FIE 2016 Special Session – Designing *The Engineer's Way*

Susan K. Donohue
Department of Engineering and Society
University of Virginia
Charlottesville, Virginia
susand@virginia.edu

Larry G. Richards
Department of Mechanical and Aerospace Engineering
University of Virginia
Charlottesville, Virginia
lgr@virginia.edu

***Abstract* – This special session will introduce participants to our method for supporting integrative learning about key science and math concepts via engineering design challenges. Engineering Teaching Kit (ETKs) are self-contained STEM education standards-based units grounded in the constructivist philosophy of education and the principles of guided inquiry and active learning. An ETK introduces P-12 students to real-world constraints engineers must consider in developing their designs such as budget, cost, time, risk, reliability, safety, and customer needs and demands. Finally, due to their inherent interdisciplinary approach, the use of ETKs also encourages the integration of other subjects in the curriculum, such as history and language arts, into lesson plans, leading to an efficient and reinforcing project-based learning environment.**

The featured design challenge is from our newest ETK, *Trash Sliders*. Students learn about force and motion while designing a vehicle with a suspension system that will allow the vehicle to navigate rough terrain while retaining its payload. The vehicle is constructed from every day items considered trash, thereby bringing considerations of sustainability and meta-recycling into the conversation. The ETK was purposefully designed to be low-cost and accessible.

This special session is for those interested in exploring a philosophy of engineering education that stresses an integrative, project-based approach to instruction and practice grounded in design, the fundamental process of engineering. This material will also be presented at the inaugural FIE K-12 Workshop.

Index Terms – Engineering design process, Engineering Teaching Kits, P-12 engineering education, STEM outreach.

I. INTRODUCTION

Engineering Teaching Kits (ETKs) are the means by which the Virginia Middle School Engineering Education Initiative (VMSEEI, now joined by *The Engineer's Way* [1]) connects and supports a community of informal and formal educators interested in using engineering design challenges to integrate and enhance learning in science, technology, and math. ETKs are self-contained standards-based instructional units grounded in the constructivist philosophy of education [2], [3] and the principles of guided inquiry and active learning [4], [5]. ETKs are designed to engage students in a series of age-appropriate engineering design challenges to reinforce targeted concepts in math, science, and technological literacy via project-based learning. These challenges provide the framework for this session's activities.

By the end of the session, participants will investigate age-appropriate expression (based on the participant's target audience) of the concepts of force and motion and related standards by working through the engineering design challenge presented in our newest ETK, *Trash Sliders*; reflect on key components of the engineering design process; and be able to identify methods for using engineering design activities to integrate various disciplines seamlessly and transparently in the curriculum as well as strengthening key "21st century skills" like systems thinking, critical thinking, and creative problem-solving.

II. MOTIVATION

In previous work, we have discussed why it is critical to incorporate engineering into the P-12 curriculum in previous work [6], [7]. Those reasons remain valid, as the number of challenges which engineers are uniquely qualified to address continues to proliferate in our technology-based society.

In this session, we will also discuss how to increase the visibility of engineering in precollege settings. It has been recognized that engineering may be "hidden" when it is used in science and math classrooms unless the discipline's emphases on distinct characteristics and activities such as problem solving, innovation, and design are stressed [8]. These emphases may also aid in truly "changing the conversation," leading to situations in which mentors encourage precollege students to study engineering because they are creative or good problem solvers or people who want to make a difference in the world. These traits are in addition to "being good at math and science" [9].

Based on extensive experience with local schools, we are dedicated to making engineering design activities affordable and accessible. Several of our recent ETKs use easily obtained and affordable materials such as Solo cups and recyclables. Realizing that cost can be a barrier to including engineering in the classroom, we will also discuss and model alternatives we have found to one-use, expensive kits in this session.

Finally, we appreciate that time for learning outside the normal curriculum is scarce in many schools. There are a number of reasons for this situation, including meeting state and national standards and preparing for testing. Combined, the continued need for professional development for both pre- and in-service teachers on STEM topics and the challenges of finding time, materials, and appropriate curricula provide a powerful argument for using a truly integrated approach to STEM in pre-college classrooms: it is a more efficient use of time and resources. ETKs are one method of realizing this outcome.

