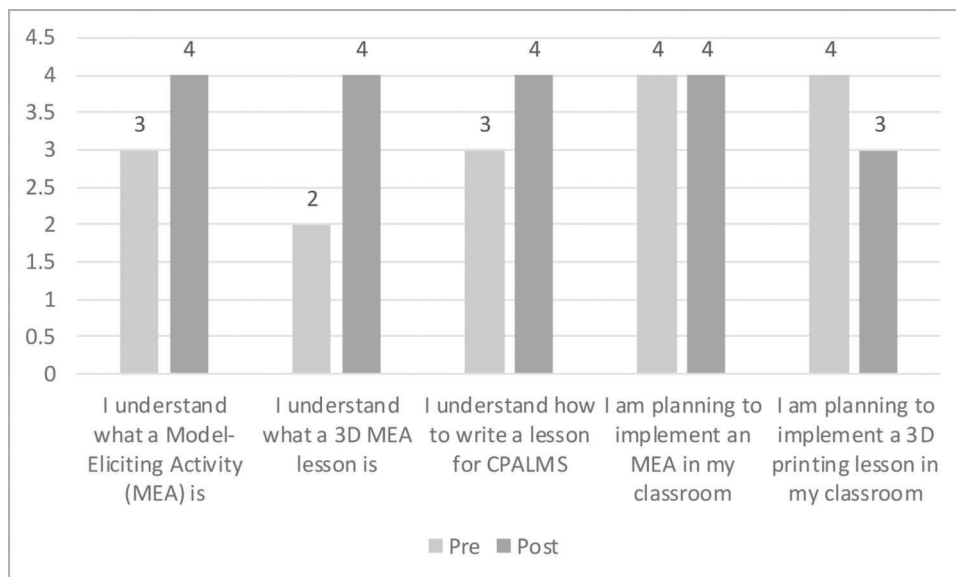


Figure 2. Median scores for pre- and post-workshop items.

Results

Workshop Survey

To address the first research question (What are teachers' views of and reactions to the PD program?), the survey contained several questions pertaining to the PD experience on both pre- and post-surveys (Figure 2).

Results showed significant increases from pre- to post-workshop on most items. A Wilcoxon signed-rank test revealed a statistically significant increase in self-reported understanding of MEAs from before the PD ($Md = 3.00$) to after the PD ($Md = 4.00$), $z = -2.72$, $p < 0.01$. Next, there were significant increases in self-reported understanding of

3D+MEAs from before the PD ($Md = 2.00$) to after the PD ($Md = 4.00$), $z = -3.11$, $p < 0.01$. Finally, teachers showed a significant increase on how to write a lesson for CPALMS from before the PD ($Md = 3.00$) to after the PD ($Md = 4.00$), $z = -2.22$, $p < 0.05$. However, there were no changes in teachers' plans for implementing an MEA in their classrooms from before ($Md = 4.00$) to after the PD ($Md = 4.00$), $z = -1.13$, $p = 0.257$. Finally, there was a significant decrease in teachers' plans to implement a 3D printing lesson in their classroom from before the PD ($Md = 4.00$) to after the PD ($Md = 3.00$), $z = -2.39$, $p < 0.05$. For details, see Table 5.

Because several participants in the workshop had participated in a previous workshop on MEA development,

Table 5
Wilcoxon signed-rank tests for pre–post workshop items—all participants.

	Group statistics		Paired differences	
	<i>Md</i>	<i>N</i>	<i>z</i>	<i>p</i> -value
I understand what an MEA is				
Pre-survey	3.00	18	–2.72	< 0.01
Post-survey	4.00	17		
I understand what a 3D MEA lesson is				
Pre-survey	2.00	18	–3.11	< 0.01
Post-survey	4.00	17		
I understand how to write a lesson for CPALMS				
Pre-survey	3.00	18	–2.22	< 0.05
Post-survey	4.00	17		
I am planning to implement an MEA in my classroom				
Pre-survey	4.00	18	–1.13	0.257
Post-survey	4.00	17		
I am planning to implement a 3D printing lesson in my classroom				
Pre-survey	4.00	18	–2.39	< 0.05
Post-survey	3.00	17		

Note. Statistical significance was sought at $p < 0.05$ using a two-tailed test. 1 = Lowest, 4 = highest.

Table 6
Wilcoxon signed-rank tests for pre–post workshop items—prior MEA workshop participants.

	Group statistics		Paired differences	
	<i>Md</i>	<i>N</i>	<i>z</i>	<i>p</i> -value
I understand what an MEA is				
Pre-survey	4.00	3	–1.00	0.317
Post-survey	4.00	4		
I understand what a 3D MEA lesson is				
Pre-survey	2.00	3	–1.63	0.102
Post-survey	4.00	4		
I understand how to write a lesson for CPALMS				
Pre-survey	4.00	3	–1.00	0.317
Post-survey	4.00	4		
I am planning to implement an MEA in my classroom				
Pre-survey	4.00	3	0.00	1.00
Post-survey	4.00	4		
I am planning to implement a 3D printing lesson in my classroom				
Pre-survey	4.00	3	–1.34	0.180
Post-survey	2.50	4		

Note. Statistical significance was sought at $p < 0.05$ using a two-tailed test. 1 = Lowest, 4 = highest.

we performed two subgroup analyses to determine if prior participation in an MEA curriculum development workshop made a difference to participants' responses. We found no statistically significant differences from pre- to post-survey (see Table 6). Participants showed the highest possible median score (4.00) on all but one item on the pre-survey. Former MEA workshop participants scored a median score of 2.00 on the item asking if they understood what a 3D MEA lesson is. Another item showed a non-significant negative difference: "I am planning to implement a 3D printing lesson in my classroom." That is, more participants anticipated implementing a 3D printing lesson in the classroom before the workshop than they did after the workshop although this item did not reach significance.

For participants who had not participated in a prior MEA development workshop, we found that responses were similar to the whole group findings (see Table 7). Results showed significant increases from pre- to post-survey on all but one item. There were significant increases in self-reported understanding for MEAs, 3D+MEAs, and how to write a lesson for CPALMS. There were no significant changes in teachers' plans from pre- to post-survey for implementing an MEA in their classroom. Finally, there was a significant decrease in teachers' plans to implement a 3D printing lesson in their classroom from pre- to post-survey.

To interpret teachers' responses to their plans on using MEAs and 3D+MEAs in the classroom, two open-ended

Table 7

Wilcoxon signed-rank tests for pre–post workshop items—excluding prior MEA workshop participants.

