Contents

Mathematics, 3D Printing, and Computational Thinking Through Work-Based Learning for Middle Schoolers (MPACT) addresses Absolute Priorities 1 and 3. We will develop and implement three middle grade curriculum units, set in the context of a workplace using digital fabrication (3D modeling and printing), designed for students to learn mathematics, computational thinking, and spatial thinking skills, as well as develop positive views of themselves and their future in STEM.

A. National Significance

MPACT will be a scalable model for high-need students in rural areas across the country, starting with a test bed in rural Central California, an area of particular need. By *high-need*, we mean students who are from non-White minority groups, who live in poverty, who are English learners, or who have disabilities. Such young people have the attendant problems of educational inequities and uncertainty about their future in the workplace.

That “many children and their families in rural America need better and more equitable educational opportunities” is the theme of a recent report (Showalter, Klein, Johnson, & Hartman, 2017), and two areas of particular need are mathematics and computer science (CS). Although rural students’ mathematics achievement is only slightly lower than the national average, high-need rural students tend to perform far lower than it (Lavalley, 2018). The number of high-need rural students varies by region; for example, in California, 57.5% of rural students are from minority groups (Lavalley, 2018). The gap in mathematics achievement between non-White and White students is smaller in rural areas than in urban areas, but it still exists. High-need students require additional resources for mathematics learning: Approximately one third of the inequities in achievement associated with differences in race and income level can be accounted for by an impoverished curriculum (Schmidt, Burroughs, Zoido, & Houang, 2015).

Further, rural youth have less access to CS than their suburban counterparts: Compared with schools in suburban districts, schools in rural areas are less likely to have CS classes or clubs, courses that teach coding, or advanced-placement CS courses (Google Inc. & Gallup Inc., 2017).

A second set of issues rural youth face are future employment and life aspirations. Rural area job growth over 2001–15 lagged behind the national average in most sectors (U.S. Department of Agriculture, 2017). This leaves rural students with a dilemma: the need for employment and the desire to stay in their home communities. Researchers on the relationship among education, work, and aspirations of rural youth and practitioners such as school counselors are trying to see beyond this duality to find more nuanced ways to characterize and influence rural youth's aspirations (Tieken & San Antonio, 2016). One promising trend is the growth in information technology occupations, and agricultural technology offers particular promise (Deloitte, 2016).

The Bureau of Labor Statistics (2018) stated that "Employment in computer and information technology occupations is projected to grow 13 percent from 2016 to 2026, faster than the average for all occupations." Some of these jobs can be done from anywhere with an Internet connection. Digital fabrication could be especially important for rural students: A recent report (Laugerette & Stöckel, 2016) predicted that technologies such as 3D printing will transform agriculture. Rural communities are beginning to recognize this potential through such efforts as the "fab lab" for digital fabrication that was established as an incubator for entrepreneurs in a rural Kansas community college (Eastwood, 2017). Fabrication technology tools are also becoming more common in other rural work such as nursing (Maryville University, 2018).

A promising way to take advanced STEM into rural communities is through work-based learning. A WestEd report (Darche, Nayar, & Bracco, 2009) describes a continuum of student experiences from career exploration to work-based learning to career preparation. Career exploration starts in early grades, typically with discrete activities or workplace tours to spark interest or motivation. Most programs in the middle of the continuum occur in high school and above (Darche et al., 2009). Yet in an NSF-funded study on the employability of young people entering technical fields (award #1700703), interviews with employers in information technology revealed great interest in reaching students as early as middle school, when interest in STEM among young people from underrepresented groups in particular needs to be encouraged.

MPACT will introduce STEM learning to high-need rural students in middle school through substantive work-based learning experiences. The MPACT curriculum units for grades 6–8 will be a groundbreaking way to improve mathematics and CS learning while simultaneously improving students' views of themselves as future workers in the growing STEM industry of digital fabrication. These units will address two important concerns for high-need rural middle school students: the opportunity to learn important mathematics and CS concepts and exposure to experiences that can influence their aspirations for work.

MPACT will use 3D digital fabrication to address content standards in CS. CS education has expanded to include "computational thinking" (CT) (Barr & Stephenson, 2011; Basu, Mustafaraj, & Rich, 2016; Wing, 2006), "the thought processes involved in formulating problems and their solutions so that the solutions are represented in a form that can be effectively carried out by an information-processing agent" (Wing, 2010, p. 1). Existing CT projects and curricula have focused on CT involving programming, but they have been criticized for failing to engage diverse students (Buechley, Eisenberg, Catchen, & Crockett, 2008). Yet CT can be opened up to include digital fabrication activities such as problem scoping and decomposing, iterating, troubleshooting, and working across multiple representational systems (Wagh, Gravel, & Tucker-Raymond, 2017). In MPACT, an important form of CT will be developed through working with and creating tangible objects, already recognized in robotics projects and through use of tools such as Arduino. Students who have been underserved by traditional CS courses focused on programming may thrive given the opportunity to model and print 3D objects. Further, this form of CT is growing in importance with 3D printing on its way to being ubiquitous (Frost & Sullivan's Global 360 Research Team, 2016).

