STANDARDS-BASED ENGINEERING CURRICULA AS A VEHICLE FOR K-12 SCIENCE AND MATH INTEGRATION

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Abstract *- After 20 years of efforts to improve K-12 science and math education, concerns loom that today's students show limited inclination to choose engineering and technology futures. With little opportunity to learn how science and math skills translate into professionally useful knowledge, students do not make informed choices about their education options and close off future career pathways.*

To develop concrete connections for K-12 students between science/math and daily life, the University of Colorado at Boulder's Integrated Teaching and Learning Program's K-12 outreach initiative developed a collection of standards-based, hands-on K-12 engineering curricula. These classroom-tested and affordable curricular units provide K-12 educators and engineering colleges with an effective and sustainable engineering resource, contributing to an improvement in technological literacy as well as expanding the pool of youngsters who imagine themselves pursuing a future in engineering and technology.

This paper examines the development of K-12 engineering curricula as an effective vehicle for science and math integration and provides assessment results.

Index Terms – K-12 education, educational content standards, engineering curriculum, lesson plans, math and science integration.

THE NEED FOR K-12 ENGINEERING

K-12 educators continue to search for new ways to increase the technological literacy of their students [1]. "Because few people today have direct, hands-on experience with technology, technological literacy depends largely on what they learn in the classroom, especially in elementary and secondary school [2]." To address this issue, the Integrated Teaching and Learning's (ITL) Outreach Program at the University of Colorado at Boulder (CU) created a comprehensive K-12 engineering curriculum that conveys science, technology, engineering and math (STEM) concepts through an interesting and hands-on approach. The curricula can be easily understood by students and implemented by teachers not trained in engineering. While not all students will pursue careers in engineering or technology, all students *can* benefit from a basic understanding of how social, economic and cultural systems are transformed by the integration of the two [3]. Improved technological literacy, even at a young age, is beneficial to society so that all citizens can make informed decisions in an increasingly technologically-driven world.

According to the 2002 National Panel Report of the Association of American Colleges and Universities, K-12 schools often do not effectively prepare students for college due to a combination of factors, including: new accountability demands (standards-based learning) on teachers, an over-reliance on educational traditions, sub-standard curricula, and poor resources [4]. A comprehensive K-12 engineering curricular experience affords students, including those typically under-represented in engineering — women and students of color — early exposure to engineering and technology options as lifelong pursuits.

The ITL Program's K-12 curriculum development and implementation initiative, which includes in-class hands-on engineering instruction, meets the objective of positively impacting K-12 students' content knowledge and career awareness. An added benefit of this approach is the creation of curricular resources that can be readily adopted by teachers because they are mapped to state science and math standards, which address teacher accountability demands, and contain appealing, affordable and teacher-friendly content.

Following is a description of the development of the ITL Program's *engineering curricula*, based on current educational standards, as a *vehicle for K-12 science and math integration*.

OVERVIEW OF K-12 OUTREACH PROGRAM

The ITL Program is dedicated to the seamless integration of engineering (applied science and math principles) into the K-12 community. Guided by the following vision statement:

"To create a K-16 learning community in which students, K-12 teachers and the College of Engineering and Applied Science explore, through hands-on doing, the role of engineering and innovation in everyday life. And, to appreciate and apply the art of engineering through designing and building solutions to meet the needs of society [2]."

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ITL's commitment is to prepare and guide elementary, middle and high school students — especially those with backgrounds typically under-represented in engineering — towards the university engineering and technology pipeline. Our *engineering in everyday life* approach is the core of the standards-based scientific, mathematic and technological curricula focused on engineering and pre-college mathematics.

A popular component of the ITL Outreach Program is the involvement of engineering undergraduate and graduate students in elementary, middle and high schools to serve as engineering role models and instructors in grades K-12 science, technology and math classrooms.

Additionally, summer workshops for K-12 teachers and students employ engineering and design/build principles to enigmatic topics — air pollution, mechanics, robotics, flight and invention — in a hands-on approach to understanding real-world applications of science and math. Through summer resident camps and mini workshops, teens (again, focusing on those populations which are typically underrepresented in engineering) are introduced to technological tools and the design/build process, opening the fun and challenging world of engineering to youth.

COLLABORATIVE PARTNERS

After much trial and error, and the contributions of many people, the ITL Program's curriculum development process has become standardized and refined. The process involves a team of varied contributors, including engineering graduate and undergraduate students, K-12 teachers, university engineering faculty, and outreach program staff.