	Group statistics		Paired differences	
	<i>Md</i>	<i>N</i>	<i>z</i>	<i>p</i> -value
I understand what an MEA is				
Pre-survey	4.00	11	−2.57	< 0.05
Post-survey	4.00	13		
I understand what a 3D MEA lesson is				
Pre-survey	2.00	11	−2.70	< 0.01
Post-survey	4.00	13		
I understand how to write a lesson for CPALMS				
Pre-survey	4.00	11	−2.04	< 0.05
Post-survey	4.00	13		
I am planning to implement an MEA in my classroom				
Pre-survey	4.00	11	−1.13	0.257
Post-survey	4.00	13		
I am planning to implement a 3D printing lesson in my classroom				
Pre-survey	4.00	11	−2.04	< 0.05
Post-survey	2.50	13		

Note. Statistical significance was sought at $p < 0.05$ using a two-tailed test. 1 = Lowest, 4 = highest.

Table 8

Open-ended response codes for future MEA use.

Response code	No. responses
Introduction to a topic	4
Summative/closing activity	3
Lesson enhancement/tie-in	3
Problem-solving/critical thinking	3
Modeling/engineering	2
Content knowledge	2
Will use more open-ended activities	2
Will not currently use/cannot use	2
General/will use	1

post-survey questions were asked: How do you think you will use MEAs in the future? and How do you think you will use MEAs with a 3D printing component in the future? Regarding MEA use, teachers responded most frequently that they planned to use MEAs as an introduction to a topic (4 out of 17 responses). Additionally, three respondents planned to use MEAs to teach problem-solving/critical thinking, and three respondents planned to use MEAs as an enhancement/tie-in to their lessons. Finally two teachers responded that they will use MEAs as a summative/closing activity and another two teachers responded that they will use MEAs for modeling/engineering in the classroom (Table 8).

With regard to 3D+MEA use, most responses centered around the lack of a 3D printer in the classroom (6 out of 17 responses). The second most frequent response mentioned writing additional 3D+MEAs or lessons relating to 3D printing (3 responses). One teacher who plans to write additional 3D+MEAs responded, “I will attempt to write MEAs that use 3D printing as a component to teach abstract content in science class and to develop manipulatives that enhance understanding.” Another teacher who

Table 9

Open-ended response codes for future 3D+MEA use.

Response code	No. responses
No 3D printer	6
Write/create 3D+MEAs	3
Modeling/engineering	2
Limited resources	1
Incorporate real-world situations	1
Teach abstract content	1
Students design 3D printed item	1
General/will use	1
Introduction to a topic	1
Summative/closing activity	1
N/A	1

plans to write a 3D lesson stated, “This is tough—I am hoping to create a 3D printing themed lesson that will give students an opportunity to learn more about the potential of 3D printing in the future.” See Table 9 for response codes and frequencies of responses.

To understand more fully why teachers might or might not choose to implement an MEA or a 3D+MEA in their classroom, an open-ended post-survey question was asked about barriers they perceive in implementing MEAs and 3D+MEAs in their classroom. With regard to MEA implementation barriers, time was the most frequently cited barrier (12 out of 17 responses). For example, one teacher responded, “Time is the biggest issue. We have too much curriculum to cover, and as important as these skills are, they do require time and that may mean that some of the curriculum does not get covered.” Table 10 provides the response codes with frequencies of responses.

With regard to barriers to implementing a 3D+MEA in the classroom, most teachers (8 out of 17 respondents) cited the lack of a 3D printer as the main factor (Table 11).

Table 10
Open-ended response codes for barriers to implementing MEAs.

Response code	No. responses
Time	12
No barriers	2
Lack of support from administration	1
Real-world data	1
Making connections	1
No 3D printer	1
N/A	1

Table 11
Open-ended response codes for barriers to implementing 3D+MEAs.

Response code	No. responses
No 3D printer	8
Limited resources/cost of 3D printing	6
Time	5
Printing issues/run time	3
Student modeling/printing issues	2
Lack of 3D printing experience	1

Table 12
Open-ended response codes for potential benefits to implementing 3D+MEAs.

Response code	No. responses
Student interest/engagement	6
Problem-solving/critical thinking	5
Practice modeling/engineering	4
Seeing ideas come to fruition	3
Other	2
Better understanding of concepts	1

Table 13
Post-survey descriptive statistics.

	N	M	SD
This workshop is a worthwhile PD activity	17	3.88	0.33
I will write more MEAs after this workshop	17	3.53	0.51
MEAs are an effective way to integrate STEM	17	3.59	0.51

Note. 1 = Strongly disagree, 4 = strongly agree.

Teachers also mentioned other barriers related to 3D printers, such as time (5 out of 17 responses), 3D printer costs, including filament and maintenance (6 out of 17 responses), and lack of experience using a 3D printer (1 out of 17 responses). For example, one participant responded, “Making sure the 3D printer works, and the time it would take to teach students to create their own solutions on a computer and then actually print (if required).”

Finally, an open-ended post-survey question asked participants what they perceive as potential benefits to implementing an MEA with a 3D printing component in the classroom. Most of the teachers who responded listed student interest/enthusiasm as the main benefit of

Table 14
Post-survey descriptive statistics—workshop evaluation.

	N	M	SD
Introductory webinar	17	3.59	0.71
NASA tours	16	4.00	0.00
Introduction to MEAs	17	3.82	0.39
MEA activities (e.g., working on an MEA in groups)	17	3.88	0.33
Overview of 3D printing	17	3.59	0.71
Feedback from facilitators	17	3.94	0.24
Working with a partner	15	3.53	0.87
Talking with NASA scientists and engineers	15	3.87	0.52

Note. 1 = Little or no value, 4 = great value.

Table 15
Open-ended response codes for improving the quality of workshop topics.

Response code	No. responses
Partner issues	2
None/good opportunity	2
More information on what to expect	1
Fully work through an MEA	1
Do not have 3D printer	1
More 3D printer experience	1
N/A	6

3D+MEAs (6 out of 17 responses). Five teachers cited that 3D+MEAs would promote problem-solving and/or critical thinking skills, while four teachers said that the main benefit was to give students the ability to bring their ideas to fruition. Other reasons listed were practicing modeling/engineering and promoting student engagement. For example, one teacher said, “Incorporates engineering processes and critical thinking skills.” Table 12 displays the frequencies of open-ended response codes to this question.

After the workshop, several questions were asked of teachers on the post-survey to determine how they perceived the workshop and MEAs (Table 13). Mean scores indicated high levels of agreement ($M > 3.00$) with the three items indicating that teachers perceived the workshop as a worthwhile PD activity, they plan to write more MEAs after the workshop, and believe that MEAs are an effective way to integrate STEM.