In middle school mathematics, the geometry of volume and surface area and topics such as ratio are clearly tied to working in 3D. Spatial thinking skills, a strong predictor of STEM success (Newcombe, 2010) and mathematics performance (Cheng & Mix, 2014; Clements & Sarama, 2011), can also be improved through the processes of integrating both physical and digital objects.

MPACT will influence students' aspirations for work as they engage in a project using design tools similar to those adults use, with the help of workplace mentors. These two aspects of the program are key to its success in linking student learning to workforce opportunities. We plan to use Tinkercad, with a long history of use by as young as elementary students, which is related to the professional product AutoCAD. Tinkercad passed an alignment review by the International Society for Technology in Education (ISTE) as a tool for supporting CT (ISTE, 2016). Using such tools provides middle school students with both a link to real-world CT and a jumpstart into an authentic design process. Students' digital designs will be shared with adult mentors at a distance who will provide both design advice and insights into the world of work.

Taking 3D printers to schools should mean taking them to the community as well. MPACT community event materials will structure opportunities at the school to open use of the 3D printers to many users. As in the Kansas fab lab, this will enable hobbyists and budding entrepreneurs to create useful and beautiful objects. MPACT graduates will return to the school to provide community members with technical assistance, and this will be a chance for them to hone their skills, too.

An Exceptional, Innovative Approach that Builds on Existing Strategies

In our description of MPACT components below, we highlight those that take a new and exceptional approach and have cited the research and programs the components are based on. In brief, MPACT is **exceptional and innovative** in two important ways: It (1) extends work-based learning beyond career exploration at the middle school level and (2) uses 3D fabrication to support learning CS and mathematics and address the needs of rural youth.

Rationale

MPACT is based on research on and principles from work-based learning, mathematics education, and computer science education, but it takes each a step further by combining them in a digital fabrication context. Each component described below is shown in the appended logic model, along with implementation activities, outcomes, and measures.

MPACT Components

Curriculum Units

Each of the curricular components is detailed below, but none of the components function independently. They will be interwoven in the 12-lesson sequence through a rigorous curriculum development process described in the Management section.

Work-Based Learning Context

Building on existing frameworks to create a new approach, a workplace context provides both motivation and grounding for learning CT and mathematics. MPACT is based on a work-based learning model that has three characteristics (Darche et al., 2009): (1) student engagement in a project from a real work setting including communication with professionals through mentorship, (2) substantive experiences to develop problem-solving skills, and (3) clear connections to content and practice standards.

There are academic learning benefits to a work-based project. Students must engage in thinking critically about the problem to be solved and generate and evaluate solutions. They are called on to make sound and strategic decisions (Office of Career, Technical and Adult Education, U.S. Department of Education, 2018). Mathematical and computational thinking both rely on these problem-solving processes (Grover & Pea, 2017; Polya, 1945). These higher order skills are addressed in curriculum standards in mathematics (for example, make sense of problems and persevere in solving them) and CT (for example, decompose problems and subproblems into parts). Further, MPACT units will enculturate students into the community of practice of the workplace. Researchers have posited for decades that learning mathematics in a context of use provides opportunities for learning standards-based mathematics (Greeno and Middle School Mathematics Through Applications Project Team, 1998). Yet often mathematics is given short shrift in work- and project-based curriculum. 3D modeling and fabrication projects can, we hypothesize, make the mathematics in a project central.

Math Standards

Ensuring that the units address grade-level content leads to increased student achievement. We will develop the units based on learning progressions relevant to volume and surface area (e.g., Battista, 2007). The needs to compare sizes of shapes that are parts of more complex shapes, to predict how large an object will be upon printing, and to predict print time will motivate students to understand and use volume and surface area. The units will address these concepts and skills, core to common state middle grade geometry standards: *Grade 6*—Understand and apply formulas to find volumes and surface areas of right rectangular prisms with fractional edge lengths, in the context of solving real-world and mathematical problems. *Grade 7*—Solve real-world and mathematical problems involving volume and surface area of complex 3D objects composed of cubes and right prisms. *Grade 8*—Know and use the formulas for volumes of cones and spheres and how they relate to cylinders.

In addition, the units will address multiplicative relationships—ratio and proportionality—as students resize objects using 3D modeling software and consider the mathematical relationship between attributes of those objects: that changes in side lengths made in the same ratio or proportionally result in a figure that appears "the same" but enlarged or shrunken. We do not anticipate that the unit will thoroughly cover all standards in this topic, but the following will be addressed: *Grade 6*—Understand ratio and use ratio reasoning in solving problems. *Grade 7*—Represent proportional relationships with equations, tables, and graphs. *Grade 8*—Compare two different proportional relationships represented in different ways.

