FIE 2015 Special Session – *Movin’ Along*: Investigating Motion and Mechanisms Using Engineering Design Activities

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**Abstract** – This special session will introduce participants to engineering design activities that use mechanisms, devices that transform one type of motion to another, to support student learning about motion, a topic that recurs throughout K-12 science studies. The activities come from new and revised K-12 Engineering Teaching Kits (ETKs). ETKs are self-contained standards-based and project-based instructional units. Their format and contents reflect an integrated approach to STEAM[d] (STEM + Art + design) education. Participants will learn key concepts guiding ETK development and implementation; discuss methods for integrating ETKs and therefore engineering design concepts, practices, and models seamlessly and transparently into their curriculum; discover how engineering design and inductive learning principles help students learn and own key concepts in STEM; and work through selected engineering design activities. 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.

**Index Terms** – Engineering design process, Engineering Teaching Kits, inductive learning, P-16 engineering education, STEM.

**INTRODUCTION**

While the intersection of engineering and humanities has long enhanced and reinforced learning in the individual disciplines, the active integration of art, music, and composition activities in STEM studies has been gaining traction in many pre-college (P-12) environments during the past few years. The growing STEAM (STEM + Art) approach emphasizes a hands-on, project-based, interdisciplinary approach to the study of science, technology, engineering, and math (STEM). To emphasize the importance of using engineering design principles to *integrate* learning in science and math and gain technological literacy, this educational movement may also be called STEAM[d]. The addition of “d”esign and the integral sign to the STEAM acronym recognizes the kinship between art and engineering as complimentary design-based disciplines and that design is an integrative process. The STEAM[d] philosophy is at the heart of Engineering Teaching Kits (ETKs), our means for delivering integrative, holistic learning. ETKs provide the framework for this session’s activities.

ETKs are self-contained standards-based instructional units grounded in the constructivist philosophy of education [1], [2] and the principles of guided inquiry and active learning [3], [4]. Our primary goal in developing the ETKs is to engage students in a series of age-appropriate engineering design challenges to reinforce targeted concepts in math, science, and technological literacy.

By the end of the session, participants will be introduced to key components of the engineering design process and the STEAM[d] movement and be able to identify methods for using engineering design activities to integrate STEAM[d] studies seamlessly and transparently in the curriculum as well as strengthening key “21st century skills” like systems thinking, critical thinking, and problem-solving.

**Motivation**

Years of K-12 outreach activities provide abundant examples of students becoming totally engaged by engineering design activities and project-based learning [5]. However, the majority of outreach initiatives tend to be short-term and episodic, with many leaders conducting activities chosen with little to moderate regards to participant knowledge, culture, experiences, or values. A main goal for our professional learning communities, therefore, is to determine how to ensure consistent exposure to engineering and computer science in ways that truly connect student and learning in context throughout the P-16 – pre-college and undergraduate – experience. Thanks to a growing body of research results, a data-driven design is possible. Realizing that a many-pronged approach is more likely to engage and encourage K-12 students to commit to postsecondary STEM studies – one thing we should have learned by now is that “one size (activity) doesn’t fit all” – we offer our philosophy and curriculum in this session for consideration.

We also recognize that the earlier interventions happen the greater the opportunities to recruit P-12 students into the STEM academic pipeline and, just as importantly, retain them.

While all P-12 students have the ability to benefit from early experience in an integrated STEAM[d] educational environment, students from underrepresented populations in
STEM may especially benefit. Many decisions about inclusion in enrichment programs such as gifted and talented courses are made in early elementary grades, and an English Language Learner / English as a Second Language student may be at a disadvantage with respect to entry into these programs if his/her English language skills cannot correctly convey his/her abilities and intelligence [6]. An integrative STEAM educational environment with a design-driven project-based curriculum, with opportunities to connect with all learning styles [7], is one means for engaging students from diverse backgrounds.

**OUR CORNERSTONE: ETKs**

Since 2002, teams of students and faculty at the University of Virginia have developed, tested, and distributed ETKs for use in science and math classes - initially in middle schools but now throughout K-12 [8], [9]. 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. The design/build/test cycle provides opportunities for creativity and exploration. No two designs are ever the same!

Over 50 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), and *Trash Sliders* (sustainability, vehicle design).

ETKs are also 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 uses 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.

**ETK 2.0**

We are actively expanding the scope of concepts, material, and activities covered in ETKs. Four of our current initiatives are described in this section.