Finally, teachers responded to eight items (Table 14) on the post-survey that asked them to rate their opinion of the value of several workshop experiences (from 1 = little or no value to 4 = great value). Teachers reported high levels of value on all of the workshop experiences ($M > 3.00$). Teachers rated the NASA tours most highly ($M = 4.00$) and the experience of working with a partner was rated the lowest, although still considered highly valuable ($M = 3.53$).

An open-ended question asked participants to list any suggestions they had for improving the quality of the eight topics (Table 15). Eight teachers responded. The greatest

number of suggestions were centered on working with a partner. Additional suggestions included providing more coverage of 3D printing, working fully through an MEA, and providing more information on what to expect. Two teachers listed comments about negative aspects of working with a partner; for example, “Working with a partner slowed down production. Both of us were new MEA and science/math which made the process very difficult.” One teacher also listed comments about the 3D printing aspects of the workshop and wanting to have more experience with 3D printing. For example, “Would like to have more experience with the 3D printing rather than just an overview!”

Finally, a post-survey item asked participants how satisfied they were with their experiences in the workshop. Participants were on average highly satisfied (1 = very dissatisfied, 6 = very satisfied), with a mean of 5.65 and SD = 0.70.

In a follow-up open-ended question asking teachers to explain reasons for their satisfaction ratings, most of the teachers who responded to the question (12 respondents out of 15) provided at least one positive explanation (Table 16). For example, one teacher responded, “I enjoy

the challenge of creating something new.” Other positive experiences mentioned were: gaining ideas for the classroom, learning a lot, good location/environment, enjoyed the NASA tours, planning to share what was learned with staff and students, and willingness to repeat this workshop. Four out of 15 teachers made comments about wanting to see more emphasis on the 3D printing aspects of the workshop. For example, one teacher wrote, “I feel extremely confident with the MEA portion of the workshop, but would love to have more experience with the 3D printer. Maybe next time we could actually design something in Tinkercad and send it to the printer to print. Would like to have seen that process step by step.”

MEA Understanding

The second research question (What is the effect of the PD program on teachers’ understanding of integrated STEM via model-eliciting activities?) was addressed via the MEA Understanding scale. We found significant pre- to post-survey increases on all of the MEA Understanding subscales (Figure 3).

A Wilcoxon signed-rank test revealed that teachers’ understanding of the principles that differentiate MEAs (e.g., the reality principle) was significantly higher after the PD ($Md = 4.50$) compared to their understanding before the PD ($Md = 2.75$), $z = -2.91$, $p < 0.01$. Next, a significant increase was found from before the PD ($Md = 3.00$) to after the PD ($Md = 5.00$) regarding teachers’ understanding of the elements needed to construct a high-quality MEA, $z = -3.19$, $p < 0.01$. In terms of teachers’ understanding of how to implement an MEA (e.g., when to intervene as students are working), there was a significant increase after the PD ($Md = 5.17$) as compared to before the PD ($Md = 3.67$), $z = -3.18$, $p < 0.01$.

Table 16

Open-ended response codes for participants’ explanations for their overall workshop rankings.

Response code	No. responses
Positive experience	12
Would like more about 3D printing	4
Informative	3
Ideas/skills for classroom	3
Days were too long	1
None/N/A	2

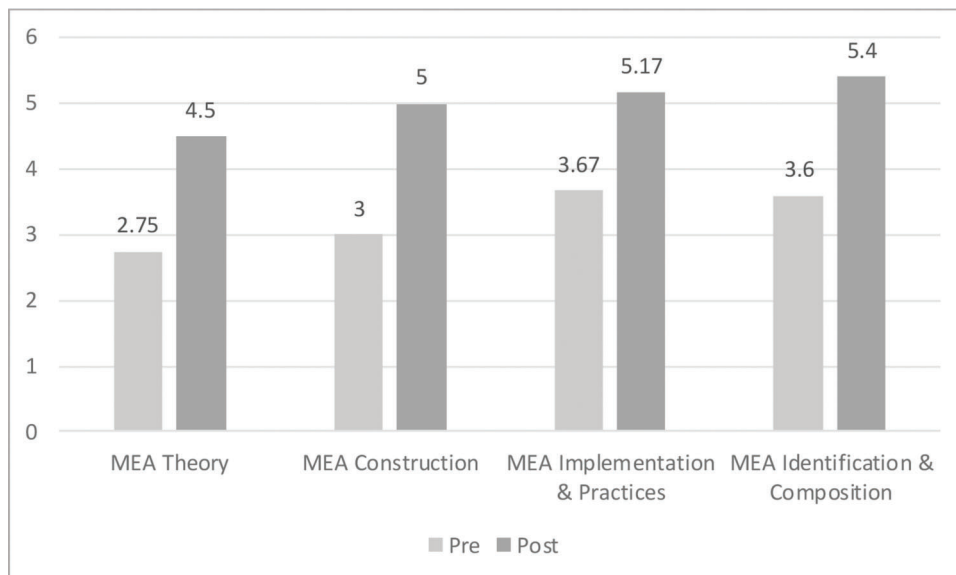


Figure 3. Median scores on the pre- and post-MEA Understanding subscales.

Table 17
Wilcoxon signed-rank tests for MEA Understanding.

	Group statistics		Paired differences	
	<i>Md</i>	<i>N</i>	<i>z</i>	<i>p</i> -value
MEA Theory				
Pre-survey	2.75	19	-2.91	< 0.01
Post-survey	4.50	17		
MEA Construction				
Pre-survey	3.00	19	-3.19	< 0.01
Post-survey	5.00	17		
MEA Implementation and Practices				
Pre-survey	3.67	19	-3.18	< 0.01
Post-survey	5.17	17		
MEA Identification and Composition				
Pre-survey	3.60	19	-3.19	< 0.01
Post-survey	5.40	17		

Note. Statistical significance was sought at $p < 0.05$ using a two-tailed test.

