Where Is the "E" in STEM for Young Children?
Engineering Design Education in an Elementary Teacher Preparation Program

Daniell DiFrancesca
Carrie Lee
North Carolina State University
Ellen McIntyre
University of North Carolina at Charlotte

Science, Technology, Engineering, and Mathematics (STEM) education initiatives in the United States have surged as the demand for high-quality STEM education has escalated (Nadelson, Callahan, Pyke, Hay, & Schrader, 2009; Parry, 2011). Despite the recent attention to improving STEM education for our students, both the Programme for International Student Assessment (PISA) and the National Assessment of Educational Progress (NAEP) still show our country's scores falling behind those of other nations (Epstein & Miller, 2011; Provasnik et al., 2012). Elementary students, in particular, are often underexposed to high-quality mathematics, science, engineering, and technology instruction, even though we know how important this exposure is to their achievement and future interest in STEM fields (Nadelson et al., 2009; Parry, 2011).

Certain initiatives, as a means of improving STEM education and increasing the number of individuals who enter STEM careers, focus both on K-12 students and teachers. Indeed, some teacher preparation programs select candidates who are already interested in these careers or who are lateral-entry professionals with STEM experience (Epstein

Daniell DiFrancesca and Carrie Lee are Ph.D. candidates in the Department of Curriculum and Instruction at North Carolina State University. Raleigh, North Carolina and Ellen McIntyre is a professor and Associate Dean of Academic Affairs at the University of North Carolina at Charlotte. Their e-mail addresses are ddifran@uncu.edu, cwlee5@ncsu.edu, and emcinty@uncc.edu

& Miller, 2011). Some teacher preparation programs focus on increasing candidates' science and mathematics content knowledge, and other initiatives focus on improving the mathematics and science teaching of in-service teachers (Borko, 2004; Radford, 1998; van Driel, Beijaard, & Verloop, 2001; Walker, 2007). These initiatives, however, continue to focus on mathematics and science alone, only two components of STEM education.

The goal of this article is to present a description of how one STEM-focused elementary teacher preparation program (K-5) incorporates *engineering*, the often-neglected component of STEM education, in an appropriate, meaningful, and substantial way. We begin with a discussion of engineering and the engineering design process that is incorporated in this STEM-focused elementary teacher preparation program. We follow this with a brief description of the program and its goals. Pertinent reflections from graduates of this program are included to exemplify the program goals. Finally, we conclude with a discussion of future research designed to evaluate the impact of this engineering component and provide recommendations for elementary teacher preparation programs that hope to expand their STEM focus.

Engineering in Elementary Education

Engineering is the practical application of scientific knowledge to solve everyday problems. While engineering fields are incredibly diverse, perceptions of careers in engineering in elementary education are limited to mechanics, laborers, and technicians (Capobianco, Diefes-Dux, Mena, & Weller, 2011). This limited exposure to engineering concepts prevents elementary students from developing an accurate understanding of what engineering entails and, therefore, from pursuing engineering careers (Capobianco et al., 2011; Rockland et al., 2010). These attitudes and limited understanding can potentially be improved by introducing young students to engineering and allowing them to engage in the practices of engineers.

The newly released Next Generation Science Standards (NGSS; 2013) highlight the importance of engineering in elementary school classrooms. By adopting the National Research Council's (NRC) broad definition of engineering, "any engagement in a systematic practice of design to achieve solutions to particular human problems" (NRC, 2012, p. 11), NGSS was able to incorporate both engineering practices and design into the standards. The eight science and engineering practices create an important distinction between investigating through scientific inquiry and problem solving with engineering design. This prevents engineering practices from being completely absorbed by common science practices. Further, the standards identify how engineering can be incorporated into science instruction. Additionally, NGSS includes a three-step engineering design process with indicators for different age groups (K-2, 3-5, 6-8, and 9-12). The emphasis on engineering in these new science standards highlights both the importance of engineering and the drive to ensure that even young students are exposed to the field and basic concepts of engineering.

