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Preliminary Considerations Regarding

Use of Digital Fabrication to Incorporate Engineering Design Principles in Elementary Mathematics Education

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The nation's need to foster advanced learning in science, technology, engineering and mathematics (STEM) is a fundamental challenge for education. President Obama (2009) recently addressed the National Academy of Sciences to call for an increased emphasis on hands-on learning to address this need:

"I want you to encourage young people to be makers of things, not just consumers of things."

The President concluded that the future of the United States depends upon our ability to encourage young people to "create and build and invent."

A position paper (Bull, Knezek, & Gibson, 2009) developed by the *Society for Information Technology and Teacher Education* (SITE) noted,

Engineering connections are largely absent in the current K-12 curriculum, but if done well could support greater student learning and interest in science and math....This strategy would mirror natural connections between engineering and the other STEM subjects (math, science, and technology) in the *real* world of research and development and technological innovation.

Subsequently, two technology association—SITE and the International Technology and Engineering Educators Association (ITEEA)—and two mathematics education associations—the Association of Mathematics Teacher Educators (AMTE) and the National Council of Teachers of Mathematics (NCTM)—began a joint exploration of methods for identifying natural connections between mathematics and engineering design in the elementary curriculum.

The working notes that follow offer a preliminary consideration of methods for employing an emergent technology—digital fabrication—as a mechanism for integrating the STEM disciplines in elementary classrooms and children's engineering as a pedagogical approach for doing so. Personal digital fabrication may lie at the heart of the next technological revolution. It can allow young people to create, build, and invent in the context of engineering design. However, successful implementation in schools will require thoughtful integration with the existing curriculum.

Background

The dialog on digital fabrication and children's engineering began at the eleventh National Technology Leadership Summit (NTLS XI) held January 2010 at Punahou School in Hawaii. The NTLS is sponsored by the National Technology Leadership Coalition (NTLC), a consortium of twelve national education associations. Leaders from NTLC associations participating in this summit included representatives from AMTE, SITE, and ITEEA (Bull et al., in press). This dialog was continued at an American Society for Engineering Education (ASEE) workshop on Elementary Engineering Education held at North Carolina State University in May 2010. A representative from the NCTM board also joined this continued discussion, addressing the broader goal of advancing STEM learning with children's engineering and digital fabrication at the center of an integrative approach to problem solving, analysis, planning, and innovation that draws on mathematics, science, and technology.

Digital Fabrication

Digital fabrication is the process of translating a digital design developed on a computer into a physical object. Neil Gershenfeld (2005) popularized this concept through Fabrication Laboratories at M.I.T. A *Fabrication Lab* is a center that allows individuals to design and make (almost) anything.

Personal fabrication systems that are the microcomputer equivalent of MIT's Fabrication Laboratories are now emerging. The next generation of personal digital fabricators now make digital fabrication in schools feasible and practical for the first time (Bull & Groves, 2009). Low cost, versatility, and ease of use make this technology accessible to K-12 educators and students and can facilitate the introduction of engineering design and manufacturing concepts into early education.

Taking a new concept from mind's eye to physical form can be fulfilling and motivating. Young students typically have not had the opportunity to see their concepts make the trip from an initial conceptual idea to a final physical form, components of the engineering design process (Bull & Groves, 2009). The advent of personal fabrication can allow students this opportunity for the first time.

Mathematics and Engineering Design

The National Academy of Engineering report, *Engineering in K-12 Education*, concluded that existing curricula do not fully exploit natural connections between engineering and the other subjects (Katehi, Pearson, & Feder, 2009, p. 156). The report recommended that engineering design be linked to mathematical analysis and modeling, noting,

Although mathematical analysis and modeling are essential to engineering design, very few of the curricula or professional development initiatives reviewed by the committee used mathematics in ways that support modeling and analysis. Despite the paucity of mathematics in most curricula, the committee believes that K–12 engineering education could contribute to improvements in students' understanding and performance on certain areas of mathematics. For example, numerical manipulations required for measurements and analyses associated with engineering design may, through exposure and repetition, increase students' confidence in their mathematical abilities. In addition, specific concepts, such as ratio and proportion, fractions, and decimals, are useful for a variety of engineering design projects. (p. 157)

Mathematics connections, in particular, are inherent in the design process as students develop mathematical models on a computer that are translated into physical objects that can be tested and analyzed. Mathematics provides an ideal context for engineering because (a) there are strong curricular connections, (b) mathematics is required at all levels, and (c) mathematics is an area of national concern.

The *Curriculum Focal Points* (NCTM, 2006) is an example of an existing set of guidelines for a mathematics curriculum for grades prekindergarten through 8. *The Curriculum Focal Points* emphasizes important mathematical topics as well as the role of mathematical processes. This development of mathematical topics and processes offers a coherent and cohesive approach to student learning that also reflects the necessary mathematics and processes required for student engagement in engineering design processes—especially in the area of digital fabrication.