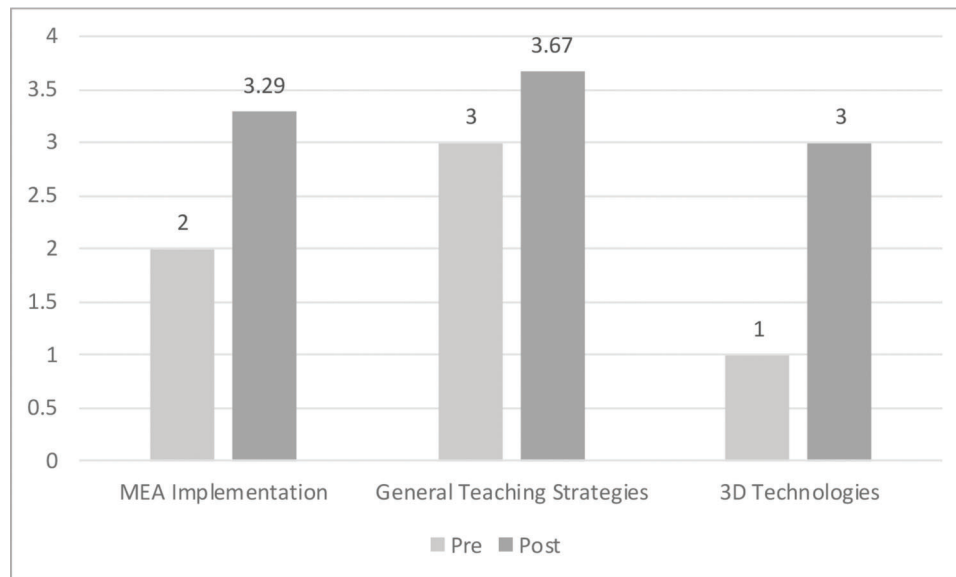


Figure 4. Median scores on the pre- and post-MEA Comfort subscales.

Finally, teachers showed significantly greater understanding after the PD ($Md = 5.40$) regarding their understanding of how to identify an MEA (e.g., the difference between MEAs and engineering design problems) than before the PD ($Md = 3.60$), $z = -3.19$, $p < 0.01$. For details, see Table 17.

MEA Comfort

The third research question asked: What is the effect of the PD program on teachers' comfort with integrated STEM instructional strategies and 3D technologies? Our findings revealed that all subscales of the MEA Comfort assessment showed significant pre- to post-survey increases (Figure 4).

A Wilcoxon signed-rank test of teachers' comfort with implementing an MEA in the classroom revealed a sig-

nificant increase from before the PD ($Md = 2.00$) to after the PD ($Md = 3.29$), $z = -3.07$, $p < 0.01$. Regarding teachers' comfort with various teaching strategies such as classroom questioning strategies, there were significant increases found from before the PD ($Md = 3.00$) to after the PD ($Md = 3.67$), $z = -2.82$, $p < 0.01$. Finally, teachers showed significant increases on their comfort with 3D technologies from before the PD ($Md = 1.00$) to after the PD ($Md = 3.00$), $z = -2.98$, $p < 0.01$. For details, see Table 18.

Design Engineering Technology

We did not find a significant increase from before the PD ($Md = 3.88$) to after the PD ($Md = 4.25$) on teachers' perceptions of the importance of DET, $z = -1.67$, $p = 0.095$; see Figure 5.

Table 19 provides further details of the results.

Table 18
Wilcoxon signed-rank tests for MEA Comfort.

	Group statistics		Paired differences	
	<i>Md</i>	<i>N</i>	<i>z</i>	<i>p</i> -value
MEA Implementation				
Pre-survey	2.00	19	−3.07	< 0.01
Post-survey	3.29	17		
General Teaching Strategies				
Pre-survey	3.00	19	−2.82	< 0.01
Post-survey	3.67	17		
3D Technologies				
Pre-survey	1.00	19	−2.98	< 0.01
Post-survey	3.00	17		

Note. Statistical significance was sought at $p < 0.05$ using a two-tailed test.

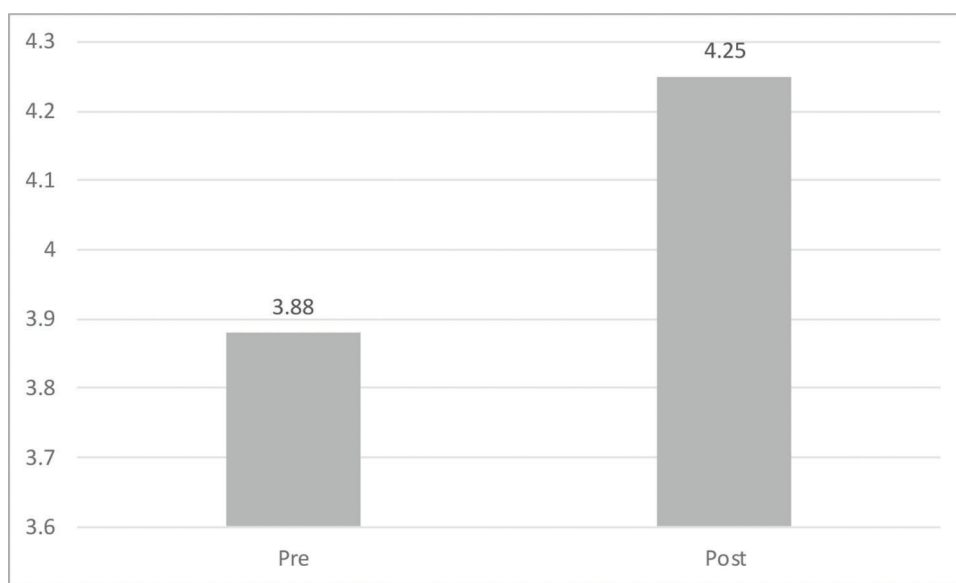


Figure 5. Median scores for pre- and post-survey DET.

Table 19
Wilcoxon signed-rank tests for importance of DET.

	Group statistics		Paired differences	
	<i>Md</i>	<i>N</i>	<i>z</i>	<i>p</i> -value
Pre-survey	3.88	18	−1.67	0.095
Post-survey	4.25	17		

Note. Statistical significance was sought at $p < 0.05$ using a two-tailed test.

Competence in Teaching and Understanding STEM Content

Finally, the last research question (What are the effects of the PD program on teachers' attitudes toward the importance of integrated STEM and their teaching and understanding of STEM content?) was addressed via four items that measured teachers' perceived

competence in teaching and understanding of STEM content (Figure 6).