Engineering graduate students research and write the lesson plans, working closely with teachers to develop relevant, age-appropriate hands-on activities and support materials. Engineering undergraduate students test and refine the activities before they are used in classrooms. K-12 teachers contribute to the selection of the curricular topics,

FIGURE 1.
YOUNGSTERS PARTICIPATE IN HANDS-ON DESIGN AND BUILD ACTIVITIES IN THEIR CLASSROOMS.

and review the literacy, math and age-appropriateness of the documents. University engineering faculty provide expert technical content review and ensure a real-world engineering context is provided for the science and math content. A review of completed curricula by someone other than the original author contributes to a higher-quality product. The outreach program team coordinates the entire process and the many curriculum development partners, including specialists in math and assessment.

CURRICULUM DEVELOPMENT AND REVIEW PROCESS

To create high-quality, comprehensive curricular documents, the ITL Program established an involved curriculum development and review process with several key steps.

First, a standardized lesson plan template is established. A thorough lesson plan contains components that make it useful for teachers and ensures content that is age-appropriate and engaging for students. (See next section for a list of lesson plan components.)

Curriculum topics are selected and are comprised of 6-10 lesson plans each (including one or more hands-on activities per lesson). Our approach was to ask K-12 teachers for their subject-area suggestions that map to the required educational standards at each grade level. By enriching and further developing subject areas that are already taught in the classroom, the engineering curricula is more likely to be a welcomed tool for both in-classroom teachers *and* engineering faculty who wish to unite their outreach initiatives with local school districts.

Engineering graduate students research and write the lesson plans, completing all components of the template. This requires the ability to creatively design motivating and grade level-appropriate content. Graduate students conduct background research on the topic and partner with a teacher to assure the age-appropriateness of content and activities. It is helpful if graduate students also refer to national [5]-[6] and state education standards [7] to discover age-targeted educational expectations germane to specific grade levels and topics.

A multi-faceted review process follows the initial lesson plan/curricular unit creation. This involves managing the input from a wide range of contributors who review and edit the documentation for: completeness; activity procedure and third-party testing; technical content accuracy; embedded assessment; and math and literacy. We found it effective to have engineering professors examine the theoretical content and engineering context, and then ask literacy, math and assessment specialists to review those components. In-classroom testing conducted by teachers and graduate/undergraduate students is also an integral part of the iterative review process.

The curriculum documents constantly evolve with revisions and refinement that incorporate corrections, improvements and suggestions gathered from in-classroom testing and teacher input. Finally, the document is reviewed for copyright permissions and aesthetic formatting, and at that point undergoes a thorough technical editing

LESSON PLAN TOPICS AND COMPONENTS

The ITL Program's K-12 curricula cover a wide range of subject areas, such as: electricity and magnetism, energy, motion, mechanics and the environment. Taking into account the educational standards to which the individual lessons are mapped, each multi-week curricular unit is comprised of up to 10 lesson plans, containing one or more related hands-on activities per lesson. See Table I for a sample of our 18 curricular units currently available.

The ITL Program's comprehensive lesson plan template includes the following components that our partner K-12 educators agreed were essential:

- Introduction/motivation,
- Background information and concepts for teachers,
- Anticipated student outcomes,
- Educational content standards met,
- Hands-on, inquiry-based activities,
- Safety issues,
- Lesson closure,
- Extension activities, and
- Embedded and summative assessment.

A lesson plan may also include various optional components such as:

- Vocabulary lists,
- Activity completion time,
- Supplies and equipment lists,
- Costs,
- Activity attachments and worksheets,
- Troubleshooting tips,
- Scaling for higher/lower level grades, and
- Visual or multimedia elements.

Special emphasis is placed on writing the introduction/motivating component, designed to hook the students in a few short sentences on the upcoming lesson. This information is important to provide for teachers so that they do not have to extemporaneously grab information from multiple sources to start the lesson.