3D Modeling Software

In a new and exceptional approach, using CAD tools in conjunction with real objects supports the development of geometric concepts and spatial reasoning skills. We build on research on dynamic geometry tools such as Geometer's Sketchpad® and Cabri®, showing their utility for learning plane geometry through the construction and manipulation of geometric objects (Battista, 2007; Christou et al., 2007; Hollerbrands, 2002;). Interaction with dynamic tools enables users to visualize geometric concepts and properties by observing the consequences of their actions on geometric objects and recognizing that certain properties are preserved (Mariotti, 2003). We also note that sensorimotor experiences with real 3D objects also lead to increased mathematics learning (Battista, 2007, 2012; Francis & Whiteley, 2015). Synthesizing these two sets of findings, we hypothesize that the affordances of rapid prototyping materials such a quick-dry clay and linking cubes, CAD tools such as Tinkercad, and the 3D printed objects that are the result will boost students' learning about 3D geometry as they move from rough prototypes that can be held in the hand, to modeled objects that can be manipulated on screen, to actual precisely replicated 3D objects.

A related set of skills known as spatial reasoning skills, such as the ability to mentally rotate an object, are not typically part of state standards, but they are, as noted in the Significance section, correlated to mathematics achievement and success in STEM. The meta-analysis by Uttal et al. (2013) indicated that not only is spatial training effective in increasing students' spatial skills, but learning gained from training is also durable and transferable to novel tasks, regardless of students' age or gender. We posit that spatial reasoning skills will be enhanced by working in the CAD environment accompanied by physical objects. This approach builds on findings that the use of concrete 3D objects made mental rotation tasks accessible to young children (Casey et al., 2008; Hawes, LeFevre, Xu, & Bruce, 2015; Nath & Szucs, 2014), but we go beyond this to hypothesize that manipulatable 2D images of 3D objects on the screen used in conjunction with a corresponding 3D print will further enhance spatial reasoning skills.

Computational Thinking

In a new and exceptional approach, students learn computational thinking skills and practices through 3D digital fabrication. Digital fabrication technology provides a connection between abstract digital forms produced by computation and real artifacts produced by converting digital designs to physical objects.

Computational thinking with a visual orientation complements symbolically oriented programming, just as visually oriented geometry and symbolically oriented algebra are important aspects of mathematics. (This is not to say that symbols go unused in 3D modeling and fabrication.) Consider the CAD environment: Students place and manipulate 3D shapes to form complex objects. The representation is 2D, so they must interpret it as 3D. They can perform operations on the shapes to rotate them, translate them, make them hollow, and more. Students must learn the type of action needed to manipulate a shape in a certain way, such as rotating it about its vertical axis by 90 degrees, understanding the constraints and affordances of the CAD system for enabling such rotation. They can then generalize that action to perform other types of rotations. Additionally, the visual and tactile nature of modeling and printing provides a motivational grounding for students who may find working with lines of code limiting.

Using elements of CT from the K-12 CS framework (2016) and from a CT framework for mathematics and science classrooms (Weintrop et al., 2016), we highlight specific CT practices that will be fostered through MPACT digital fabrication units, as follows.

Structured problem decomposition or modularization to create computational artifacts. Creating a complex design for digital fabrication involves understanding the modular components of the design and how the components interact: decomposing a problem. As students create a complex shape, they need to modularize it in order to create, say, the leg and then the arm of a toy doll. Then the leg module can be applied again to create both legs of the doll.

Developing and using abstractions. The 3D shapes presented in 2D on the screen are abstractions of the more complex imperfect shapes found in the world. Further, the modules defined in the CAD environment will be used later by simply referencing their names, abstracting the details of the modules.

Testing and refining computational artifacts by systematically debugging. Composed shapes often do not print as expected. Shapes that appear to sit on top of each other on screen may in fact be separate, with one floating above the other, so that the print will fail. Through repeated experiences in the 3D CAD system and with guidance from teacher and curriculum, students will start to develop methodical approaches to debugging such problems.

Understanding efficiency and performance constraints. 3D printing is known to take a long time. There are questions of efficiency to investigate and analyze that really matter: Would it take just as long to print two shapes on one print as it would to print them sequentially? Should designs be printed out at a smaller scale for first prototypes to speed up printing? How much time would that save?

Reusing and remixing designs to create new ones. Being able to skillfully reuse or remix existing designs to meet new design criteria is an important CT skill; the accessible digital CAD files afford this.

Teacher Professional Development (PD)

Well-prepared teachers are critical to MPACT. PD goals are to ensure teachers understand the units, increase teachers' pedagogical content knowledge of 3D geometry and CT, provide the technical skills teachers need, and develop teachers' strategies for teaching with work-based projects. The initial 4-day PD workshop will be activity based, content rich, and conducted in communities of practice (a school's entire mathematics departments plus the CS teachers, if any)—all features of successful PD (Desimone, 2009).

However, a 4-day workshop will not be sufficient to ensure teachers have all the knowledge and skills to teach the units. Just-in-time PD will be provided in several ways, including but not limited to the following: (1) live online meetings to support teachers in activities such as planning; (2) teachers using the MPACT website during implementation of the unit to discuss with each other and with mentors common problems of practice and to share students' models, addressing the issue of rural teachers' isolation; and (3) on-demand how-to videos addressing predictable technical problems.

A curriculum guide will also be a source of professional learning for teachers. Topics will include students' likely misconceptions, questions to ask and likely answers, lesson timing, student-mentor communications, and assessment with sample rubrics provided.

