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Taking Professional Development From 2D to 3D: Design-Based Learning, 2D Modeling, and 3D Fabrication for Authentic Standards-Aligned Lesson Plans

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SPECIAL ISSUE: TINKERING IN TECHNOLOGY-RICH DESIGN CONTEXTS

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Abstract

There is currently significant interest in 3D fabrication in middle school classrooms. At its best 3D printing can be utilized in authentic design projects that integrate math, science, and technology, which facilitate deep learning by students. In essence, students are able to tinker in a virtual world using 3D design software and then tinker in the real world using printed parts. We describe a professional development activity we designed to enable middle school teachers who had taken part in a three-year Math Science Partnership program to authentically integrate 3D printing into design-based lessons. We include some examples of successful design-based lesson plans.

Keywords: design-based learning, 2D modeling, 3D fabrication, professional development, math science partnership

Introduction

Many students underperform in mathematics and science in the United States (Marshall, Smart, & Alston, 2017). Some educational approaches that positively impact student achievement in these areas include project-based learning, design-based learning, complex instruction, rich tasks, and engaging in productive struggle. We have worked to support middle school teachers through a three-year Math Science Partnership including university faculty from engineering, mathematics education, and educational psychology, as well as practicing engineers and a regional in-service professional development organization. Through this work, we have come to understand that design projects can be tailored to use 2D modeling activities together with 3D fabrication and combined with educational approaches such as complex instruction to powerfully impact student learning (Cohen, Lotan, Scarloss, & Arellano, 1999).

Leveraging 3D Fabrication for Education

There is currently significant interest in fabricating 3D structures in middle schools using 3D printing (Ladeji-Osias et

al., 2016). Researchers and practitioners cite potential benefits such as career awareness, technology skill development, experiential learning, and opportunities for creativity. A relationship to the maker movement, tinkering, and promotion of entrepreneurship is often discussed (Ladeji-Osias et al., 2016). A number of practitioners and researchers propose 3D printing as part of STEAM (Science, Technology, Engineering, Arts, and Mathematics) (Magloire & Aly, 2013). The STEAM approach is sometimes advocated as a means of introducing creativity and overcoming student beliefs that STEM (Science, Technology, Engineering, and Mathematics) is uninteresting and difficult (Magloire & Aly, 2013). This approach is evident in a number of reports on using 3D printers with students in the middle grades (Brown & Burge, 2014; Buhler, Gonzalez, Bennett, & Winick, 2015; Starrett, Doman, Garrison, & Sleigh, 2015). Many of these projects focus on using stock images from libraries such as Thingiverse and Tinkercad to produce parts that students then use to engage in creative tinkering (Buhler et al., 2015; Magloire & Aly, 2013). However, the integration of mathematics or science standards into these activities is often very limited. We believe that there is a significant opportunity to get much more from 3D fabrication in schools.

Practicing engineers and designers use 3D printing as a rapid prototyping tool (Sass & Oxman, 2006). This enables them to design virtual 3D versions of parts or products with professional computer software (e.g., Autodesk) and then make a physical version of that part or product using a 3D printer. This physical version is tested against design criteria to determine if it is fit for the purpose. The part or product is then redesigned, printed, and tested again as needed. This iterative process continues until the part or product meets all design criteria. This design process is readily accessible to students in the middle grades using software such as Tinkercad (by Autodesk). This process can be used to clearly connect what students do with a 3D design to authentic real-world activities and careers. In essence, 3D design and printing allows practicing engineers and designers, including students, to tinker in both the real world through printed parts and in the virtual world through the use of 3D design software.

While developing 21st-century skills through 3D design and printing, along with authentic connections to design and engineering careers, are significant and laudable goals, we believe that educators should also be developing rich and authentic activities that enable students to develop a deep understanding of mathematics and science content through design-based learning utilizing 3D printers. Too often, use of 3D printers or other “new” technology devolves into “bells and whistles” that generate some interest from students, but do not realize the true potential for utilizing that technology to develop deep learning in relevant content areas. In order to realize that potential, approaches to teaching mathematics and science cannot follow traditional didactic teacher to student knowledge transmission models.

Integrating Problem- and Design-Based Learning with 2D Modeling and 3D Fabrication

Problem-based learning (PBL), since its inception within medical education, has been thoroughly student-centered, multidisciplinary, and facilitative of lifelong learning (Boud & Feletti, 1997). Over the last 30 years, PBL has been adopted across pK–16+ educational contexts including and beyond STEM disciplines. At its heart, “PBL is an instructional (and curricular) learner-centered approach that empowers learners to conduct research, integrate theory and practice, and apply knowledge and skills to develop a viable solution to a defined problem” (Savery, 2006, p. 5). Design-based learning (DBL) can be considered a subtype of PBL where solutions require 2D and/or 3D modeling and fabrication, and where redesign and iterative prototype testing is emphasized (Doppelt, 2009; Dym, Agogino, Eris, Frey, & Leifer, 2005; Fortus, Dershimer, Krajcik, Marx, & Mamlok-Naaman, 2004; Kolodner et al., 2003; Mehalic, Doppelt, & Schunn, 2008).