III. Our Cornerstone: ETKs

Since 2002, teams of students and faculty at the University of Virginia in partnership with local K-12 teachers have developed, tested, and distributed ETKs for use in science and math classes - initially in middle schools but now throughout K-12 [10], [11]. An ETK is a set of five 50 minute standards-based lesson plans designed to teach targeted math and science concepts in the context of the engineering design process. Lessons are structured to develop understanding of key concepts at both abstract and concrete levels.

The primary goal of ETKs is to promote awareness of and excitement about the nature of engineering. Each ETK emphasizes the engineering design approach to problem solving through a series of design challenges, and includes real-world constraints such as budget, cost, time, risk, reliability, safety, and customer needs and demands. Students develop an appreciation for the tradeoffs involved in the practice of engineering, and how engineering decisions have an impact on society, culture, and the environment.

Over 60 ETKs are in various stages of development; a dozen are in frequent use in schools in the United States and several other countries in both classroom and professional development workshop settings. The most popular ETKs are *RaPower* (solar cars); *Save the Penguins* (heat transfer); *HoverHoos* (hovercrafts); *Under Pressure* (submersible vehicles); *Brainiacs* (biomedical engineering involvement in the fight against cancer); *Catapults in Action* (projectile motion); *Bridges to Engineering* (bridge design and construction); *Harness the Wind* (formerly *Wind-E* – wind turbine blade design and alternative energy); and *Trash Sliders* (sustainability and vehicle design), our latest ETK and the one demonstrated in this session.

ETKs are designed to integrate other subjects in the curriculum with the exploration of STEM concepts. For example, an interdisciplinary team of eighth-grade teachers at a Central Virginia middle school used the *Catapults in Action* ETK as the basis for a week-long series of integrated classes on medieval history, thus folding history, art, and language arts activities into the study of catapults and projectile motion. The potential for similar multidisciplinary activities can be found in all ETKs and thus make them appropriate for use in STEAM programs.

Further, ETKs are designed to be adaptable and flexible. As previously stated, ETKs were initially developed for students in grades 6 – 8, but have been proven scalable for use by students at all grade levels by varying the amount of scaffolding and support given.

IV. Concepts and Standards Underlying ETKs

In Virginia, public school students in grades K-6 study various topics in the following subject strands as per the Science Standards of Learning [12; p. 1]

- Scientific Investigation, Reasoning, and Logic
- Force, Motion, and Energy
- Matter
- Life Processes
- Living Systems
- Interrelationships in Earth/Space Systems
- Earth Patterns, Cycles, and Change; and
- Resources

There are also standards for life and physical sciences for middle school students, and for earth science, biology, chemistry, and physics for high school students.

As can be expected, the majority of ETKs under development focus on the Force, Motion, and Energy subject strand since these ETKs are developed by 4th year capstone teams whose members are mechanical engineering majors.

The K-8 subject strands in mathematics, along with the grade-specific foci, will be discussed at the session. Middle and high school students in public schools, depending on the courses in which they're enrolled, will be subject to standards in algebra I – III, trigonometry, geometry, functions and data analysis, computer mathematics, probability and statistics, discrete mathematics, and mathematical analysis [13].

We also base ETK lesson plans and activities on standards from national groups and professional associations (e.g., Common Core [14], Next Generation Science Standards [15], and the International Technology and Engineering Educators Association [16]) and states recognized as the "gold standard" (e.g., Massachusetts [17]).

V. The Engineering Design Process

The engineering design process is at the heart of the discipline. ABET Student Outcome 3(c) directly addresses the need to know and apply the process. The cornerstone and capstone model, providing design education at the beginning and completion of the undergraduate engineering program, is widely used. Yet, we acknowledge that assessment of student learning in design classes is an admittedly difficult process and as a result, students may go through their undergraduate careers without having their misconceptions corrected, much less identified.

There are many models of the design process in use, but for they have several features in common: engineering design is problem-based and starts with the identification of a problem and research on that issue; a design space is defined; solutions are developed and evaluated; the best solution is selected for prototyping; and an internally iterative cycle of design-build-test occurs [17] – [22]; and, when a stopping rule is encountered, the artifact is reviewed to determine if it meets, within tolerances, expectations or whether the design team needs to re-enter the process at a phase appropriate to the amount of redesign that needs to occur. Throughout, there is communication among team members and with client(s) [23].

The design/build/test cycle part of the engineering design process is not limited to the production of a prototype; it also provides opportunities for creativity and exploration while reinforcing the iterative nature of the process. Failure is thereby supported and at times even encouraged, for learning comes from determining what doesn't work as well as what does. The key is to give students the opportunity to investigate improvements to their design.