*I. Addressing Misconceptions*

A major addition to our initial ETK content is a set of activities and instruments to assess and remediate misconceptions in mathematics and science. We are using adapted and authored concept inventories to assess misconceptions and discrepant events to provide an opportunity for reformulating misconceptions.

**Ia. Defining Misconceptions**

It is important to understand the process of cognition when developing definitions of concepts and misconceptions. The most basic definition of cognition is the “process of knowing…and the content of those processes.” It is a **fundamental** concept in the science of learning, since learning is dependent on prior knowledge and the nature of changes students can make in both processes and content. (see, for example, [10]; emphasis added) The primary components affecting a person’s level of cognition are declarative knowledge and procedural knowledge. Declarative knowledge can also be defined as “semantic information…(knowledge about ideas)” and procedural knowledge as the “complement” of declarative knowledge; together, they “represent categories for describing knowledge in general” [11, p. 28]. The interplay between the acquisition and application of sets of related declarative and procedural knowledge helps students identify and internalize underlying concepts. However, students may internalize concepts incorrectly for a variety of reasons, and the resulting misconceptions can be a factor in student disengagement and other negative (re)actions.

A concept, therefore, is a mental construct or model that helps a person organize knowledge. It is inductively built from interactions and experiences [2]. Misconceptions, also known as alternative frameworks or invented theory, arise from a flawed development process in which the cognitive process of trying to connect new information to existing knowledge reshapes the new information to fit with the structure of the existing knowledge [12]. They can be remarkably resistant to change [2], [13], [14]. A misconception is distinct from *misunderstanding*, a situation in which a learner does not have sufficient correct information for comprehensive comprehension. The former is a cognitive issue; the latter, a factual issue.

The physics education community has long been involved in the assessment and remediation of misconceptions, especially with respect to Newtonian forces. The concept inventories in this area were pioneered by physicist David Hestenes and his colleagues at Arizona State
University beginning in the 1980s; see, for example, [15], which is one of many articles on the Force Concept Inventory. Other validated methods for evaluating conceptual knowledge are peer instruction [16], direct interview [17], and strategy writing [18].

IIb. Addressing Misconceptions in Movin’ Along

Common misconceptions with respect to motion and the concept with which it’s typically paired, force, include the following [19], [20]:

- Action-reaction forces act on the same body.
- Friction can’t act in the direction of motion.
- The normal force on an object is equal to the weight of the object by the 3rd law.
- The normal force on an object always equals the weight of the object.
- Equilibrium means that all the forces on an object are equal.
- Only animate things (people, animals) exert forces; passive ones (tables, floors) do not exert forces.
- Once an object is moving, heavier objects push more than lighter ones.
- You need force to keep a car moving.
- Friction is an inherent part of an object.
- Going at a steady velocity in a circle around the Earth means there are no accelerations.
- Your weight tells you have much stuff you have.
- Equilibrium is the absence of forces.
- “Energy” and “force” are interchangeable terms.

These misconceptions about force and motion are challenging, in part, by the following “classic” discrepant events that nonetheless should have further distribution:

- The coin, card, and glass exercise, which addresses misconceptions regarding friction and inertia [20]
- The Coke / Diet Coke exercise, which addresses misconceptions regarding buoyancy and density [21]
- The hollow egg and book exercise, which addresses misconceptions about material strength, shapes, and forces [22]
- The glass full of water and card exercise, which addresses misconceptions about gravity [23]

These discrepant events were researched and adapted for inclusion in the HoverHoos/Save the Glades, Under Pressure/Save the Whales, Bridges to Engineering, and Imagineer Your Ride ETKs. We are developing a set of new discrepant events for Movin’ Along.

II. Grounding the ETKs in Society’s Problems

ETKs are also being updated to address the need to connect STEM to student context and experience by grounding an ETK’s theme in real world issues. In Save the Penguins, for example, student learning about materials science and heat transfer and supporting design activities occur within the context of an environmental issue that affects them - climate change - using an appealing subject population: penguins [24]. Similarly, HoverHoos was restructured as Save the Glades and Under Pressure was restructured as Save the Whales in order to have students connect the practice of engineering to the solution of large scale societal problems.

This restructuring is prompted by the noted phenomenon of attracting students from underrepresented populations in STEM by offering socially relevant projects and the chance to solve society’s needs via engineering design projects (see, most recently, [25]).