Core commonalities across rigorous applications of PBL or DBL pedagogy include (for more detail, see Boud & Feletti, 1997; Duch, Groh, & Allen, 2001; Fortus et al., 2004; Hmelo-Silver, 2004; Kolodner et al., 2003; Torp & Sage, 2002):

- Authentic ill-structured problems from the real world that are meaningful to learners and enable diverse solution paths and multiple solutions;
- Learner-centered projects, where the instructor’s role is to activate intrinsic motivation, facilitate learner inquiry processes, and facilitate learner reflection and consolidation of learning;
- Multidisciplinary sources of information and approaches to understanding problems;
- Peer collaboration with careful attention to group dynamics to ensure full participation; and
- Assessment that focuses on both processes and products of learning.

These approaches benefit all students including those in low-achieving brackets (Chang & Chiu, 2005). The benefits of folding authentic contexts into classroom tasks provide an opportunity for greater engagement of students in their own understanding of realistic situations as well as developing students’ own scientific reasoning for those situations (English & Doerr, 2003; Fortus, Krajcik, Dershimer, Marx, & Mamlok-Naaman, 2005).

One useful definition of design is provided by Dym, Agogino, Eris, Frey, and Leifer (2005): “Engineering design is a systematic, intelligent process in which designers generate, evaluate, and specify concepts for devices, systems or processes whose form and function achieve clients’ objectives or users’ needs while satisfying a specified set of constraints.” According to Dym and colleagues (2005), once the design process is mastered students are able to (a) tolerate ambiguity and cycle from divergent to convergent thinking processes in an iterative loop to find a design solution, (b) maintain sight of the big picture, (c) handle uncertainty, (d) justify and make decisions, (e) think as part of a team in social processes, and (f) think and communicate in several languages of design. Further, these new types of solutions often relate to real problems in our environment that require manual manipulation of physical elements and materials (Acher, Arcà, & Sanmartí, 2007). Such manipulation exposes students to authentic problems and provides experience that skilled teachers can use to guide students to improved content knowledge (Edelson, 2001).

Another important advantage offered by modeling activities is closely connected to students designing their own artifacts (Fortus et al., 2005). Such design improves their ability to manipulate and navigate changing circumstances and perspectives, including actively taking ideas apart and putting them back together based on data-driven speculation (Lesh & Zawojewski, 2007). Students are actively involved as they create explanations, make predictions, and argue their

positions based on evidence they collect (Edelson, 2001). These new proficiencies that students develop go beyond low-level skills fostered in test-driven curricula to multileveled solutions and organized collections of knowledge (Acher et al., 2007; Lesh & Zawojewski, 2007). However, it is important to recognize that this approach to teaching and learning puts the teacher in a very different role than traditional didactic knowledge transmission models suggest.

This design-based approach to teaching content and developing problem-solving skills dictates a new role for the teacher. Teachers must shift from an evaluative perspective to an interpretive one as they move away from guiding students to correct answers and toward emphasizing student engagement and student learning autonomy (Doerr & English, 2006). Teachers should encourage student reflections on their own reasoning as well as their interpretations of problem situations (Lesh & Zawojewski, 2007). Rather than warning students when they take a wrong step in their solution efforts, teachers need to encourage students to focus on interpretation-specific ideas expressed even in incorrect solution paths and their connections to the problem at hand (Acher et al., 2007). Being “wrong,” generating “incorrect” solutions, and trying designs that “do not work” become incredibly powerful learning experiences that skilled teachers draw on to deepen content knowledge.

This design-based learning approach is a powerful form of inquiry because in general there are many possible solutions and students almost always work in teams (Doppelt, Mehalik, Schunn, Silk, & Krysinski, 2008). Because students are working together, thoughtful implementation of lessons allows all students to contribute to developing a successful design. Thus, this approach is ideally suited for the development of educational activities that incorporate group-worthy tasks (Lotan, 2003) and utilize complex instruction (Cohen et al., 1999) to facilitate all learners contributing meaningfully to every task. These approaches are powerful ways to help close the achievement gap (Boaler, 2008).