Young children can engage in the practices of the engineering field through solving problems using the engineering design process. According to the NRC (2012) framework, this process is key to helping students to learn about engineering, which then increases their interest in the field. NGSS (2013) introduces a three-step engineering design process (Define, Develop Solutions, Optimize) for students, but other models have also been used in engineering education. One popular elementary engineering curriculum is the Engineering is Elementary (EIE) Program, which uses a five-step approach, described below, to lead students through the engineering design process (Cunningham & Hester, 2007). EIE's model is advantageous for elementary programs not only because of its wide adoption, but also because it uses simple terminology and scaffolds students by breaking down the steps. The three-step model developed for NGSS identifies the same major steps but does not provide the same level of support for K-5 students. Due to these differences, the EIE five-step engineering design process has been adopted by the STEM-focused elementary teacher preparation program described in this article.

The Engineering Design Process

The teacher educators in the STEM-focused elementary program teach candidates the EIE model (Cunningham & Hester, 2007), which has a cyclical, five-step process that leads students to:

1. Ask (define the problem and identify constraints);
2. Imagine (brainstorm ideas and choose the best one);
3. Plan (draw a diagram and collect materials);
4. Create (follow the plan and test it);
5. Improve (discuss possible improvements and repeat steps 1-5).

By following the steps, using additional scaffolding when needed, children are engaged in the problem-solving process that is at the heart of engineering design. These five steps are simple enough that even lower elementary school students can be actively involved in the engineering process (Cunningham & Hester, 2007).

Gerlach (2010) provided an example the application of this process in an engineering design challenge with his fifth grade students. He begins by engaging students with a video of how planes and other machines fly and provides them with background knowledge for their design process. He introduces the steps of the engineering design process that the students will use and provides them with the challenge (Ask): From the provided materials, build an X-plane that travels the farthest distance. Students work in pairs, beginning their design phase by making and experimenting with a paper plane (Imagine). Students take initial measurements as a means to set goals and use graph paper to plan and design their plane using various materials, such as Styrofoam lunch trays, paper clips, pencils, plastic knives, scissors, and toothpicks (Plan). This inquiry activity encourages students to imagine multiple ways to reach their goal before choosing a design to build. Additionally, they must explain their design and reasoning to their peers before they begin building. Once the model is built (Create), students engage in a cyclical process of test, redesign, and recreate to refine their model, while also noting changes on their drawing (Improve). Before the final test flight, students explain their model to the class, using the correct flight terminology that was introduced in the video and expanded upon during the design/redesign phase.

Continued exposure to and application of the design engineering process, as described above, has been observed to increase motivation for problem solving and discovery learning in elementary school students (McGrew, 2012). The engineering design process, however, is rarely adopted as a regular part of classroom lessons. Sporadic exposure to unconnected engineering design projects can seem disjointed and prevents students from adopting this process. Additionally, it is possible to use the engineering design process as a vehicle for teaching mathematics and science content (McGrew, 2012) by making explicit connections to the conceptual knowledge that the children should gain and by helping them to see the link between exploration and learning. For example, modeling of mathematical ideas is heavily emphasized in the Common Core State Standards for Mathematics, and this process can be enhanced through the use of the engineering design process. The engineering design process will aid students as they engage in modeling in which they "routinely interpret their mathematical results in the context of the situation and reflect on whether the results make sense, possibly improving the model if it has not served its purpose" (National Governors Association, 2010). Because teachers receive little preparation for teaching engineering processes to their students and often lack training on using these processes to help students learn content, these connections to learning are often nonexistent. Exposing students regularly to the design engineering process through integrated lessons is key to increasing student motivation and efficacy in mathematics, science, and engineering. Our STEM-focused program's inclusion of engineering design tackles this challenge by improving teacher candidates' understanding and use of the engineering design process.

Overview of ATOMS: A STEM-Focused Elementary Education Program

ATOMS,[1] which stands for Accomplished Teachers of Mathematics and Science, is a STEM-focused elementary education program that encompasses rigorous general education courses, innovative methods courses that are conceptually focused, extensive field work aligned with coursework, and program coherence (McIntyre et al., in press). As part of their General Education Program (GEP), the elementary education pre-service teachers (also called "candidates" in this article) are required to take 27 credit hours of coursework in STEM content before being admitted into the teacher preparation professional courses. While most of these credits are in mathematics and science, elementary candidates also are required to take one GEP course that focuses on the "E" in STEM. Teacher candidates select one of two introductory engineering-based courses: Materials in Engineering, a course offered by the College of Engineering for non-engineering majors, or Design Thinking, a course taught by the College of Design, a requirement for all students in that college. Both courses provide teacher candidates with a basic understanding of engineering as a field and an introduction to the engineering design process.