Lesson and Activity Example

An elementary curricular unit on *rockets* includes several lessons on the subject of *motion*. The first lesson introduces Newton's Laws of Motion in the context of what an engineer must understand when designing rockets or cars. In this lesson, students explore rocket motion with a slingshot-like device that projects a weighted wooden block backward to produce forward motion (on the somewhat frictionless wheels) of a homemade "rocket car." (The supplies to construct this device may be purchased at a hardware store for less than $20.) This activity demonstrates Newton's 3rd Law of Motion: that for every action there is an equal and opposite reaction. Students compare the reaction of the rolling platform to the action of the forcefully ejected weighted block. By increasing the wooden block's mass and seeing that the distance traveled by the rocket car decreases, Newton's 2nd Law (F=ma) is illustrated. Students can graph the mass of the block vs. the distance the car travels, which becomes a math reinforcement exercise that helps students grasp the real-life engineering connection between math and basic laws of science.

ENGINEERING CURRICULA AS A VEHICLE FOR K-12 SCIENCE AND MATH INTEGRATION

Science and math are fundamental K-12 subjects taught throughout the world. Using engineering — as a real-world application of the same principles that students learn early on — to explore STEM learning provides a gateway to creative real-life solutions.

TABLE I
AN EXAMPLE OF FIVE OF THE 18 CURRICULAR UNITS AVAILABLE FOR CLASSROOM USE.

UNIT TOPIC	CURRICULAR UNIT DESCRIPTION	GRADE LEVELS	# LESSONS	# TOTAL ACTIVITIES
Human Body	Delve into engineering in genetics, the cell, muscles, movement, heart, kidney, ear and eye.	Elementary School	10	30
Sound & Light	Discover how engineering relates to the travel of sound. Explore sonar, characteristics of sound, light, colors, lenses and how light travels.	Elementary School	10	26
Electricity & Magnetism	Explore the applied world of electrons, circuits, magnetism, electromagnets and electricity in the home.	Elementary School	10	30
Laws of Motion	Explore Newton's Laws of Motion to understand how engineers use friction and circular motion.	Middle School	5	15
Water Engineering	Investigate wetlands, well water and drinking water, and how engineers mitigate water pollution.	Middle School	6	11

Consider an elementary child first being introduced to Newton's 2nd Law of Motion through a hands-on demo involving a wooden block and fishing sinkers (the previously described "Newton rocket car"). In middle school, that same student might be challenged to describe gravity for a science fair project. Already knowledgeable about the concepts of force, mass and acceleration, the student capably demonstrates her understanding. In high school, she may be faced with a more sophisticated challenge: to build a rocket for a physics project. Again, she succeeds, in part because of her early exposure to engineering and the laws of motion. As a young adult, she is better prepared to explain the world around her and envision herself choosing an engineering career path.

While this is an idealized scenario, providing students with the ability to make solid real-life connections between science, math and our world at an early age is a very real challenge for educators. The ITL Program has assessed the effects of our inquiry-based engineering curricula in the classroom and discovered that K-12 curricula using *engineering as a vehicle to integrate math and science* fundamentals increases the understanding of STEM concepts by K-12 students. The hands-on, minds-on and ears-on activities at the heart of our curricular lessons awaken curiosity and create fun learning experiences while engaging students in active problem solving.

PROOF IS IN THE ASSESSMENT

For the past four years, the ITL Outreach Program has partnered with four local Colorado school districts and more than 180 classes to develop and deliver engineering curricula. Funded by National Science Foundation (NSF) and Department of Education (DOE) grants, our interactions with elementary, middle and high school teachers and youngsters allow graduate and undergraduate students the opportunity to assess the effectiveness of our lessons and activities in actual classrooms.

Since an entire grade level at most schools study the same subject matter over a period of weeks, an excellent opportunity exists to compare the content learning of an "experimental" classroom (*with* direct engineering curriculum interaction) with that of a "control" classroom (*without* direct engineering curriculum interaction). The assessment methodology used for the comparison was pre-/post-content testing (per unit topic) of students in both experimental *and* control classrooms. Content testing was chosen because K-12 standardized testing does not test for engineering content.

For quantitative results, pre-/post-content tests — comprised of 10 multiple-choice questions related to the curricular unit topic being studied — were utilized. The same test was conducted at the beginning and end of the multi-week unit instruction. To assure internal validity of our assessment, teachers reviewed content tests, assessment workshops were provided for graduate students, control groups were used, and content tests were administered to both the experimental and control groups at the same time intervals. All participating students signed consent forms authorizing their content test scores to be used anonymously for research. Each pre-test was coded and then paired (by the graduate students) to a post-test for each student, ensuring integrity of content gains (or losses). In the past year, we collected 1,139 matched pre-/post-tests from eight schools and 13 curricular units in grades 3-8.