3D printing and the associated use of design software offers a rich toolkit that can be used for engaging students in rich, authentic tasks that are standards-aligned. The resulting modules lend themselves to incorporating the very best current practices in mathematics and science education. In summary, we suggest the following six benefits to a standards-aligned design approach to 3D printing in the middle grades:

1. 3D design and printing are well suited to enable students to develop deep understanding of the engineering design process.
2. Authentic design activities provide motivation for geometric and algebraic tinkering within a 3D design software environment.
3. 3D printing provides concrete realizations of virtual products that can be manipulated in the real world.

4. Fabricated parts can be used to test against design criteria and the results shared with others to provide opportunities for reflection and thus inform redesign.
5. The entire process of design and printing inherently facilitates a design-based learning approach.
6. The process is completely analogous to that used by practicing engineers and designers and thus lends itself to authentic design problems and promotes career awareness.

Methods: Our Math Science Partnership Context

Teachers Engaged in STEM and Literacy (TESAL) was a three-year Math Science Partnership including two weeks of professional development each summer, two days each semester, and classroom observations/support throughout the year (see Figure 1, next page). Each year was themed around science and literacy foci (Year 1: Physical Science/Argumentation; Year 2: Life Science/Informational; Year 3: Earth Science/Narrative) with grade-appropriate standards-focused mathematics. Participating teachers were asked to remain in the program all three years and create, then implement and refine, at least two lesson plans per year. TESAL involved teachers from four counties with 41% to 67% low-income students, less than 80% highly qualified teachers in mathematics or science, and below-average mathematics and science test scores in a state well below the national average. The 24 participating teachers had 1 to 32 years' teaching experience (median = 8 years) and considered themselves science educators ($n = 11$), mathematics educators ($n = 8$), special educators teaching math or science ($n = 4$), or technology educators ($n = 1$). All participants had a bachelor's degree; 17 (70%) were highly qualified per federal definitions. We will not discuss the literacy component of TESAL in this paper due to space considerations.

A key strength of TESAL was that the collaborative project team involved WV Regional Education Service Area personnel who have authentic long-standing relationships with key schools and teachers in the area working closely with university faculty who have deep engineering, science, and mathematics content knowledge, as well as education pedagogy, curriculum resource, literacy, and educational evaluation/research expertise. This sort of team was quite unusual in the mostly rural Appalachian area where we work.

TESAL incorporated characteristics of effective professional development in mathematics and science in that it was ongoing, content-focused, embedded in the work of teaching, and aligned with state CSOs (content standards and objectives) (Bolyard & Moyer-Packenham, 2008; Cochran-Smith & Lytle, 2009; Desimone, 2009; Desimone, Smith, & Phillips, 2007; Lee 2004/2005; Peck, Barton, & Klump, 2007; Speck,

Year 1	Year 2	Year 3
Physical Science Roller Coaster Argumentative Literacy JASON Resources	Life Science Design Project Informative Literacy JASON Resources	Earth Science Design Project Narrative Literacy JASON Resources
Develop, Teach and Evaluate Lesson Plans For two Design Based Instruction lessons per year		
Classroom Visits Observe and Discuss Content Strengths and Weaknesses with Teachers Develop Workshop Content		
Workshops Targeted Professional Development to Support Lesson Plan Development and Implementation		



Figure 1. Project TESAL program design and participating teachers building roller-coaster.

2002). Teachers engaged in significant mathematics and science content related to the work of teaching as they developed, designed, implemented, and refined modules to address middle grade content standards and objectives in mathematics, science, literacy, and engineering design. Teachers collaborated with peers and experts in engineering design, literacy, science, and mathematics education as part of a team moving through learning, development, and implementation cycles.

National standards documents make it clear that mathematics is an essential tool for scientific inquiry, and science is a critical context for developing mathematics competence (National Council of Teachers of Mathematics, 2000; National Research Council, 2006). Mutually reinforcing science and mathematics understandings while teaching either discipline is a pragmatic and readily available interdisciplinary opportunity (Center for Educational Policy, 2007; Czerniak, 2007). *A Framework for Science Education* (National Research Council, 2012) gives engineering and technology a greater focus. In our approach, *Common Core State Standards for Mathematics* (CSSM; Common Core State Standards Initiative, 2011) content domains (e.g., measurement/data, modeling), and standards for mathematical practice (e.g., persevering and making sense of mathematical problems, modeling mathematics, choosing appropriate tools) are integrated with science and engineering practices from next-generation standards (e.g., “asking questions/defining problems,” “using mathematics/computational thinking”), as well as crosscutting concepts focused on “systems/system models.” Engineering design projects provide extensive opportunities for engaging in

practices common to both the CSSM and *Framework*: defining problems, constructing explanations, developing models, and attending to precision.