For the item measuring competence in understanding STEM content, we found that teachers responded significantly higher on the post-survey ($Md = 9.00$) than on the pre-survey ($Md = 7.50$), $z = -2.16$, $p < 0.05$. Furthermore, teachers also responded significantly higher after the PD ($Md = 9.00$) than before the PD ($Md = 8.00$) for the item that asked teachers about their perceived

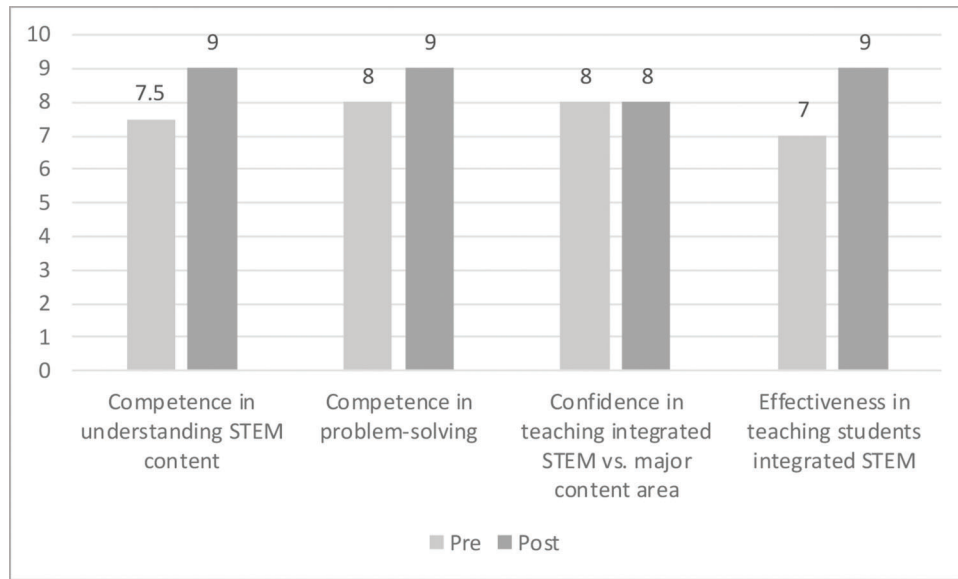


Figure 6. Median scores for competence in teaching and understanding STEM content.

Table 20

Wilcoxon signed-rank tests for competence in teaching and understanding STEM content.

	Group statistics		Paired differences	
	<i>Md</i>	<i>N</i>	<i>z</i>	<i>p</i> -value
Competence in understanding STEM content				
Pre-survey	7.50	18	-2.16	< 0.05
Post-survey	9.00	17		
Competence in problem-solving				
Pre-survey	8.00	17	-2.59	< 0.05
Post-survey	9.00	17		
Confidence in teaching integrated STEM vs. major content area				
Pre-survey	8.00	17	-0.85	0.395
Post-survey	8.00	17		
Effectiveness in teaching students integrated STEM				
Pre-survey	7.00	18	-1.57	0.117
Post-survey	9.00	17		

Note. Statistical significance was sought at $p < 0.05$ using a two-tailed test.

competence in problem-solving, $z = -2.59$, $p < 0.05$. We found no significant increase from before the PD ($Md = 8.00$) to after the PD ($Md = 8.00$) for the item measuring teachers' confidence in teaching integrated STEM versus their major content area, $z = -0.85$, $p = 0.395$. Similarly, we found no significant difference from before the PD ($Md = 7.00$) to after the PD ($Md = 9.00$) regarding teachers' perceived effectiveness in teaching students integrated STEM, $z = -1.57$, $p = 0.117$. For details, see Table 20.

Discussion

In response to a need for teachers who are equipped to design and implement integrated STEM activities in their classroom, three of the authors designed, developed, and implemented a PD experience for teachers. This PD experience was created around an authentic learning task

framework and included 40+ hours of face-to-face training, curriculum development tasks, exposure to real-world engineering problems, discussion with on-site scientists and engineers, and collaboration within peer curriculum development teams. Below, we discuss teachers' perceptions about the PD training, the knowledge that teachers gained in the workshop, teacher comfort and attitudes toward integrated STEM, and the design features embedded in the workshop.

Our first research question asked about teachers' views of and reactions to the PD program. There were significant increases on almost all workshop survey items. That is, teachers showed a significantly greater understanding of MEAs, 3D+MEAs, and curriculum development following completion of the workshop. The one item that did not reach significance assessed whether teachers planned to implement an MEA in the classroom (Table 5). Based on

analysis of open-ended responses, most teachers who responded cited that lack of time to implement an MEA was the reason why they were not planning to implement one in the classroom. However, an analysis of only the prior MEA workshop participants (Table 6) showed that all prior MEA workshop participants were already planning to implement an MEA in their classroom on the pre-survey (median of 4.0 out of 4.0), and their responses were the same on the post-survey (median of 4.0 out of 4.0). Although most participants cited a lack of time as a barrier to implementing an MEA, because MEAs involve several “big ideas” embedded in the problem (Moore, Doerr, Glancy, & Ntow, 2015, p. 361), it is possible to cover more concepts in just one MEA. Additionally, research on MEA implementation shows numerous benefits to the traditional classroom, including increasing equity across different groups of students whose skills are not captured on traditional assessments (Iversen & Larson, 2006; Katims, Nash, & Tocci, 1993), identification of misconceptions (Self et al., 2008), and increased conceptual understandings (Yoon, Dreyfus, & Thomas, 2010). For this reason, it might be necessary to emphasize the usefulness of MEAs in the classroom.

Next, we found a significant decrease from pre- to post-survey for responses to the item which asked if teachers would implement a 3D printing lesson in the classroom (Table 5). Looking at the open-ended responses, the greatest number of teachers said that the lack of a 3D printer in the classroom was the reason they would not implement a 3D printing lesson, followed by lack of time. This finding contradicts research on participatory design showing increased ownership over reform-based curriculum (Kyza & Georgiou, 2014) thus leading to greater implementation and positive student outcomes (Voogt et al., 2011). However, 3D+MEAs are unique in that they require a 3D printer so it is unclear how many participants would plan to use them if they had 3D printer access.

Regarding their experiences in the workshop, responses indicated an overall very positive trend, with mean scores of at least 3.5 out of 4 on all components (Tables 13 and 14). Somewhat surprisingly, teachers rated the least positive aspect as working with a partner. Based on responses to the open-ended question asking for suggestions to improve the workshop, some teachers felt that having a partner was challenging due to differences in subject matter backgrounds or the idea that they would work faster as individuals. However, most of the respondents rated working with a partner highly ($M = 3.53$ out of 4). In general, research shows that collaborative curriculum development helps teachers learn from one another through this process (Schkedi, 1996; Schneider & Pickett, 2006; Voogt et al., 2011).

Our next research question asked if the workshop had an effect on teacher knowledge about MEAs. Results of the study showed significant increases on all subscales for

MEA Understanding (Table 17). This is similar to other studies in which a PD focused on understanding new curricular materials supported the development of teachers’ pedagogical content knowledge (Kyza & Nicolaidou, 2016). We found the largest gains for the MEA Construction subscale, meaning that teachers gained knowledge about how to write a high-quality MEA for use in the classroom. This is not surprising since the majority of the workshop was dedicated to MEA writing and feedback.

With a fundamental understanding of their own lesson and how MEAs function in general, it follows that teachers with no prior knowledge about MEA writing or theory would show significant gains in these areas. The smallest gains were found for the MEA Implementation and Practices subscale. One reason for the reduced improvements for MEA implementation and practices might be that the workshop only covered MEA implementation and practices briefly in a lecture format before moving into design and construction, which was a primary focus of the training. With a reduced focus on implementation, it is understandable that smaller changes were observed for this subscale.