After successful completion of their GEP, the candidates begin their professional courses in their junior year, which include two mathematics methods courses, two science methods courses, and one engineering design methods course. These courses are taught by elementary education department faculty who specialize in the respective content areas. The faculty member who teaches the engineering education methods course has a joint appointment in the College of Education and the College of Engineering. The fall methods classes focus on preparing teachers to teach in Grades K-2, and spring courses focus on preparing teachers to teach in Grades 3-5. During the two semesters of methods courses, teacher candidates also are in a field placement site where they observe their cooperating teachers and teach several self-designed lessons throughout the year. In the fall semester, teacher candidates are placed in a kindergarten, first, or second grade classroom. Similarly, the spring semester field placements are third, fourth, or fifth grade classrooms. Student teaching spans the entire senior year, with students placed in classrooms for two half-days per week during the fall of their senior year and full-time during the spring of their senior year. During the senior year of student teaching, candidates are placed in a single classroom with one cooperating teacher.

The Engineering Design Methods Course

The engineering design methods course, Children Design, Create, and Invent, was created in an effort to build on the candidates' foundational understanding of the engineering design process initiated in the GEP course (either in the Engineering or Design Colleges). This methods course is taught by an engineer whose work focuses on education, especially of young children. The course emphasizes the relationship among science, technology, engineering, and mathematics by engaging students in analyses of educational standards in these fields and the creation of integrated, standards-based learning activities. Teacher candidates practice inquiry-based, developmentally appropriate pedagogy and technology to teach children engineering, mathematical, and scientific concepts and guide them through the engineering design process. Both technology and the engineering design process are infused into the strategies used within the class, which include group lab work, electronic communication, portfolio submissions, inquiry activities, and a culminating integrated lesson project.

As described earlier, the incorporation of engineering concepts in the preparation of teachers of young children poses a challenge for teacher preparation programs that have traditionally focused on the classic subject areas of reading, mathematics, social studies, and science because the incorporation necessitates a redesign of the program to incorporate these critically important concepts and skills. Scholars (e.g., Bagiati, Yoon, Evangelou, & Ngambeki, 2010) have lamented the lack of early exposure to engineering concepts for young children and have recommended that teacher candidates be exposed to these concepts, not only to improve their own understanding but also to highlight the relevance of engineering for young students.

ATOMS seeks to train candidates in engineering pedagogy through this process. This critical component of the STEM-focused program has three major goals for these prospective elementary teachers. First, the program is designed to help pre-service teachers make connections among engineering design, and mathematic practices (e.g., modeling), and science practices (e.g., inquiry). Second, the program aims to help pre-service teachers to create integrated STEM lessons by incorporating the engineering design practice into mathematics and science lessons.

Third, this exposure to and practice with the engineering design process works to improve pre-service teacher candidates' attitudes toward engineering in the hope that they will value engineering and expose their future students to this neglected component of STEM.

Connections among Engineering Design, Mathematics Practices, and Science Practices

One of the effective ways that the ATOMS program attends to the engineering component of STEM education is through purposeful incorporation of the engineering design process in each of the mathematics and science professional methods courses. Often, mathematics and science take over the focus in the interdisciplinary approach to STEM (Brown & Borrego, 2013). The ATOMS program's explicit attention to the inclusion of engineering design components in mathematical processes and scientific inquiry attempt to counter this practice. The idea is that, by providing details on the analogous nature of the three disciplines within the methods courses, candidates not only gain an understanding of the engineering design process but also come to understand mathematics and science more deeply as well.

Within the mathematics methods courses, for example, teacher candidates discover how the engineering design process is interwoven into the Common Core State Standards content and practice standards (National Governors Association, 2010). Teacher candidates engage in class activities to define and exemplify the practice standards, and, within this context, alignment with engineering design processes are made visible. For example, Practice Standard 1, "Make sense of problems and persevere in solving them," is presented as analogous to the engineering process as students consider problems (Ask), monitor and evaluate their strategies (Plan), and revise their strategies to reach a solution (Improve).