Middle grade content standards and objectives include engineering design in the science framework, but the design process is not easy to learn. This is at least partially because design is a dynamic iterative process rather than a specific skill or piece of content knowledge. Such processes have less often been part of traditional teacher training. Therefore, teacher preparation and scaffolding are key to implementation of design-based learning and related student learning gains (Puntambekar & Kolodner, 2005). TESAL addressed teachers’ knowledge of pedagogy and their content knowledge (Hiebert & Grouws, 2007). Teachers need to know how students develop understanding of content, how to set significant learning goals, how to select/implement appropriate instructional tasks, and how to assess learning (Hiebert, Morris, Berk, & Jansen, 2007). In order to successfully impact student learning, teachers must have a deep understanding of the mathematics and science they teach. Well-designed professional development experiences are integral to developing such knowledge and skills (Desimone et al., 2007). TESAL targeted improved mathematics and science content knowledge in an engineering design-based approach (Doerr & English, 2006). We worked to shift students and teachers from being processors of information toward becoming creators of mathematics and science models as tools to help solve societally relevant scientific challenges through design and development of appropriate technologies (Lesh & Zawojewski, 2007).

A Brief Example of Our Approach

Teachers experienced an engineering design lesson as learners in groups designing and building a paper roller coaster where a marble should take 45 seconds to traverse the track. Mathematical modeling was used to predict time based on coaster design components. We introduced the design process and emphasized redesign in this context. Redesign led to a literacy assignment to write an instruction manual on how to build the redesigned coaster. Groups had to build each other's coaster from that instruction manual. They then developed roller-coaster-based lessons for their classrooms.

Conversations during the coaster project, content knowledge tests, and later classroom observations highlighted specific content knowledge gaps for teachers. Teachers had misconceptions about how mass of a marble influences travel on the track, confusing how potential energy, kinetic energy, force, and speed differentiate. We developed new Web-based design modules for teachers requiring them to build and test ramps at various heights to launch small and large marbles first to hit a target and later to hit a target with enough force to break a napkin. Measurements from designs with small marbles were used to build mathematical models predicting mechanics with large marbles. Scaffolding for mathematical modeling was an Excel file with embedded equations and dynamic trajectory graph. Models were tested against observations. We knew the scientific and mathematical content of the modules would challenge teachers. Teachers individually completed these Web-based versions and experienced struggles similar to those experienced by their students. Teachers completed modules a second time in groups during professional development where peers and content experts provided scaffolding as needed and worked to adapt portions of modules to middle grade students.

Teachers have developed their own design-based lesson plans that integrate both math and science standards using a similar approach. One math teacher wanted to have students more effectively learn how to find areas of 2D and 3D shapes and represent these graphically to solve real-world mathematical problems. They designed an engaging gingerbread house design competition that could be completed in five classroom periods of 50 minutes each. The design steps and associated standards are shown in Table 1 (see next page).

The teacher produced a student handout to describe the process and scaffold the activity as shown in Figure 2 (see following pages). The following pictures illustrate the key elements from the gingerbread house design. In Figure 3 (see following pages) we provide examples of student-drawn plans for their houses. Students collaborated to build the house in Figure 4 (see following pages). Once building began, students struggled with the need for support to hold up the roof and

to provide a strong base. Constraints in the design process promoted productive struggle. Some students measured the dimensions of the structure to determine the surface area (see Figure 5, following pages), while others determined the area of one cracker and multiplied by the number of crackers used. The diversity of houses built in a single 50-minute class period is displayed in Figure 6 (see following pages). Figure 7 (see following pages) shows the structural testing of the houses.

The gingerbread house project allowed students to work on concepts of calculating area from 2D drawings and from 3D physical shapes and was aligned with appropriate Common Core math standards. It allowed each group to develop unique design solutions as evidenced by the diversity of the built gingerbread houses. Structural testing added an interesting component whereby students had to decide how to use their budget of graham crackers to build a tall structure that was reinforced enough to withstand shaking and blowing. This structural testing component was important to prevent the project from having a single solution and also opened up the problem so that all students could contribute to a discussion about the design rather than deferring to those students who seemed to have mastered calculating area of shapes. It was evident in classroom observations that all of the students were engaged in the activity, and especially noticeable was the engagement of students who did not typically participate in mathematics class, with some of these students taking the lead on aspects of the project, especially measurement. We developed a 3D printing professional development (PD) specifically to build on the design approach used in the gingerbread house model while incorporating a 3D design environment and authentic links to the work of professional designers and engineers.

The 3D Printing Professional Development

In the fall of 2017 we planned and implemented a one-day PD to 15 teachers who participated in TESAL. All of these teachers had experience with engineering design as described in the preceding section. The outline for the PD was:

- 8:30 a.m.–9:00 a.m. Housekeeping and Orientation to the Day
- 9:00 a.m.–11:30 a.m. Experiencing as Learners: 3D Printing Engineering Design Activity
- 11:30 a.m.–1:00 p.m. Discussing as Teachers: (How) can 3D printing be authentically integrated into design-based lessons you already have planned? Any new lesson ideas?