Mentors

Workplace mentors guide students through their 3D modeling process and discuss with them workplace norms, contributing to students' content learning and influencing their attitudes toward future work. Mentors will come from workplaces as diverse as a prosthetics design firm and an industrial 3D printing company. Each mentor will contribute 3 hours per week to digital communication with one small group of students. Mentors will complete a 2-hour online training before interacting with students. Communications will be structured through prompts on the MPACT website that correspond to the curriculum, focusing the discussion on CAD files that students share with their mentors but including discussions of activities and norms in the workplace. Students' communication may be in the form of an "exit ticket"—a common pedagogical device for formative assessment. Teachers will get to know the mentors and how to best use their guidance for students during unit implementation.

Community 3D Printing Outreach

In a new and exceptional approach, community members will be invited to the school on weekends to use the 3D CAD tools and printers. Hobbyists or budding entrepreneurs will have access to the equipment to make objects of their choosing, with guidance from former MPACT students. Event materials will include advertising to appeal to those new to 3D printing.

Building on the rural fab lab (see Significance), participants may create replacement parts, useful objects, or artistic products.

MPACT Implementation

The MPACT curriculum components will work together in 12-lesson sequences, designed to be taught over a semester once a week. In mathematics class, the curriculum will be a supplement to the adopted curriculum on geometry and ratio/proportionality. In CS class, it will be an opportunity to address CT. The timeline accommodates making prints between lessons.

MPACT will rely on a secure web-based environment for delivery of the curriculum and just-in-time PD and for communication among teachers, mentors, and students. The student-facing curriculum and the curriculum guide will be available via web pages and as a printable PDF. Teacher-teacher communication and mutual help and guidance will be supported via hashtags in social media.

Students will work in small groups on their projects, with whole class discussions to solidify concepts and practices. The teacher will circulate during small group time, asking questions, prompting progress, and noting which students' work could contribute to the whole class discussion. Engaged in their projects, students will be using CT practices and nascent and explicit forms of mathematics concepts. Teachers will use prompts in the curriculum and discussion to move the nascent to the more fully developed and explicit. Mentors and students will communicate over the course of the semester as often as once a week.

B. Project Design and Management Plan

MPACT Goals, Objectives, and Outcomes

The MPACT goals, objectives, and outcomes are clearly specified and measurable, with the ultimate goal of student achievement and attitudinal change (Table 1).

Table 1. MPACT Goals, Objectives, and Outcomes

Goals	Objectives	Outcomes
1. Develop and pilot three 12-hour work-based curriculum units addressing important content standards	SRI codesigns with teachers from 2–4 schools (at least one rural, all majority high-need students) to create three curriculum units that • Are based on a real workplace scenario using 3D digital fabrication • Address standards from grades 6–8 math: ○ Volume ○ Scaling/ratio/proportionality • Address spatial reasoning skills • Address computational thinking practices • Support teachers' ease of implementation	An expert panel (workplace, math, CT) reviews the curriculum and rates it "excellent." Observations and interviews with pilot teachers reveal they were able to use the materials easily.
2. Train and support teachers to implement this curriculum with fidelity, using a 4-day workshop and just-in-time professional development activities	SRI designs and delivers a 4-day workshop for pilot and treatment teachers covering • Pedagogical content knowledge • Curriculum implementation • Technical expertise • Work-based learning principles. Teacher use just-in-time PD for: • Using and troubleshooting technology • Teaching strategies supporting students' learning.	An expert panel (workplace, math, CT) reviews the PD plan and rates it "excellent." Observations of the workshop reveal that all 3 areas of knowledge were addressed, aligned with the plan. All pilot teachers and 90% of teachers in treatment schools attend the PD and use at least one form of just-in-time PD, as determined by project records.
3. Create mentor/mentee relationships between adults who use 3D printing in the workplace and middle school students to influence students' views of their future	SRI designs 2-hour online training for mentors to help them understand how to communicate with middle schoolers. Online training is delivered via the MPACT website. SRI designs structured supports for meaningful communications between mentors and students.	Mentors complete 2-hour online training. Mentors exchange weekly digital communication with small groups of students on student designs and mentors' workplace practices, as observable from the MPACT website. Digital communication results in revised student designs, as observable from MPACT website.
4. Implement the units: work-based curriculum that enables learning of important academic content and influences students' attitude about the workplace	Teachers implement curriculum to intended population. Students have opportunity to learn • Grades 5–7 math: ○ Volume ○ Scaling/ratio/proportionality • Computational thinking • Spatial reasoning skills. Students have opportunity to develop • Positive and concrete views of their future in the workplace.	Teachers implement curriculum with 6,000 students, at least at 50% of whom are in rural agricultural-area schools and all schools serve majority high-need students, as indicated in program records. The implementation fidelity survey and observations reveal that the curriculum was implemented with at least 75% fidelity.
5. Improve students' academic outcomes through curriculum	Increase student learning of mathematics content. • Volume • Scaling/ratio/proportionality Increase student learning of CT practices.	Increase the proportion of student population who meet or exceed grade 6–8 math proficiency standards on the Smarter Balanced Assessment by 10%. Increase student performance on spatial visualization assessment by 10%.