Graphical depictions of our engineering design process, including the high-level, systems view of the process and our view of the design-build-test cycle will be presented at the session.

VI. Promoting Creativity Via ETKs

As described in [7], we are in the process of upgrading the basic ETK format to include information, instruments, and activities to aid in the identification and remediation of misconceptions; repositioning many ETKs to address societal problems; and developing guides that deliver concepts and design challenges in a condensed format. We are also investigating how to promote creativity in the design process. Creativity is vital to the process of innovation, and innovation is vital to meaningful and significant outcomes in virtually every profession and, eventually, to the ability of a society to be competitive locally, nationally, and globally. It is certainly central to the study and practice of engineering, a design-centric profession [24].

At this time, we are investigating the impact of the way in which participants are given instructions about the engineering design challenge. Anecdotally, we have noted over the years that if we did not provide participants pictures of the object to be built during the engineering design challenge portion of the ETKs that we tended to see very creative designs. This observation holds for all groups with which we work: K-12 students, undergraduates, and in- and pre-service teachers. Following on a previously reported research goal to determine ways to teach creativity [25], we consciously removed pictures of examples from our materials in 2015 and developed neutral terms to describe objects and processes.

In this work, we define as innovation or divergence from the expected in the design of the resulting prototype or artifact. Divergent thinking is one method of expressing creativity; the other main type of creative thinking is convergent, although various sources add logical thinking [26] and synthesis, analysis, and practical thinking [27].

Trash Sliders ETK [28]

Trash Sliders is the latest ETK to be placed in wide distribution. It has been rated highly by a diverse group of audiences: middle school students in the classroom, high school students in summer programs, and professional development workshops for P-12 educators. A primary reason for its success is the social context in which the lessons and activities are placed. It addresses the problems of trash and waste and the resulting environmental and social impacts, sustainability, and meta-recycling while engaging participants in a review of concepts of force and motion, an introduction to the design of vehicle suspension systems, and finally designing a vehicle that can transport materials without loss of payload over rough terrain.

The use of recyclable materials in designing, building, and testing the vehicle and the lessons on suspension systems, touching on springs and dampers, are the primary features distinguishing *Trash Sliders* from the myriad ETKs that have been developed over the years. The emphasis on sustainability and reuse align the lesson plans and design challenge well with recycling initiatives in many schools and communities. In addition, the recyclable materials help make this ETK affordable and accessible. Participant engagement can occur before the ETK is formally administered by having students bring in items used in vehicle design such as gallon jugs, 2L bottles, and bubble wrap.

In keeping with our research into promoting creativity using ETKs, we found that the variation in designs observed in all instances is incredible. By carefully crafting the instructions not to steer participants in a certain direction for their designs and not showing examples before the design challenge began, participant/student creativity shone through. They produced designs we never imagined.

VII. Session Agenda

The session is structured as follows:

- Welcome, Introductions, and Agenda Review (10 minutes)
- Initial Exercises (20 minutes)

  Participants will develop a plan to create their vehicle after investigating the available materials and concepts underlying a vehicle suspension system. The basics of force and motion throughout P-12 with respect to standards will also be covered.
- Regroup, Reflect on Lessons Learned, and Review of Important Discussion Points (15 minutes)
- Follow-on Activities (40 minutes)

Participants will work in groups with the facilitators to design-build-test their vehicles. We will also discuss scaling the design activity to various grade levels. This discussion will include a review of expectations as to cognitive development and skill levels for students in those grades.

- Concluding Activities and Discussions (5 minutes)

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AUTHOR INFORMATION

Susan K. Donohue, Lecturer and ENGR 1620 Academic Co-ordinator, Department of Engineering and Society, School of Engineering and Applied Science, University of Virginia, Charlottesville, VA, susand@virginia.edu. Her research interests include P-16 engineering education with an emphasis on design; development of skills important to success in the engineering profession, such as systems thinking, spatial skills, and creativity; and identification and remediation of misconceptions. She serves as the 2017 Program Chair for the American Educational Research Association's Constructivist Theory, Research, and Practice SIG.

Larry G. Richards, Professor, Department of Mechanical and Aerospace Engineering, University of Virginia, Charlottesville, VA, 434.924.3191, lgr@virginia.edu. His research interests include P-16 engineering education, engineering design and manufacturing, innovation, and entrepreneurship. He also leads the Virginia Middle School Engineering Education Initiative (VMSEEI).

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