We began the Engineering Design Activity by having teachers form groups of three, giving each group two 3D printed gears, and asking them to tinker with the gears and make observations (see Figure 8, following pages). After five minutes of tinkering,

Table 1. Gingerbread house design steps and content standards covered.

Design Step	Standard	Description
Designing a house on graph paper.	MS-ETS1-1.	Define the criteria and constraints of a design problem with sufficient precision to ensure a successful solution, taking into account relevant scientific principles and potential impacts on people and the natural environment that may limit possible solutions.
Calculating the surface area and basal area of the house based on the drawing.	CCSS.Math.Content.6.G.1.	Find the area of right triangles, other triangles, special quadrilaterals, and polygons by composing into rectangles or decomposing into triangles and other shapes; apply these techniques in the context of solving real-world and mathematical problems.
Building the house from graham crackers.		
Calculating the surface area and basal area by measuring the physical house.	CCSS.Math.Content.6.G.1.	Find the area of right triangles, other triangles, special quadrilaterals, and polygons by composing into rectangles or decomposing into triangles and other shapes; apply these techniques in the context of solving real-world and mathematical problems.
	CCSS.Math.Content.6.G.4.	Represent three-dimensional figures using nets made up of rectangles and triangles, and use the nets to find the surface area of these figures. Apply these techniques in the context of solving real-world and mathematical problems.
Decorating the house and displaying it with the class as a block of houses.		
Testing the house against the weather.	MS-ETS1-2.	Evaluate competing design solutions using a systematic process to determine how well they meet the criteria and constraints of the problem.
Redesigning the house.	MS-ETS1-3.	Analyze data from tests to determine similarities and differences among several design solutions to identify the best characteristics of each that can be combined into a new solution to better meet the criteria for success.

we facilitated a group discussion with the prompt, “What did you notice about these?” Some of the teacher responses included:

1. The gears rotate in opposite directions.
2. The small gear has 12 teeth.
3. The large gear has 28 teeth.
4. It takes 7 turns of the small gear to make the large gear turn 3 times, so the ratio between the gears is 7:3.
5. The large gear has 28 teeth while the small gear has 12 teeth, so the ratio between the gears is 28:12.
6. The ratio between the gears is $28/12 = 2.33:1$.
7. The teeth on each gear are the same size.
8. The ratio of the diameters of the gears is the same as the ratio of the number of teeth.
9. There are two different diameters needed to describe the size of each gear (the diameter to the base of the teeth and the diameter to the tip of the teeth).
10. Gears can be used to explore proportional relationships.
11. Gears can be used to explore ratios.
12. Gears can be used to explore lowest common multiples.
13. Gears can be used to multiply by fractions.

Gingerbread House Design

Task: Your task is to design and build a gingerbread house that has a solid structure and creative design using specific criteria.

Day 1: Design a gingerbread house on graph paper that meets the following criteria:

- Minimum area of base of 15 square inches
- Solid structure
- Functional roof
- One entrance
- You can only use one packet of graham crackers
- The structure must be as tall as possible BUT be able to withstand winter weather conditions

From your drawing determine:

Height: _____

Area of the base: _____

Surface area: _____

Day 2: Build the gingerbread house that your group designed using the materials available to you. The dimensions of your house should reflect the measurements in the fact sheet above. Stay as close to your original design as possible. Be creative!

Day 3: Measure the dimensions of your house and complete the table below.

	Original Design	Actual House	Difference
Height			
Area of the base			
Surface area			

How did the dimensions of the original design compare to the actual ginger bread house your group built? What constraints affected your design?

Day 4: According to meteorologists, Gumdrop Avenue will experience blizzard like conditions accompanied by a magnitude 4 earthquake. We will test your structure on a shaker table and blow on it with a heavy duty fan.

Day 4: Does your gingerbread house need to be re-designed? Below, design a plan for improving your existing design. How will you improve the structure of your existing gingerbread house?

Figure 2. Gingerbread house design handout.



Figure 3. Students designed gingerbread houses on paper.



Figure 4. Students collaborated to build gingerbread houses.



Figure 5. Students measured physical dimensions of their gingerbread house.

Following the group discussion, teachers were introduced to Tinkercad and walked through the process of constructing a 3D model of gears and a holder with pins to place the gears on (see Figure 9, following pages).

Once teachers had drawn their initial gear train with 28 teeth and 12 teeth, they then redesigned the gears and holder for two new gears with different numbers of teeth and printed their design. This required them to calculate the spacing between the center of the gears and adjust the spacing between the support pins accordingly. We observed teachers watching their gear trains printing so they could determine if their calculations were correct—and they were clearly excited when they were!