Goals	Objectives	Outcomes
	Increase student learning of spatial thinking skills.	Increase student performance on CT practices and skills assessment by 10%.
6. Improve students' attitudinal outcomes through curriculum	Improve student attitudes related to work.	Increase the proportion of students who agree or strongly agree to survey questions about positive attitudes towards work by 20%.

Management Plan

We have carefully budgeted the program by task, ensuring it can be accomplished on budget. The tasks have been scheduled to guide progress through the work, ensuring the program can be completed on time (Table 2).

Table 2. MPACT Schedule

	Activity	Responsibility
Ongoing	• Monthly team meetings—all activity reported on and feedback for improvement provided • Monthly implementation site check-ins to obtain feedback and ideas for improvement • Monthly project leaders meeting • **MILESTONE** Monthly report from AIR to SRI on project progress, with emphasis on critical improvement time periods such as when the curriculum is being revised.	Knudsen, Remold, Stevens, Walters, and all relevant staff
Year 1		
10–12/18	• Planning: interview and observe teachers, administrators from coastal region and other schools/districts involved. Gather data including mathematics achievement. • SRI chooses workplace setting (company) for unit. • SRI recruits workplace mentors for 2-4 pilot schools. • SRI, AIR, and SMCOE recruit codesign pilot teachers. • **MILESTONE** Teachers and mentors recruited, workplace setting chosen.	Knudsen, Remold, Stevens, San Mateo County Office of Education (SMCOE)
1–5/19	• SRI leads development of 3 curriculum units and experts examine curriculum, give feedback for improvement. • SRI develops website with resources for teachers, students, and mentors, plus communication methods. • SRI designs PD using pedagogies of practice framework to create activities that support curriculum implementation. • AIR designs instruments. • SRI trains workplace mentors. • **MILESTONE** Experts' review of curriculum materials complete. • **MILESTONE** Draft Instruments complete.	Knudsen, Remold, Stevens, Kim, Rafanan, Lara-Meloy, SMCOE
Year 2		
8–12/19	• Codesign teachers attend 4-day PD led by SRI development team • Pilot unit: ○ Teachers implement units. ○ SRI-AIR teams observe to detect revisions for continuous improvement. ○ SRI implementation support team troubleshoots and supports teachers. ○ Teachers use just-in-time PD. ○ Workplace mentors communicate with students weekly.	Remold, Kim, Rafanan, Lara-Meloy, Walters

	Activity	Responsibility
	• AIR pilots instruments with pilot classes. • SRI recruits workplace mentors for next 20 schools. • **MILESTONES** Pilot complete; workplace mentors assigned.	
1–8/20	• SRI, SMCOE, and AIR recruit implementation teachers—20 treatment and 20 control schools. • SRI revises curriculum and PD, gets expert review. • Expert reviews II complete. • AIR completes design and revision of instruments. • SRI delivers 4-day PD for teachers, in several workshops over summer. • SRI trains workplace mentors. • **MILESTONES** Final versions of instruments complete; training of teachers and mentors complete.	Knudsen, Stevens, SMCOE (recruitment); Kim, Rafanan, Lara-Meloy, Walters
Year 3		
8/20–5/21	• SRI maintains and monitors MPACT website. • Unit implementation: Grades 6–8 teachers in 20 schools use 15-hour curriculum, either over semester 1, semester 2, or shorter time period. ○ Teachers implement units. ○ SRI development team and AIR evaluation team observe to inform revisions. ○ SRI implementation support team troubleshoots tech and supports teachers. ○ Teachers use just-in-time PD. ○ Workplace mentors communicate with students weekly.	Remold, Rafanan, Lara-Meloy, Walters
6–8/21	• AIR gathers data from districts on standardized tests. • Preliminary analysis of data. • SRI revises units and PD. • Deliver 2-day follow up PD on revised unit. • **MILESTONES** Data analysis report complete; units revised; PD delivered.	Walters, Knudsen, Kim, Rafanan, Lara-Meloy
Year 4		
8/21–5/22	• SRI maintains and monitors MPACT website. • Unit implementation: 20 schools use 15-hour curriculum, either over semester 1, semester 2, or shorter period. ○ Teachers implement units. ○ SRI development team and AIR evaluation team observe to inform revisions. ○ SRI implementation-support team troubleshoots tech and supports teachers. ○ Teachers use just-in-time PD. ○ Workplace mentors communicate with students weekly. • AIR administers pre- and post-test and survey. • **MILESTONES** Curriculum implementation in treatment schools complete; instruments administered to students.	Remold, Rafanan, Lara-Meloy, Walters
6–12/22	• AIR performs data analysis. • SRI prepares materials and website for broader dissemination.	Knudsen, Kim, Rafanan, Lara-Meloy, Walters
Year 5		
	• SRI disseminates through conference presentations, a social media campaign, and in association with 3D printer companies. • AIR writes final reports and articles for peer-reviewed journals. • **MILESTONES** Final report and articles complete; curriculum and website disseminated.	Knudsen. Remold, Walters

Personnel

The SRI core team has more than 10 years of experience working together on projects involving curriculum and PD design. Their roles are well established, and they work well and efficiently together. Personnel background and responsibilities are listed below.