Children's Engineering and Digital Fabrication

In a time of increased emphasis on assessment and testing, curricular constraints preclude addition of new content in the elementary grades. Conveniently, addition of new content is not necessary to promote engineering design via children's engineering given its interrelatedness to science, mathematics, and technology. In the elementary grades, children's engineering can be described as design under constraint, optimizing to a goal, with verifiable tasks that allow children to build a solution to an engineering problem. This approach offers opportunities for contextualized mathematics, suggesting the incorporation of engineering concepts that employ digital fabrication can be connected to existing mathematics content. Note that *engineering design* in the context of children's engineering is not a curriculum but rather a pedagogical approach to motivate learning.

Current research shows positive impacts from the integration of engineering design into elementary classrooms. Koch and Burghardt (2002) reported that engineering design can be readily used by elementary school teachers and, in particular, children with special needs benefit from this pedagogical strategy. Burghardt and Krowles (2006) found that engineering design strategies can help low performing fifth-grade students become more mathematically proficient and cause a significant positive shift in student attitudes towards mathematics. In a study with five middle school teachers and 60 students, Akins and Burghardt (2006) reported that engineering design was used to improve student mathematical content knowledge and disposition toward mathematics. In a subsequent study that included a comparison group, Burghardt and Hacker (2008) reported similar findings for a larger number of experimental students (p. 128). There were statistically significant improvements in student learning and disposition toward mathematics.

Thus, children's engineering in elementary education can incorporate mathematics learning in a summative task or it can motivate the learning of new mathematical or scientific ideas (provide a need for learning). However, effective implementation will require identification of seamless points of intersection with mathematics education. Mathematics educators at both pre- and in-service levels will be important partners in this endeavor to bring children's engineering into the elementary curriculum.

Objectives

Early studies (Burghardt & Knowles, 2006; Eisenberg & Buechley, 2008) suggested that integrating mathematics, science, and engineering in a highly motivating task that makes use of digital fabrication can facilitate learning, developmental skills, and student engagement. In order to realize this potential, it will be necessary to

1. increase elementary teachers' competence and interest in teaching STEM content, specifically the elementary mathematics relevant to engineering design, through introduction of digital fabrication in preservice and inservice teacher education and mathematics content courses, and

2. increase elementary children's understanding of mathematics in an applied context while simultaneously exposing them to ideas of engineering design.

Fulfilling these objectives can enhance the ways in which the STEM disciplines are approached in the nation's elementary classrooms and the ways teachers are prepared and supported to facilitate student learning and development in this new learning space.

Assessment

If engineering design is employed as a teaching pedagogy for developing mathematics content while implementing tools for digital fabrication, then new content standards for assessment are unnecessary. Existing assessment instruments and methods can be utilized to assess student understanding for those who make use of tools for digital fabrication. The ultimate goal is student achievement in mathematics, so all other measures are subordinate to that primary goal. Assessment could be centered around state, NCTM (2002)mathematics, or the upcoming Common Core standards.

There are also goals that deserve attention in assessment. Short-term goals that can be measured impact upon beliefs, motivation, and engagement. It will be difficult, but essential, to develop mechanisms for measuring longitudinal changes. Assessment of both pre- and in-service teachers' knowledge, beliefs, and actual teaching with regard to both engineering design principles and mathematics is also important.

Recommendations and Next Steps

Elementary teachers enjoy creating classroom materials, as evidenced by the popularity of books and resources related to bulletin boards and paper crafts, as well as the presence of mechanical die cutting systems in many schools. This level of engagement with creating materials can be used to introduce engineering design concepts and associated mathematical content. Elementary teachers' increased engagement with engineering and mathematics can, in turn, be used as a context for teaching effectively in an authentic context that elementary students may find appealing.

Teachers can potentially introduce engineering and mathematics to elementary students in an engaging context that will support the development of crucial attitudes, skills, and concepts that encourage and support interest in STEM-related careers. The infrastructure needed to support these objectives includes four essential components:

1. Digital Fabrication Hardware for the Classroom
2. Digital Design Software for the Classroom
3. A Digital Fabrication Library and Collaborative Space
4. A Curriculum that Incorporates Engineering Design Principles

Effective integration of children's engineering into the elementary curriculum will likewise require integration of related topics into teacher preparation programs and professional development supports necessary to implement an integrated curriculum with fidelity, together with the infrastructure outlined in the first three items. Engineering education and educational technology associations (ASEE, ITEEA, and

SITE) and collaborating colleges of engineering should provide leadership for development of appropriate hardware and software. Educational associations (AMTE, ASTE, and NCTM) should provide recommendations for appropriate steps for consideration of connections to existing learning content and process standards in consultation with engineering and technology associations.

Engineering and technology associations should collaborate with educational associations to explore ways in which design principles based on digital fabrication can successfully increase teachers' engagement with engineering, mathematics, and related competencies. This exploration should also examine ways in which increased teacher engagement and competence may produce a positive impact on students, boosting their performance and engagement with engineering and mathematics.

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Notes

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