Another example of alignment with the engineering design process is the prominence of attention to discourse within the methods courses. Practice Standard 3 of the CCSS-M states that students should be able to "construct viable arguments and critique the reasoning of others." To address this standard, teacher candidates learn strategies for how to promote student questioning and explanation in the method courses. This focus parallels the elements of communication and dissemination of solutions within the engineering design process (Improve). The process of finding the solution and the justification for the process is just as meaningful as the solution itself. As teacher candidates begin to understand how the practices outlined for mathematics instruction are analogous to the processes outlined for work within engineering, stronger connections are made between the two fields. Teachers can more readily utilize engineering concepts to guide their mathematics instruction when they are taught to make connections between engineering processes and mathematics instructional practices (Brown & Borrego, 2013).

Further, the ATOMS mathematics methods courses emphasize how the engineering design process is foundational in strategic instructional sequences. Educators teach using an instructional sequence outlined in cognitively guided instruction that places student thinking at the forefront and models how students must construct their own "invented strategies" for solving problems (Carpenter, Fennema, & Franke, 1996). This progression is intended to help students understand mathematics by creating and revising their own strategies for problem solving, just as Imagine and Improve are used within the engineering design process. The goal is to increase students' flexibility and efficiency in their problem solving, which revamps the traditional sequence of direct strategy instruction and repetitive practice for student mastery. Through examination of student work and reconstruction of their own problem-solving processes, teacher candidates are able to internalize why the design process is so important for conceptual understanding.

In science education, a primary goal for teacher candidates is to understand and implement inquiry-based science practices while also increasing their understanding of science concepts. The ATOMS program values inquiry-based learning, defined as "a process where students are involved in their learning, formulate questions, investigate widely, and then build new understandings, meanings, and knowledge" (Towers, 2010, p. 246). Inquiry-based teaching serves as the foundation for both science methods courses. A significant part of the ATOMS science methods courses includes addressing the eight NGSS (2013) connections between science and engineering practices: asking questions, planning and carrying out investigations, analyzing and interpreting data, and engaging in arguments from evidence, which align with traditional inquiry practices. These inquiry practices also closely align with the steps in the engineering design process. Lewis (2006) further compares the engineering design process with the scientific inquiry process, noting that both are used to answer questions. While the engineer uses a prototype to test predictions, the scientist uses experimentation. The engineering design process asks students to analyze results from testing their designs, similar to the inquiry process's focus on evidence in argumentation. Explicit attention to these similarities helps teachers to make connections to engineering processes and to find ways to bring engineering into their classrooms. The ATOMS program's science methods courses capitalize on these similarities, which helps pre-service teachers to understand how to use the engineering design process to teach science content.

The emphasis on connecting mathematics, science, and engineering practices in the ATOMS methods courses is essential for pre-service teachers to understand the importance of engineering for young students. Because the engineering design process aligns so well with both mathematics and science practices, it is the perfect vehicle for helping pre-service teachers to see the value of including engineering in their classes.

Opportunities to Practice Integrating Engineering Design

An essential part of the ATOMS program is the opportunity for pre-service teachers to practice integrating the engineering design process into other content areas and then to use these lessons while student teaching, which leads to more effective teaching practices (Ball & Forzani, 2009; Capraro, Capraro, & Helfeldt, 2010). While the candidates are taught about the interrelated fields within STEM and the analogous processes among engineering, mathematics, and science, as described above, the candidates also are taught that integration of these fields can be an efficient way to teach. Elementary teachers often feel pressured for time in their already overloaded instructional schedules. While some elementary schools offer science enrichment courses that allow for time to be spent on engineering design, many schools are not able to. The ability to integrate multiple content areas is efficient and sometimes is the only way that teachers are able to incorporate topics such as engineering into their lessons. In any case, pre-service teachers need an opportunity to practice creating integrated lessons and implementing them in classrooms to make this a frequent practice in their future instruction.

ATOMS teacher candidates begin fieldwork in local elementary schools during their sophomore year. While coursework provides a theoretical foundation with content and pedagogical knowledge, fieldwork is often cited as the experience with the most impact for teacher candidates (Darling-Hammond, 2009; Feiman-Nemser, 2001). It is while pre-service teachers are implementing lessons in the classroom that they truly grapple with their instructional choices. Initially, the ATOMS methods courses focused on students' making connections between the engineering design process and mathematics and science practices. However, it became clear from student reflections that pre-service teachers needed more opportunities to design integrated lessons. For example, in a program evaluation reflection, one teacher candidate reported designing an integrated unit on air and weather. She was able to successfully integrate the science standards with the engineering design process and tied this success to the activities and experiences in the engineering course:

> It was good . . . that we did engaging, hand-on activities. For instance, my big unit is air and weather. We took a few examples of lesson plans that we had been shown in our engineering class and also one of our science classes, so we had the kids engineer sails, and they were able to realize the wind has to catch for the sail to make it go farther. They realized a flat piece of paper would not work so they'd have to go back and revise it.