Our next research question asked about teacher comfort with integrated STEM instructional strategies and technologies such as 3D modeling and 3D printing. Significant increases were found on all subscales for MEA Comfort (Table 18). The largest gains were found for the 3D Technologies subscale. The reason teachers may have shown a greater increase in their comfort with 3D technologies is because the pre-survey showed that teachers started with little to no knowledge of this area ($Md = 1.00$). The idea that lack of initial 3D technology familiarity underlies significant gains is sensible given that these skills and tools are traditionally associated with careers in engineering and digital media production. Teachers showed the least amount of gains for the General Teaching Strategies subscale. One explanation for the smaller gains in this area could be because many teachers have already encountered or practiced these strategies in their teaching. Similarly, other programs that immerse teachers in real-world research experiences and curriculum development have aided in increasing teachers’ confidence to teach innovative curricula to their students, among other positive outcomes (Billiar et al., 2016). Although our program is a week-long experience, it is a positive finding that teachers shifted their understanding of teaching practices and demonstrated increased comfort with student-centered teaching strategies.

With regard to teacher attitudes toward the importance of integrated STEM and understanding of integrated STEM content, we found no significant differences on the Importance of Design/Engineering/Technology scale (Table 19). Pre-survey responses were already fairly high ($Md = 3.88$) and these items relate to attitudes around design, engineering, and technology, which might require more time or

experience in the classroom to change. Regarding teachers' self-reported competence in teaching and understanding STEM content, we found significant increases on two of the competence items from pre to post survey (Table 20). These significant items related to competence in understanding STEM content and competence in problem-solving. During the workshop, teachers practiced problem-solving by designing and continually improving their MEA through iterative updates. The teachers were faced with the challenge of developing an MEA that could also encompass a 3D manipulative or 3D design task. Some 3D models did not work when first tested, and teachers were forced to make modifications throughout the workshop not only to arrive at a final solution for their model, but also for the curriculum with which it was intended to integrate. Working with engineers and science experts may have given teachers the opportunity to discuss STEM content and better understand how to translate content into a 3D-enhanced lesson idea. Prior studies have shown the effectiveness of curriculum design on teacher professional growth; for example changing teachers' beliefs about classroom practices and improving pedagogical content knowledge (Kyza & Nicolaidou, 2016; Voogt et al., 2011). One item that was not significant was confidence in teaching integrated STEM versus a major content area. Pre-survey scores were already high ($Md = 8.00$), which did not leave much room for improvement on the post-survey. Because this is a self-report measure, it may be that teachers overestimated their confidence in teaching integrated STEM due to unfamiliarity. The second item with no significant change was teachers' perceived effectiveness in teaching students integrated STEM. The lack of significance makes sense because this item is more focused on classroom practices, which teachers did not experience in the workshop.

Recommendations

Based on our findings and experiences with this novel teacher PD program that integrated 3D models, MEA development, and engineering topics in an immersive environment, we have some recommendations for holding similar programs.

First, we strongly recommend an embedded approach to encourage teachers or other curriculum developers an opportunity to interact with engineers and scientists in the setting where the research is occurring. Possible examples include an academic research lab, field experience, or manufacturing facility. The realistic nature of this context helps ensure that curriculum correctly reflects real-world concepts and thus provides students with authentic STEM experiences or situations within which they can demonstrate open-ended problem-solving skills. This recommendation is based on our results which were positive with regard to knowledge, competence, and participant experiences.

Second, we recommend that future PD opportunities of this type include features that correspond to one or more types of authenticity. Immersion was used in this PD to correspond to context and task authenticity, but we believe that both impact and personal authenticity could be supported through local or regional partnerships with agreements to consider the outcomes of the workshops as potential solutions to real-world problems. As part of this recommendation, it may be valuable for future workshops to include not only research-focused engineers, but also engineers employed by local commercial manufacturers. In this way, a stronger impact and personal authenticity may be found.

Some recommendations emerged from observations of participants. In some cases, participants were disappointed to learn after arrival that the workshop was not intended to teach them hands-on methods for 3D modeling and printing. Our workshop was focused on curriculum design from an embedded vantage point with the aid of a technology-focused team, but was not marketed or intended to be an opportunity for teachers to learn 3D modeling and printing as a way to improve their skills in these areas. There may be an opportunity here for future workshops of this type to define more clearly what the intentions are and also what they are not. It may be that some participants saw some key terms and interpreted promotional materials in a way unintended by the planning team. For these reasons, we recommend stronger communication describing the expected outcomes of the training.

From our observations, some participants had problems in determining an ideal curriculum development partner and shared topic. In our workshop, teachers first decided on 3D+MEA topics, and then paired with another participant based on shared interests. In some cases, the match was not exact, which led to some participants sacrificing portions of their lesson concept to ease co-development of a single lesson. In future workshops, this issue may be prevented by having partners join before tours so they can collaboratively develop an idea from the ground level. Another idea is to have teachers sign up for the workshop in pairs or teams from their school. In this way, teachers can more easily support one another when implementing the curriculum.

Although some teachers had struggles in working with a partner, we found a lower rate of success when teachers were tasked with writing two MEAs following the workshop. In contrast, all groups of participants completed a 3D+MEA before the conclusion of the workshop. We believe this may have to do with time and motivational factors to write curriculum outside of the structured workshop setting. Although there was a monetary incentive, it may not have been enough to motivate teachers sufficiently. Our recommendations are to complete any curriculum writing in the workshop so that teachers can feel supported, receive immediate feedback, and not have to compete with outside distractions and demands on their time.

Another recommendation is to solicit additional input from engineers and scientists about problems and challenges they face in their work. Perhaps they may be able to provide a short list of topics that are true real-world problems in their area. These ideas could then be discussed as potential concepts for 3D+MEA lesson development. An additional recommendation, speaking directly to the problem of idea formulation, would be to solicit brief video interviews with a variety of STEM professionals who could then be available at any time during the workshop through that form of media. One issue we faced was in scheduling these valuable resources, but having interviews on hand for playback at any time during the curriculum development may be useful.

Limitations and Future Directions

This teacher PD program sought to produce lesson plans, 3D models, unique experiences for teachers and curriculum developers, as well as exploratory research about the participants so we could better understand the development process and overall experience within this technology-forward immersive setting. This study involved a small number of non-random participants and as a result cannot be easily generalized to a larger population. However, we believe this PD program provides insight into the learning and experience of teachers who did participate.