III. Parent-Teacher Guides

Another addition to the ETK library are detailed guides for parents and teachers, in part to promote the family engineering movement [26] so that student learning is supported in both formal and informal learning environments, and in part to provide additional support to activity leaders who may not necessarily have a background in the topic(s) covered by a given ETK. These guides provide background on the engineering design, science, and math concepts addressed in the targeted ETK as well as information to use in guiding students and other participants through the design challenges. This support is especially important for the growing number of parents searching for engineering education opportunities for summer enrichment or to supplement a homeschool curriculum.

IV. Scaling ETKs to Fit Time Constraints

We have also successfully tailored ETKs to fit time and interest constraints. For example, we have successfully adapted RaPower and Save the Penguins to 3 hour versions for summer camp activities [27] and to 90 minute versions for professional development sessions [28]. Similarly, we have created a 90 minute version of Wind-E for outreach and enrichment programs [29], [30] and professional development [28]. Ninety minute versions of HoverHoos (Save the Glades) and Under Pressure (Save the Whales) were piloted at the Village School’s Take Your Daughter to Work Day [31].

THE BASICS OF MOVIN’ ALONG

The main subjects covered in the Movin’ Along ETK are from the discipline of kinematics, or the study of motion. We focus on types of motion and the mechanisms used to transform and redirect motion. There are four types of motion in mechanical systems: linear, or motion in a straight line; oscillating, or repetitive motion about a central point or between different states; reciprocating, or motion (sometimes called “strokes”) back and forth or up and down in a straight line; and rotational or rotary motion, motion that is circular. In constructing mechanisms to redirect motion or transform one type of motion to another, gears and/or linkages are used. The resulting mechanisms include the cam, slide, and follower, which transforms rotary and reciprocating motion; the chain and sprocket, which translates rotary and linear motion; the crank, link, and slider, which transforms oscillating and rotary motion; the peg and slot, which transforms oscillating to rotary motion; the rack and pinion, which transforms rotary motion to linear or reciprocating; and the rope and pulley and wheel and axle,
which transform rotary motion to linear [32], [33].

Mechanical systems abound in our world, but students may not be aware about how many are involved in their lives. For the opening exercise, students are asked to brainstorm about the systems they encounter on a regular basis and why we would need to transform one type of motion to another. Vehicles provide good examples due to the high probability of student familiarity with commonly available/used ones. To make the discussion concrete, students work through how bicycles transform rotary motion to linear motion.

The larger societal context includes discussions about the need for alternatives to the internal combustion engine and other methods of mechanical propulsion, which lead to the major issues of depletion of non-renewable sources of energy and climate change. For example, marine propulsion methods are, at best, 70% efficient. Increasing this efficiency by 10% would result in annual saving of millions of gallons of fuel and the related monetary and environmental costs. As it happens, many marine species achieve up to 87% efficiency; a number of researchers are involved in designing propulsion systems inspired by sea turtles, manta rays, dolphins, penguins, and whales [34], [35]. This problem formulation adds the opportunities to discuss how engineers can help preserve endangered species and bio-inspired design practices.

Design challenge activities include the assembly of automata, a mechanical system (typically, a toy like a Jack in the Box) that’s constructed to look as though it’s moving on its own; designing and building kinetic sculptures and Rube Goldberg systems (an overdesigned mechanical system built to accomplish a very simple goal) out of various types of mechanisms; and spirographs, in which students choose the type of gears and linkages they want to use in tandem to make drawings. The last one can involve the designing of gears, for example, in a CAD program for construction on a 3D printer, thus including other activities that may be in the curriculum and giving students to construct linkages among seemingly disparate learning activities.

**SESSION AGENDA**

The session is structured as follows:

- **Welcome, Introductions, and Agenda Review** (10 minutes)
- **Initial Exercises** (20 minutes)
  Participants will construct a set of physical models that illustrate different types of motion – linear, rotary, reciprocating, and oscillating – and mechanisms for translating one type of motion to another. They will be encouraged to explore how their models could be joined with others to form a functioning mechanism or system of systems. The final product may be an automaton, a kinetic sculpture, or a Rube Goldberg system; participant interest will drive this decision.
- **Regroup, Reflect on Lessons Learned, and Review of Important Concepts** (15 minutes)
- **Follow-on Activities** (40 minutes)
  Participants will work in groups with the facilitators to elaborate on their designs. We will also discuss scaling the activities to various grade levels. This discussion will include a review of expectations as to cognitive development and skill levels for students in those grades, necessary to the proper scaling and scaffolding of the activities.
- **Concluding Activities and Discussions** (5 minutes)

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**REFERENCES**


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