This teacher candidate was aware of how to integrate the engineering design process within her science lesson to help students become more autonomous in the learning process. The students were planning, creating, and improving their vehicle structures and learning about the effects of wind and resistance. While this example is exciting, it became clear that more explicit practice should be made available so that all ATOMS teachers could integrate engineering into their lessons.

To address this need, the ATOMS program instructors designed an integrated STEM lesson assignment that asked teacher candidates to create a lesson in which their elementary students designed a labyrinth and tested several mathematical and sciences concepts with their design. (This assignment is described in more detail in Carrier, Faulkner, & Bottomley, submitted for publication.) This experience allowed teacher candidates to see the challenges that they could face with integrated lessons and provided a structured opportunity for candidates to collaborate with peers on how to overcome these issues. The ATOMS program reinforces the importance of integrating the engineering design process within other content areas by modeling this behavior in all of the required methods courses. Notably, ATOMS addresses concerns that teacher preparation programs are plagued by superficial pedagogy, disconnection among courses, and a lack of organizational themes and goals (Feiman-Nemser, 2001; Hollins, 2011).

Attitudes and Opinions toward Engineering Design

A critical goal of the engineering design course is to improve preservice elementary teachers' attitudes toward teaching engineering. Research has shown that efficacy and confidence are predictors of the ability to teach STEM content areas (Nadelson et al., 2013). When teachers are given the opportunity to learn more about these content areas and practice teaching these subjects to students, their efficacy and confidence increase (Nadelson et al., 2013). This improvement in attitude toward STEM can increase the time that teachers spend teaching these subjects and may help teachers to generate positive STEM attitudes in their students (Nadelson et al., 2013). By including coursework and a methods course in engineering, as well as explicit instruction on how engineering design can be integrated into math and science lessons, ATOMS aims to improve pre-service teachers' attitudes toward and confidence in teaching engineering and the design process.

Through program evaluation interviews with current and former students, evidence of ATOMS teachers' positive attitudes toward engineering was found. Many students believed that the course was valuable, and some even wished the program had offered more engineering classes. When asked what was missing from the program, one senior said, "More STEM classes . . . We had that one engineering STEM class; I would have liked to have seen more than just one." While this student noted wanting more STEM classes, she failed to see the math and science courses as part of the STEM courses. This speaks to the need for explicit connections to be made among the methods courses. A fellow program senior already had been able to use her engineering methods background as an advantage over other teachers:

> It really helps for us to have the STEM background, through the mathematics, through the science, and through the engineering; especially the engineering. . . . A lot of the teachers here [in her student teaching school] didn't know. They could do the science, they could do the mathematics, but they weren't really sure about the engineering, the creative aspect. . . . I have spoken at staff meetings about the engineering class that we took. That part of it is really nice and I feel like [I] definitely have a leg up compared to others, so I definitely think that it creates a STEM-focused teacher.

Program reflections also confirmed the rarity of one's observing engineering in elementary school classrooms. One alumnus stated,

> I enjoyed the engineering class with the different activities that were provided for us . . . but I don't feel like that kind of thing is going on in the schools really, right now. Not that it shouldn't, but how do we get it started?

Some candidates were fortunate to student teach in schools that focus on STEM education. "I really liked that we had our engineering course because [student teaching site] is adopting STEM, so that made us feel special because we knew all about the engineering, and that's something that no other elementary program really does." The candidates both noticed and cared about the lack of engineering design in their field placement schools, which shows that they value the engineering component of their education and want to incorporate this into their teaching. Improving attitudes toward engineering is essential to improving engineering education.

Implications and Future Directions

The goal of the ATOMS teacher preparation program is to educate elementary teachers so that they are skilled and confident in teaching all areas of the STEM curriculum, including engineering. The Children Design, Create, and Invent course is important to the ATOMS program and works to improve teacher candidates' attitudes toward the engineering design process and its appropriateness for elementary level students. To ensure that graduates value engineering and understand its relevance to the content they are teaching, ATOMS is taking the first step toward increasing understanding and skill in engineering in the elementary grades.