Once teachers had completed their redesigns, we discussed in more detail how gears could be used to multiply numbers by using the prompt, “If you turn one of your gears by one full revolution, how much does the gear it is connected to turn?” For the original gears, one revolution of the first gear turns the second gear by 12 teeth or $12/28$ ths of a revolution. The teachers were then asked to explore what fractions they could turn the gears by, which for a gear with 12 teeth (not including fractions of teeth when turning) leads to $1/12$, $1/6$, $1/4$, $1/3$, and $1/2$.

Teachers then discussed how they can authentically integrate 3D printing into design-based lessons they already have planned

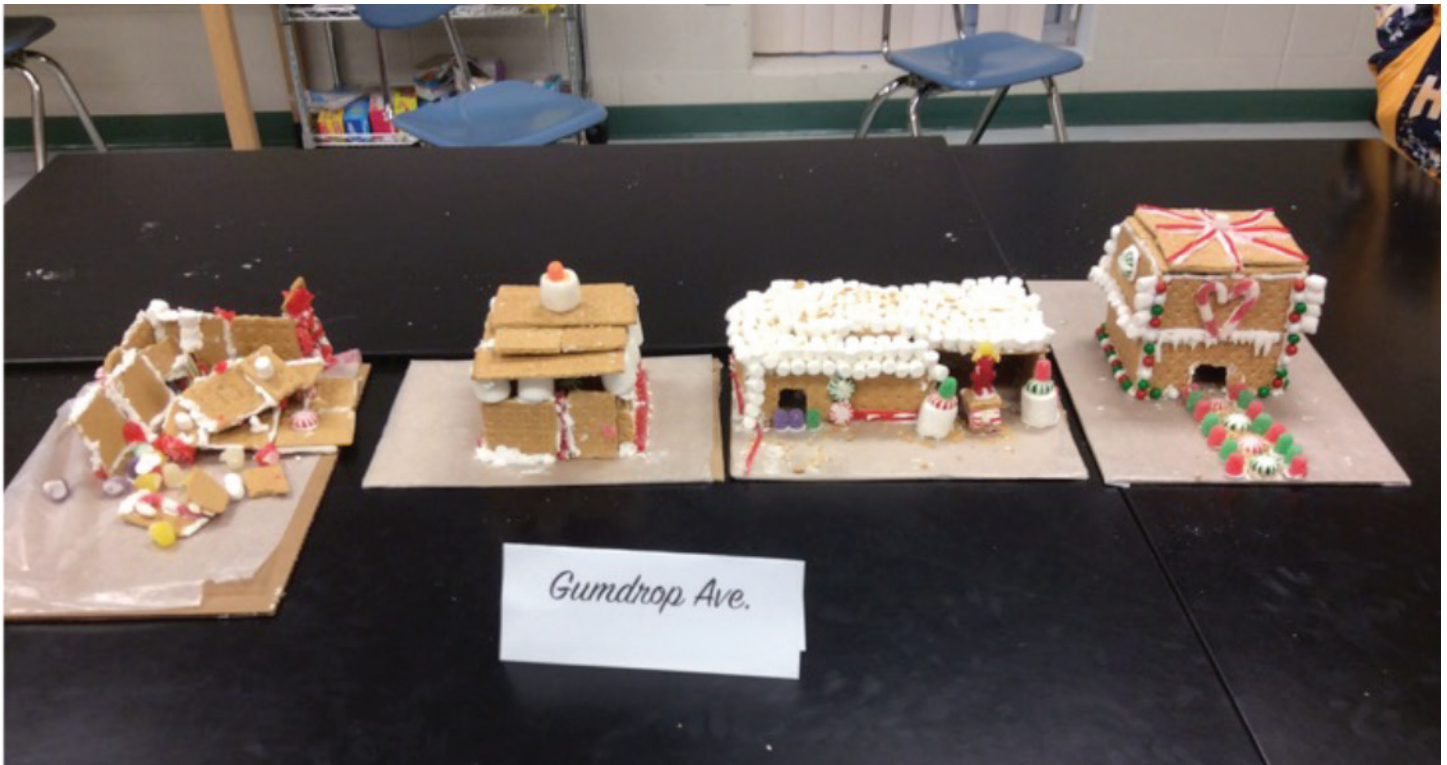


Figure 6. A row of houses on Gumdrop Avenue illustrating diversity of designs.



Figure 7. Structural testing on a shaker table (wobbly desk) with fan blowing on highest setting.