Jennifer Knudsen, the program director, will oversee all project activities and manage the project. A veteran curriculum and PD designer, as well as director of a series of projects on mathematical argumentation, she has led multimillion-dollar projects. Knudsen has been instrumental in the design of curriculum and PD that use technology to better serve all students.

Julie Remold, the program co-director, will lead the ethnographic data collection and analysis and co-manage the project. She has 15 years of experience studying STEM interventions in K-12 settings to contribute to the design of qualitative data collection and analysis used in the iterative design process. Since 2013, Remold has been leading research on the impacts of making and tinkering activities in a range of STEM education settings.

Hee-Joon Kim, the curriculum lead, will oversee the development team's creation of the units. A mathematics education researcher, she has worked on several government-funded and commercial projects where her main role has been to develop or evaluate standards-aligned innovative curriculum materials accompanied by dynamic technology for middle grade students.

Satabadi Basu, the computer science/computational thinking expert for the program, will work with Kim to ensure that CT standards are met. As a CS education researcher, she has worked on several government-funded research projects as well as commercial projects where her roles have encompassed designing and developing learning environments, digital tools, and assessments for fostering synergistic science and computational thinking practices.

Ken Rafanan, the technology and implementation lead, will oversee development of the MPACT website, which will contain all content for just-in-time PD and all digital communication among students, teachers, and mentors. He has over 12 years of experience and previously developed mathematics learning activities integrating design thinking and 3D printing for a large urban school district and a large commercial client.

Teresa Lara-Meloy, the professional development lead, will oversee the development team's design and delivery of the PD workshops. With 18 years' experience in mathematics curriculum and PD, she has designed workshops for small- and large-scale projects and led synchronous online activities. Lara-Meloy is co-principal investigator on a project investigating the differential affordances of dynamic mathematical representations for English learners.

Harriette Stevens, the school and district liaison, will lead SRI's recruitment and maintain relationships with schools over the project. As former director of the University of California's EQUALS program, she led statewide programs for equity in mathematics education and worked closely with state, district, and school leaders.

Kirk Walters, the director of program evaluation, will lead and manage AIR's evaluation of MPACT. A managing researcher at AIR, Walters has led rigorous evaluations of mathematics curriculum and professional development interventions, including large-scale experiments funded by the U.S. Department of Education's Institute of Education Sciences and the National Science Foundation (NSF).

San Mateo County Office of Education (SMCOE) provides services for schools and school districts in San Mateo County, which includes a rural coastal agricultural district. The SMCOE staff will recruit schools from the entire rural coastal region of California, including Santa Cruz and Monterey counties, working closely with those county offices of education.

About the Team's Principled Design Process

Through an innovative curriculum development process, we will bring together schools, business/industry, and curriculum designers in a partnership to design and implement standards-based curriculum based on what developers uncover in the workplace. Curriculum developers will conduct ethnographic studies in digital fabrication workplaces to aid in developing realistic scenarios and to uncover the mathematical concepts and reasoning and CT that workers use to accomplish tasks. These will translate into storylines in a project for students to take on. The mathematics of the workplace together with the mathematics of common state standards will indicate the mathematics opportunities to be built into the curriculum.

> Overall, we will be guided by the four-stage design research approach Reeves (2006) defined, with a phase in addition to Reeves, important to this project, in italics below: collaboratively identify and analyze problems, *understand the workplace context relative to the academic context*, develop prototypes based on theory and principles, and engage in iterative cycles of testing and refinement. Part of this work will be codesign: "a highly facilitated, team-based process in which teachers, researchers, and developers work together in defined roles to design an educational innovation, realize the design in one or more prototypes, and evaluate each prototype's significance for addressing a concrete educational need" (Penuel, Roschelle, & Shechtman, 2007, p. 53)

Performance Feedback and Continuous Improvement

Several mechanisms for feedback and continuous improvement are built into our project (see Table 2). First are the monthly project meetings that all relevant staff will attend. As appropriate, project evaluator AIR will give feedback to the SRI teams, particularly on implementation issues, based on data it is collecting and report on its progress on the evaluation. The project leads will also give each other feedback, working closely together. Second, a panel of experts will review the curricular materials at two points when improvements can be made. Finally, project leaders Knudsen, Remold, Walters and Stevens will meet monthly to assess progress, decide on any process improvements, and assign responsibility for making them. This will be critical during school recruitment.