How can other teacher preparation programs learn from the ATOMS program? ATOMS can serve as a model for other elementary teacher preparation programs that wish to improve their teacher candidates' knowledge and appreciation of engineering. Further, while the methods course that we described above is important to us, we suggest that there are really only two essential steps that teacher preparation programs that wish to improve STEM teaching must take: (a) engage faculty or other entities focused on STEM content in the preparation of K-12 teachers, and (b) plan for a strong evaluation of your program.

Engaging Colleagues

Teacher education programs across the nation have long partnered with liberal arts programs within their universities in the teacher preparation process. Many professors of English, Biology, and Mathematics, for example, see themselves as teachers of teachers and may offer courses, direct advice to students, or even dedicate entire programs in their units to prepare K-12 teachers. This important change in recent decades is one answer to criticisms that teachers do not have the amount of content knowledge that is critically important for K-12 teaching success. Nevertheless, it is rare to see colleges of education's collaborating with engineering or design colleges. Professors in those areas often see their units as professional units as opposed to general education units and, thus, are not in the teacher education business. However, these colleagues can be persuaded to see themselves as contributing not only to stronger K-12 education but also to the preparation of students who may eventually apply to their programs (and actually be fully prepared for them!). We have persuaded colleagues to care about teacher education by appealing to them as parents and grandparents. We have asked, "Think of your own child's elementary teacher. Are you satisfied with his or her teaching of the physical sciences, engineering concepts, mathematics?"

Many professors in these disciplines know that elementary teachers can lack necessary content knowledge in these areas and may eventually see the need to help. It should be the job of educators to help all areas of higher education see their responsibilities to the K-12 world.

Even if colleges or universities do not have engineering or design colleges, teacher educators can and should find assistance from professionals with engineering backgrounds. There are many sources for this sort of professional development, including museums, companies, and nonprofit organizations. Many are thrilled to be asked and want to be part of a movement to improve their communities through educational outreach. It is our responsibility as teacher educators to form the necessary partnerships to provide the ever-important content knowledge essential for the preparation of a college curriculum in STEM areas. The ATOMS program builds on this critical content knowledge by making explicit connections to mathematics and science practices and providing teacher candidates with opportunities to design and implement integrated STEM lessons. If teacher educators expect their candidates to implement the innovative ideas taught in the preparation program during the candidates' induction years, the importance of explicit connections cannot be overstated. When explicit connections are missing, candidates struggle to see these innovative approaches as relevant to their classrooms. By creating collaborative, STEM-focused elementary teacher preparation programs, colleges and universities can overcome the current deficits in elementary engineering education.

Program Evaluation

The second necessary component to any successful teacher preparation program is a strong systematic evaluation of the program for the purposes of continuous improvement and public relations. While many programs have a continuous improvement goal as part of their accreditation process, our field has failed to promote our own success. This lack of self-promotion has led to a lack of proof that what we do matters. This, in turn, has contributed to recent public criticism of traditional teacher preparation programs.

The program evaluation of ATOMS focuses on candidates' responses to the program as well as documentation of practices in classrooms after completion of the program and an examination of their pupils' achievement in relationship to classroom practices. This longitudinal, developmental, value-added study is a comparative study of graduates of ATOMS with graduates of other teacher preparation programs. In this study, we will examine teacher knowledge, pedagogical content knowledge, efficacy, beliefs, instructional practices, and the achievement of pupils in the elementary classrooms studied. These forthcoming data will provide clearer evidence of the need for concentrated STEM work in the elementary teacher preparation programs.

Other sorts of evaluations can be designed based on program goals and resources. For example, anecdotal evidence of teaching practice and attitudes can provide an extremely useful foundation for teacher preparation programs to rethink aspects of the programs. Focus-group interviews of graduates of the programs can be especially revealing. Comments about the program, if positive, can be used on websites or promotional brochures to illustrate the program's strengths. Negative comments can be used to revise the program. No matter how the program evaluation is conducted, it has become increasingly clear that the need for communication about what happens in preparation programs is essential. Our field needs it, the teachers need it, and the many children who might one day enter STEM careers need it.

Note

[1] Project ATOMS is a National Science Foundation-funded project.

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