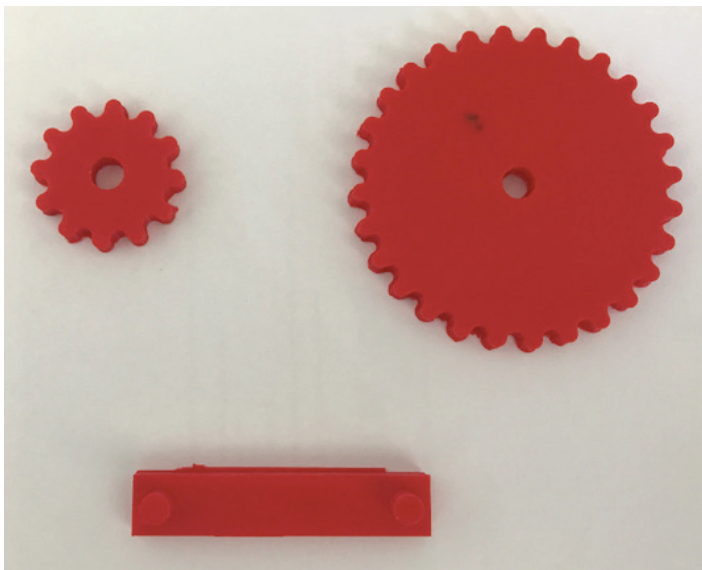


Figure 8. 3D printed gears.

and new lesson ideas. We developed the following lesson plan incorporating these ideas to design and build a mechanical computer (see Figure 10 and Table 2, see following pages).

Practitioner-Generated Lesson Plan Concepts

As part of a survey we gave TESAL teachers, we solicited answers to the question:

“Describe how you can use 3D printing in lessons you will teach to your students. Be as specific as you can be. Include both the content you will focus on and the activities you will use. Provide multiple examples if you have multiple ideas.”

We received answers from 13 teachers, which our analyses grouped into four themes:

1. Mathematical manipulatives and visual models: fractions; polygons; 3D shapes.
2. Scale models: atoms; molecules; chromosomes; cells; flowers; kitchens; land forms; tectonic plates; to measure density.
3. Machines: simple machines; Rube Goldberg machines; gears; wind turbines.
4. Designing and building a useful product.

We did not provide any prompts to the teachers. Here is one interesting idea expressed by a teacher:

“My thoughts are to have the class create a kitchen with a specific area and let each group design specific items for the kitchen without collaborating with the other groups. After the items are designed, the groups would come together to combine the items in the kitchen. The hope would be that there would not be enough room and it would have to be redesigned. After the final kitchen is completed, the design would be printed with the 3D printer to compare and share with other classes.”

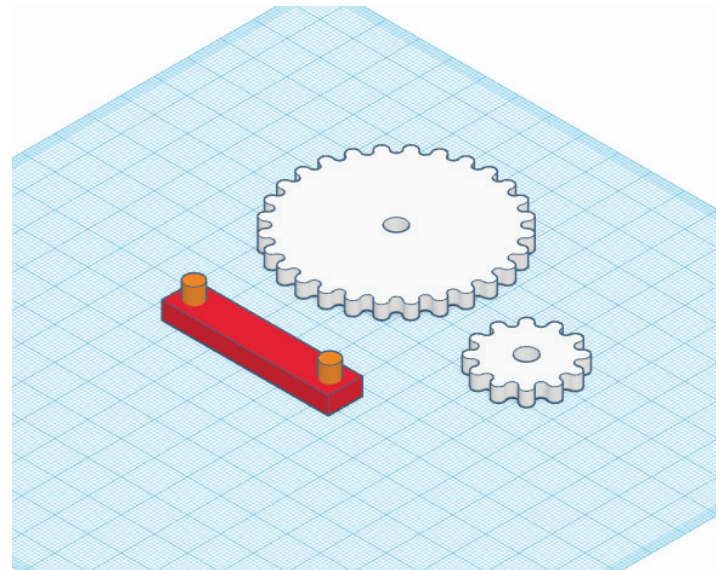


Figure 9. 3D drawing of gears and pin supports in Tinkercad.

This idea could be further developed in light of a recent paper on using an architecture design project to enable students to “solve real-life problems involving angle measure, area, surface area, and volume” (Bush, Albanese, Karp, & Karp, 2017). The authors described the use of 3D modeling software by students (in this case they used Google SketchUp) to design a home given a set of criteria and constraints. We believe this design project could be augmented with 3D printing and that physically placing items within a scale model of different iterations of student designs would be highly beneficial.

We believe that 3D printing can be incorporated into engineering design lesson plans that provide rich authentic contexts in which students can experience deep learning. We also believe that if these lesson plans are carefully constructed, they can be used in group-worthy tasks that enable students to contribute to the project in multiple ways in line with approaches like complex instruction that lend themselves to reducing achievement gaps.