Dissemination of Information from the Project

The project will result in a complete, polished package of curriculum materials, PD plans and materials, and an easy-to-implement website template. These components will be available as OER content, increasing the likelihood of replication of MPACT at a variety of sites. Curriculum adoption is a widely recognized form of replication in education. CS materials for middle school are in demand, as preludes to high school materials such as *Exploring Computer Science*. That content is OER, however, does not guarantee its use. We will explore successful OER mathematics curriculum strategies, including working with a nonprofit distributor. We will also establish a dissemination website that will be maintained after the project ends. We will present at conferences relevant to mathematics and CS educators and leaders, and our use of social media will result in dissemination to an even broader audience. Additionally, we will consider 3D printer manufacturers to distribute the curriculum. At $500 for a hobbyist's 3D printer and prices ever lowering, these machines are within reach of most schools, even those with fewer resources than most suburban schools. The MPACT website will feature ways to obtain grants for printer purchases.

AIR will produce reports, conference presentations, and papers for peer-reviewed journals on the project outcomes, which, if positive, will lead to wider dissemination of MPACT materials.

C. Project Evaluation Plan

As independent evaluator, AIR will provide formative and summative information throughout the 5-year project. The proposed evaluation team consists of AIR experts who have successfully led experimental and quasi-experimental evaluations of interventions designed to improve math teaching and learning, and they will conduct an efficient, high-quality evaluation in two main phases. The formative phase will augment SRI's development and continuous improvement of the MPACT intervention. The summative phase will measure the implementation and impact of the MPACT program and is designed to meet What Works Clearinghouse (WWC) evidence criteria, with reservations. (During proposal development, AIR, SRI, and SMCOE discussed the feasibility of a school- or teacher-level random assignment study that, if successfully executed, would meet WWC standards without reservations. SMCOE thought the quasi-experimental design would be much more feasible, based on its prior research-related activities across the county.) The project's diverse sample of schools and teachers and rich repository of implementation data will be used to guide the replication of this innovative intervention in other contexts.

Formative evaluation phase. During the first 2 years of the project, AIR will provide SRI will supplemental information to support the ongoing improvement of each component of MPACT as it is being piloted. The formative research questions will address (1) teacher and administrator perceptions of the relevance, coherence, and feasibility of implementation of the PD supports, curriculum units, and project-based design tools; (2) mentor and mentee perceptions of the integration of the 3D printing workplace component with the middle school math curriculum; and (3) pilot participant recommendations about how to maximize the engagement and participation of administrators, teachers, and students as the full intervention is implemented.

These data collection activities will not only support the ongoing improvement of MPACT, but also allow AIR to develop, refine, and finalize the implementation fidelity and quality measures to be incorporated into the summative evaluation. In prior collaborations with developers of multifaceted interventions similar to MPACT, AIR has co-constructed implementation indices that indicate relevant thresholds of use for each facet of the intervention and for the program overall and used them to further investigate which metrics are most strongly associated with student achievement. AIR will also finalize the design for the impact evaluation during the formative phase of the project. This work will involve finalizing the summative teacher and student measures to be used and identifying an appropriate matched set of comparison schools using district and school administrative records.

Summative evaluation phase. The summative evaluation will occur during the last 3 years of the project, with data collection in years 3 and 4. Three research questions aligned with MPACT's logic model and project goals will guide this phase (Table 3). The first and second questions address the effects of MPACT on teachers' mathematics knowledge and attitudes toward teaching mathematics and the effects on students' mathematics achievement and attitudes towards learning math and work in the future. The third question focuses on assessing implementation fidelity and quality.

The summative evaluation will incorporate multiple sources of data and established, psychometrically sound measures (see Table 3).

Table 3. Evaluation Questions, Outcomes, Data Collection Tools & Measures

Research Question	Outcomes	Data Collection Tools & Measures
RQ1. What is the effect of MPACT on middle school teachers' math content knowledge, pedagogical content knowledge, and attitudes toward teaching mathematics?	a. Teachers' math content knowledge and pedagogical content knowledge b. Teachers' attitudes toward teaching mathematics	a. Mathematical Knowledge for Teaching assessment (Hill et al, 2008) b. Teacher surveys
RQ2. What is the effect of MPACT on students' spatial reasoning skills, mathematics achievement, CT learning and attitudes toward work in the future?	a. Student learning of CT b. Students' mathematics achievement c. Students' spatial reasoning skills d. Students' attitudes toward work in the future	a. Purdue Spatial Visualization Test (Guay, 1977) b. Smarter Balanced Assessments; study-created assessment c. AIR-made assessment

Research Question	Outcomes	Data Collection Tools & Measures
		d. Student surveys
RQ3. To what extent is MPACT implemented as intended?	Implementation fidelity and quality	Observation protocols; teacher & mentor surveys; teacher logs

Implementation Measures. AIR will observe the summer PD, follow-up PD sessions, and lessons from each of the three curricular units to measure implementation fidelity. The observation protocols will capture the extent to which planned agendas and course objectives matched what was delivered, as well as participant and student engagement. For the curriculum units, MPACT teachers will be video recorded to allow for in-depth analyses of implementation by AIR math education experts—e.g., the extent to which the mathematical content is clear and integrated with the work-based activities. All the summer trainings, two lessons for each MPACT teacher and a random sample of the follow-up PD sessions will be observed. AIR will determine implementation fidelity through observation protocols and surveys used in prior experimental and quasi-experimental studies, adapted as needed.