In the future, studies should be conducted to assess the strength and quality of each type of authenticity in similar PD settings and seek to understand how those experiences can translate into stronger curriculum products and student learning experiences. Future research can explore whether results can be replicated in other settings, such as a manufacturing facility or university research laboratory.

Additionally, we believe this type of setting may represent an ideal situation for testing and development of a rubric for assessing the alignment of curriculum products for different types of authenticity. Through these research approaches, students may be presented with curriculum that reflects realistic situations similar to those they might find upon entering society after completing their formal education.

Regarding the implementation of 3D+MEAs in the classroom, not having access to a 3D printer may pose a significant barrier for teachers wishing to implement this type of activity. One solution is to obtain pre-printed objects to use with MEAs and to omit the 3D design and printing component. Another option is to have students design and redesign their ideas via drawing. 3D printers are becoming more prevalent in the K–12 setting (Peterson, 2015). As 3D printers become more prevalent in classrooms, limiting factors will be focused less on access and more on time to print.

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References

- Abell, S. (2007). *Handbook of research on science education*. Mahwah, NJ: Lawrence Erlbaum Associates.
- Bethke Wendell, K., & Rogers, C. (2013). Engineering design-based science, science content performance, and science attitudes in elementary school. *Journal of Engineering Education*, 102(4), 513–540.
- Billiar, K., Hubelbank, J., Quinn, J., Oliva, T. A., Rolle, M. W., & Camesano, T. A. (2016). Participating in authentic engineering projects improves teachers' ability to teach the design process to middle school students. *Proceedings of the American Society for Engineering Education's 123rd Annual Conference and Exposition*, New Orleans, LA.
- Bjögvinsson, E., Ehn, P., & Hillgren, P. (2012). Design things and design thinking: Contemporary participatory design challenges. *Design Issues*, 28(3), 101–116.
- Carr, R. L., Bennett IV, L. D., & Strobel, J. (2012). Engineering in the K–12 STEM standards of the 50 U.S. states: An analysis of presence and extent. *Journal of Engineering Education*, 101, 539–564.
- Carroll, J. M., Chin, G., Rosson, M. B., & Neale, D. C. (2000). The development of cooperation: Five years of participatory design in the virtual school. *Proceedings of the 3rd Conference on Designing Interactive Systems: Processes, Practices, Methods, and Techniques*, New York, NY.
- Cook, M. P. (2006). Visual representations in science education: The influence of prior knowledge and cognitive load theory on instructional design principles. *Science Education*, 90(6), 1073–1091.
- Cunningham, C. M. (2007). Engineering is elementary: An engineering and technology curriculum for children. In *American Society for Engineering Education Annual Conference & Exposition*, Honolulu, Hawaii.
- Diefes-Dux, H. Hjalmarson, M. A., Miller, T., & Lesh, R. (2008). Model-eliciting activities for engineering education. In J. S. Zawojewski, H. Diefes-Dux, & K. Bowman (Eds.), *Models and modeling in engineering education: Designing experiences for all students* (pp. 17–36). Rotterdam, The Netherlands: Sense Publishers.
- Diefes-Dux, H. A., & Salim, W. W. A. W. (2012). Transforming the first-year engineering experience through authentic problem-solving: Taking a models and modeling perspective. *Procedia—Social and Behavioral Sciences*, 56, 314–332.
- Farmer, C., Klein-Gardner, S., & Nadelson, L. (2014). *Standards for preparation and professional development for teachers of engineering*. Retrieved from https://www.asee.org/documents/papers-and-publications/papers/outreach/Standards_for_Preparation_and_Professional_Development.pdf
- Hirsch, L. S., Berliner-Heyman, S., & Cusack, J. L. (2017). Introducing middle school students to engineering principles and the engineering design process through an academic summer program. *International Journal of Engineering Education*, 33(1(B)), 398–407.
- Hong, T. H., Purzer, S., & Cardella, M. E. (2011). A psychometric re-evaluation of the Design, Engineering and Technology (DET) Survey. *Journal of Engineering Education*, 100(4), 800–818.