Conclusions

Our model utilizes iterative design and redesign to address “the engineering problem” of building teacher content knowledge, and we model that approach for our teachers to use in order to target and strengthen STEM content knowledge and engagement in their students (Curtis et al., 2017c). Middle school teachers engaged in our professional development program have shown increased content knowledge, teaching efficacy, STEM career awareness, and student technology use (Curtis et al., 2017a, 2017b). Our teachers have generated many strong design-based lessons and have described

Design and build a mechanical computer

The first computer was invented and designed by Charles Babbage in the 1820's. Unlike modern computers that are made up of electronic components and microchips the computer designed by Babbage used gears to perform calculations.

Babbage's machine was not able to be produced at the time because they did not have the technology to accurately produce all the different gears needed to make it work.

In this unit your team will design a computer that can perform calculations using gears. You will decide what gears to make and what size they should be. You will then design the gears in Tinkercad and print them with a 3D printer to build your computer.



Day 1 – What calculations can you do with gears?

We have a big box of gears in the classroom. Take some gears for your group (you can bring them back and try new ones too). As a group, play with the gears and discuss ways you can use gears to do calculations. Think of the types of calculations you might want to do and try to do them.

Day 2 – Learn how to use Tinkercad to design gears

Day 3 & 4 – Design and print your first set of gears and build your computer

Day 5 – Present your computer to the class (show the types of calculations it can do and explain how it works)

Day 6 – Rethink what your computer can do and redesign

Day 7 & 8 – Design and print your second set of gears and build your second computer

Day 9 – Present your computer to the class (show the types of calculations it can do and explain how it works)

Day 10 – write a group report on your computer including reflections on what you have learned.

Figure 10. Lesson plan for design of a gear-driven computer.

how design-based instruction facilitated the engagement of all students, including students receiving special education services and students they previously had difficulty engaging (Curtis et al., 2016). We have found the following key features central to our teachers' success:

- Authentic ill-structured problems from the real world that are meaningful to learners and enable diverse solution paths and multiple solutions.
- Learner-centered instruction where the instructor's role is to activate intrinsic motivation, facilitate

learner inquiry processes, and facilitate learner reflection and consolidation of learning.

- Multidisciplinary sources of information and approaches to understanding problems.
- Peer collaboration with careful attention to group dynamics to ensure full participation.
- Assessment that focuses on both processes and products of learning.

If this list looks familiar, it should. It is the same list of core commonalities across rigorous applications of PBL or DBL

Table 2. Mechanical computer design steps and content standards covered.

Design Step	Standard	Description
Explore calculations with gears.	CCSS.Math.Content.7.G.B.4.	Know the formulas for the area and circumference of a circle and use them to solve problems; give an informal derivation of the relationship between the circumference and area of a circle.
	CCSS.Math.Content.7.RP.A.1.	Compute unit rates associated with ratios of fractions, including ratios of lengths, areas and other quantities measured in like or different units. <i>For example, if a person walks ½ mile in each ¼ hour, compute the unit rate as the complex fraction ½ / ¼ miles per hour, equivalently 2 miles per hour.</i>
	CCSS.Math.Content.7.RP.A.2.	Recognize and represent proportional relationships between quantities.
	CCSS.Math.Content.7.RP.A.2.A.	Decide whether two quantities are in a proportional relationship, e.g., by testing for equivalent ratios in a table or graphing on a coordinate plane and observing whether the graph is a straight line through the origin.
Design first computer.	CCSS.Math.Content.7.G.A.1.	Solve problems involving scale diagrams of geometric figures, including computing actual lengths and areas from a scale drawing and reproducing a scale drawing at a different scale.
Present to class.	MS-ETS1-2.	Evaluate competing design solutions using a systematic process to determine how well they meet the criteria and constraints of the problem.
Redesign computer.	MS-ETS1-3.	Analyze data from tests to determine similarities and differences among several design solutions to identify the best characteristics of each that can be combined into a new solution to better meet the criteria for success.
Present redesign to class.	MS-ETS1-2.	Evaluate competing design solutions using a systematic process to determine how well they meet the criteria and constraints of the problem.
Prepare group report.		

pedagogy we described earlier as emerging from previous literature. To this list, we contribute the following specifically from our own work:

- Tinkering and modeling design solutions in 2D.
- Using mathematics to predict effectiveness of potential design solutions.
- Tinkering and fabricating design solutions in 3D for testing.
- Comparing mathematical predictions to measurements from fabricated design solutions and considering sources of error.

- Facilitating productive struggle and tinkering in iterative redesign with group dynamic approaches such as complex instruction.
- Explicitly connecting big ideas, key concepts, and STEM learning objectives engaged while tinkering, designing, and redesigning in 2D and 3D.

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