Outcome Measures. To measure math teachers' content and pedagogical content knowledge (Ball, Thames, & Phelps), AIR will create an assessment using items from the Mathematical Knowledge for Teaching assessment (MKT), a validated instrument that has been widely used in research settings over the past two decades (Hill et al., 2008; Learning Mathematics for Teaching, 2006). The items will come from two validated MKT forms, Number and Operations and Geometry, which align with the content domains of MPACT. AIR will also collect survey information on teachers' attitudes toward the mathematics and mathematics teaching and learning, as well as information on computer elective courses and work-based learning opportunities available for students to describe the service contrast between MPACT and non-

MPACT schools. AIR will create this survey from validated instruments used in prior studies (e.g., two relevant NSF-funded projects AIR has led).

Three assessments will be administered to measure student learning. The Purdue Spatial Visualization Test: Visualization of Rotations (Guay, 1977) will assess students' spatial visualization skills. This test has been used to predict student success in STEM learning (e.g., Gimmestad, 1990; Sorby, 2009). The other two tests are assessments of middle school math achievement. The first is California's state test, the Smarter Balanced Assessment. Grade 6–8 students' math scaled scores and achievement levels will be used. The customized test will more narrowly assess 3D geometry, ratio and proportional reasoning, and computational thinking—the three domains most closely aligned with MPACT. AIR will construct the assessment with validated items, including a bank that AIR assessment experts developed that has been used in summative state assessments. The student survey will include validated measures of engagement, motivation, and confidence in learning mathematics as well as measures of students' perceptions of future careers in STEM.

Evaluation design that meets WWC standards with reservations. In the impact evaluation, AIR will use a propensity-score matching (PSM) approach designed to meet WWC standards with reservations. The evaluation will examine outcomes for math teachers and students after 1 and 2 years of implementation (Years 3 and 4 of the project). MPACT is estimated to reach 60 teachers in 20 schools in San Mateo, Santa Cruz and Monterey Counties, an average of three grade 6–8 teachers and 150 students per school—a total of 3,000 students in each cohort.

AIR will use administrative records from 23 districts in San Mateo, Santa Cruz, and Monterey Counties to create a matched sample of 20 comparison schools that are not offering

MPACT but are otherwise similar on key characteristics; to the extent possible, matching will occur within each district.[1]

These characteristics include school size, pre-intervention student achievement in math and reading, and the proportion of economically disadvantaged students, students of color, and English learners. AIR will evaluate the quality of the matching by examining whether the matched treatment and control group means for each measure included in the matching process are within 0.25 standard deviation of each other (the baseline equivalence threshold to meet WWC standards with reservations). If the differences are greater than 0.25 standard deviation, AIR will refine the matching approach to achieve a baseline equivalence acceptable to meet WWC standards with reservations.

Using the final analytic samples of MPACT and comparison schools, teachers, and students, AIR will address each impact research question separately for Year 3 (the first cohort) and Year 4 (the second cohort). An intent-to-treat multilevel regression model will be used to estimate the relationship between treatment status and each outcome while controlling for school characteristics to allow for residual covariate adjustment (beyond matching procedures). The model will account for the nesting of students within teachers and within schools.

To answer the first research question, the effect of MPACT on teachers' knowledge and attitudes, MPACT teachers' average MKT scores and survey scores will be compared with control teachers'. The study is powered for a minimum detectable effect sizes (MDES) of .52 for

[1] In addition, the matching approach assumes schools will implement the treatment for grades 6-8. If some schools choose to implement the treatment in only one or two grades, the matching will be based on the participating grade levels.

each teacher outcome in each cohort. This effect size is consistent with findings from other studies that have used math teachers' content knowledge as an outcome (e.g., Garet et al., 2016).

To answer the second research question, the effect of MPACT on students' spatial reasoning skills, math achievement, and attitudes, AIR will compare scaled achievement and survey scores of MPACT students and students in control schools. The MDES for each student outcome is 0.17.[2]

Implementation and replication. To supplement the impact analyses and to provide guidance for how MPACT might be implemented in other settings, AIR will analyze the multiple sources of implementation data—observation data, teacher and mentor surveys, teacher logs (see Table 3). In collaboration with the SRI development team, AIR will produce an index describing critical thresholds of implementation by fidelity domain (e.g., PD) and indicators within each domain (e.g., teacher attendance, hours of participation). This practical index will be available for other districts and schools to consider as MPACT becomes more broadly available. AIR's exploratory impact analyses will also examine whether and how the effects of the program vary by school context. This information could also help other districts and schools determine the conditions that best support future implementations of the program. An additional exploratory analysis will lend insight into the promise of the MPACT community 3D printing events, through analysis of a survey of participants.

[2] Across both conditions and for each cohort, power calculations assume 40 schools, 120 teachers, and 6,000 students; for teacher outcomes: R^2 = 0.1 for level 1 (teachers) and 0.2 for level 2 (schools); ICC = .05; for student outcomes: R^2 = 0.5 for level 1 (students), 0.7 for level 2 (teachers), and 0.8 for level 3 (schools); ICC = .10 for levels 2 and 3.