- Hsieh, B. (2015). The importance of orientation: Implications of professional identity on classroom practice and for professional learning. *Teachers and Teaching*, 21(2), 178–190.
- Hsieh, H., & Shannon, S. E. (2005). Three approaches to qualitative content analysis. *Qualitative Health Research*, 15(9), 1277–1288.
- Irwin, J. L., Pearce, J. M., Anzalone, G., & Oppliger, D. E. (2014). The RepRap 3-D printer revolution in STEM education. Paper presented at the 121st ASEE Annual Conference & Exposition, Indianapolis, IN.
- Iversen, S. M., & Larson, C. J. (2006). Simple thinking using complex math vs. complex thinking using simple math. *Zentralblatt für Didaktik der Mathematik*, 38(3), 281–292.
- Katims, N., Nash, P., & Tocci, C. M. (1993). Linking instruction and assessment in a middle school mathematics classroom. *Middle School Journal*, 25(2), 28–35.
- Kyza, E. A., & Georgiou, Y. (2014). Developing in-service science teachers' ownership of the PROFILES pedagogical framework through a technology-supported participatory design approach to professional development. *Science Education International*, 25(2), 57–77.
- Kyza, A. E., & Nicolaidou, I. (2016). Co-designing reform-based online inquiry learning environments as a situated approach to teachers' professional development. *CoDesign*, 1–26. <https://doi.org/10.1080/15710882.2016.1209528>
- Lachapelle, C. P., Phadnis, P. S., Jocz, J., & Cunningham, C. M. (2012, March). The impact of engineering curriculum units on students' interest in engineering and science. Presented at the NARST Annual International Conference, Indianapolis, IN.
- Lesh, R., & Yoon, C. (2004). Evolving communities of mind—In which development involves several interacting and simultaneously developing strands. *Mathematical Thinking and Learning*, 6(2), 205–226.
- Mayring, P. (2000). Qualitative content analysis. *Forum: Qualitative Social Research*, 1(2). Retrieved from <http://www.qualitative-research.net/index.php/fqs/article/view/1089/2386>
- McBride, J. (1991). Integrating elementary/middle school science and mathematics. *School Science and Mathematics*, 91(7), 285–292.
- Moore, T. J., Doerr, H. M., Glancy, A. W., & Ntow, F. D. (2015). Preserving pelicans with models that make sense. *Mathematics Teaching in the Middle School*, 20(6), 358–364.
- Moore, T. J., & Hjalmarson, M. A. (2010). Developing measures of roughness: Problem solving as a method to document student thinking in engineering. *International Journal of Engineering Education*, 26(4), 820–830.
- Namey, E., Guest, G., Thairu, L., & Johnson, L. (2008). Data reduction techniques for large data sets. In G. Guest & K. M. MacQueen (Eds.), *Handbook for team-based qualitative research* (pp. 137–162). Lanham, MD: Altamira Press.
- National Academy of Engineering. (2010). *Standards for K–12 engineering education?* Washington, DC: National Academies Press.
- National Academy of Engineering & National Research Council. (2009). *Engineering in K–12 education: Understanding the status and improving the prospects*. Washington, DC: National Academies Press.
- National Academy of Engineering & National Research Council. (2014). *STEM integration in K–12 education: Status, prospects, and an agenda for research*. Washington, DC: National Academies Press. <https://doi.org/10.17226/18612>.
- National Research Council. (2012). *A framework for K–12 science education: Practices, crosscutting concepts, and core ideas*. Washington, DC: National Academies Press.
- National Science Board. (2015). *Revisiting the STEM workforce: A companion to science and engineering indicators 2014*. Arlington, VA: National Science Foundation.
- National Science Teachers Association. (2017). *About the Next Generation Science Standards*. Retrieved from <http://ngss.nsta.org/About.aspx>
- Peterson, T. (2015). 3D printers add a new dimension to classrooms: Schools use 3D printers to foster creativity, build enthusiasm and teach real-world skills. *EdTech*. Retrieved from <http://www.edtechmagazine.com/k12/article/2015/01/new-dimension>
- Purzer, S., Duncan-Wiles, D., & Strobel, J. (2013). Teaching about engineering optimization and trade-offs to fourth and fifth graders. (Special Issue on Engineering and Science). *Science and Children*, 50(5), 34–39.
- Ragusa, G., & Mataric, M. (2016). Research experiences for teachers: Linking research to teacher practice and student achievement in engineering and computer science. Proceedings of the American Society for Engineering Education Conference, New Orleans, LA.
- Razzouk, R., Dyehouse, M., Santone, A., & Carr, R. L. (2014). Plants versus pollutants: An interdisciplinary model-eliciting activity to bring engineering design practices and real-world context to the science classroom. *Science Teacher*, 81(9), 43–49.
- Reid, K., & Floyd, C. (2007). The Tsunami model eliciting activity: Implementation and assessment of an interdisciplinary activity in a pre-engineering course. Proceedings of the 2007 American Society of Engineering Education Annual Conference.
- Reimers, J. E., Farmer, C. L., & Klein-Gardner, S. S. (2015). An introduction to the standards for preparation and professional development for teachers of engineering. *Journal of Pre-College Engineering Education Research (J-PEER)*, 5(1), 40–60.
- Schkedi, A. (1996). School-based workshops for teacher participation in curriculum development. *Journal of Curriculum Studies*, 28(6), 699–711.
- Schneider, R., & Pickett, M. (2006). Bridging engineering and science teaching: A collaborative effort to design instruction for college students. *School Science and Mathematics*, 106, 259.
- Self, B. P., Miller, R. L., Kean, A., Moore, T. J., Ogletree, T., & Schreiber, F. (2008). Important student misconceptions in mechanics and thermal science: Identification using model-eliciting activities. Proceedings of the 38th ASEE/IEEE Frontiers in Education Conference, Saratoga Springs, NY.
- Shadish, W. R., Cook, T. D., & Campbell, D. T. (2002). *Experimental and quasi-experimental designs for generalized causal inference*. Wadsworth Cengage Learning.
- Shuman, L. J., & Besterfield-Sacre, M. E. (2009). E-MEAS: Introducing an ethical component to model eliciting activities. Proceedings of the 2009 ASEE Annual Conference & Exposition, Austin, TX.
- Shuman, L. J., Besterfield-Sacre, M. E., Yildirim, T. P., Bursic, K. M., & Vidic, N. (2011). CCLI: Model eliciting activities: Experiments and mixed methods to assess student learning—Part II. CD Proceedings, 2011 ASEE Annual Conference and Exposition, Vancouver, BC, June 26–29.
- Singer, J. E., Ross, J. M., & Jackson-Lee, Y. (2016). Professional development for the integration of engineering in high school STEM classrooms. *Journal of Pre-College Engineering Education Research (J-PEER)*, 6(1), 29–44.
- Smithsonian Institution. (2017). *Smithsonian X 3D Beta*. Retrieved from <https://3d.si.edu/>
- Strobel, J., Wang, J., Weber, N. R., & Dyehouse, M. (2013). The role of authenticity in design-based learning environments: The case of engineering education. *Computers & Education*, 64, 143–152.
- Tazaz, A., Wilson, R. M., Schoen, R., Blumsack, S., King, L., & Dyehouse, M. (2013). Utilizing model eliciting activities (MEA's) to engage middle school teachers and students in storm water management practices to mitigate human impacts of land development. American Geophysical Union, Fall Meeting.
- Tillinghast, R. C., Wright, M. T., Arnold, R. D., Zunino, J. L., Pannullo, T. L., Dabiri, S.,... Gonzalez, M. C. (2014, March). Integrating three dimensional visualization and additive manufacturing into K–12 classrooms. Paper presented at the 4th IEEE Integrated STEM Education Conference, Princeton, NJ. DOI: <https://doi.org/10.1109/ISECon.2014.6891051>
- Voogt, J., Westbroek, H., Handelzalts, A., Walraven, A., McKenney, S., Pieters, J., de Vries, B. (2011). Teacher learning in collaborative curriculum design. *Teaching and Teacher Education*, 27, 1235–1244.

- Westerlund, J. F., Garcia, D. M., Koke, J. R., Taylor, T. A., & Mason, D. S. (2002). Summer scientific research for teachers: The experience and its effect. *Journal of Science Teacher Education*, 13(1), 63–83.
- Wiggins, G., & McTighe, J. (1998). *Understanding by design*. Alexandria, VA: Association for Supervision and Curriculum Development.
- Yasar, S., Baker, D., Robinson-Kurpius, S. R., Krause, S., & Roberts, C. (2006). Development of a survey to assess K–12 teachers' perceptions of engineers and familiarity with teaching design, engineering, and technology. *Journal of Engineering Education*, 95(3), 205–216.
- Yoon, C., Dreyfus, T., & Thomas, M. O. J. (2010). How high is the tramping track? Mathematizing and applying in a calculus model-eliciting activity. *Mathematics Education Research Journal*, 22(1), 141–157.
- Zawojewski, J. S., Hjalmanson, M. A., Bowman, K. J., & Lesh, R. (2008). A modeling perspective on learning and teaching in engineering education. In J. S. Zawojewski, H. Diefes-Dux, & K. Bowman (Eds.), *Models and modeling in engineering education: Designing experiences for all students* (pp. 1–16). Rotterdam, The Netherlands: Sense Publishers.