Data was analyzed using a multivariate analysis of variance procedure. Figure 2 graphs the result of this analysis, which showed a significant interaction effect indicating that experimental and control groups demonstrated different learning gains. While both the control and experimental groups began at the same place and showed gains over the course of their learning, the experimental group using the engineering curriculum scored significantly higher than the control group on the post-test, demonstrating positive gains to student learning due to the curricula and instruction.

SUSTAINABILITY

Systemic pedagogical reform is most successful if new curriculum becomes institutionalized within a school or district. Thus, creating a *sustainable* program must be the focus of any curriculum development initiative; the existence of curriculum alone does little to assure its ongoing implementation.

There are several approaches to achieve sustainability, including: broad dissemination of curricular lessons, professional development for teachers, and K-12 community/university partnership.

Dissemination may be accomplished via the Internet by providing a resource for educators seeking innovative tools for integrating engineering into their science and math classrooms. To that end, a searchable, web-based digital library — *TeachEngineering.com* — populated with standards-based K-12 curricula will be available in late

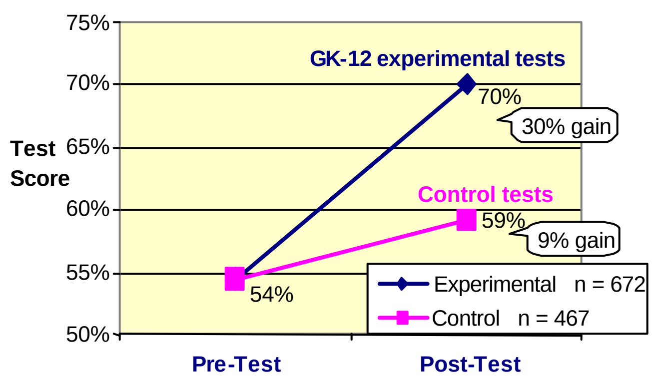

FIGURE 2
SUMMARY OF STEM CURRICULA CONTENT LEARNING GAINS, GRADES 3-8, 2002-03.

2004. The more than 150 engineering curricular lessons being developed by the ITL Program and to be included in the library are inquiry-based and offer a unique approach to connecting engineering with everyday life. Several university partners are collaborating to create this NSF-funded collection, including the University of Colorado, Worcester Polytechnic Institute, Colorado School of Mines, Duke University and Oregon State University. The *TeachEngineering* web site will provide educators with access to a growing curricular collection, as the contents evolve under the stewardship of the American Society for Engineering Education. Curricula in the digital library are aligned with national and several states' educational standards and include quality-control criteria to ensure teacher-friendly, cost-effective lessons that integrate STEM concepts through engaging engineering explorations. For additional information, see the ITL Program web site at: http://itll.colorado.edu/TeachEngineering.

Teacher professional development to support in-classroom implementation of the engineering curriculum is key to a sustainable program. Teacher buy-in is essential for the curriculum to become a prevalent means of integrating engineering into K-12 education. The ITL Program offers two-day summer workshops specific to individual curricular units. Led by engineering professors, these for-credit workshops are an excellent way for teachers to gain confidence in and knowledge of a curricular unit prior to bringing it into their classrooms. These workshops are also offered in areas other than our local community, expanding the dissemination.

As with many outreach initiatives, a K-12 school district/university partnership is key in encouraging use of newly developed curriculum. In the fall 2003, CU will pilot a yearlong service-learning technical elective, the *Engineering Outreach Corps*, in which upper-class undergraduate engineering students deliver engineering into the K-12 classrooms. *Corps* students will team with partner teachers to teach the supplemental engineering lessons and activities and serve as engineer role models, as a sustainable way to enhance the science and math learning within our local schools, and educate today's youth to envision and prepare themselves for a future in engineering or technology.

CONCLUSION

The ITL Program's K-12 curriculum development project makes connections between science, math and technology through real-life engineering examples and applications. "Because our economy is increasingly being driven by technological innovation, and because an increasing percentage of jobs require technological skills, a rise in technological literacy would have economical impacts [2]." Since accountability demands on teachers are increasing, lesson plans that are relevant for teachers and the lives of youngsters may begin to make a systemic pedagogical change among our K-12 community of learners.

Taken together, the *TeachEngineering* digital library curriculum collection, teacher professional development workshops, and the *Engineering Outreach Corps* course, promotes teacher and engineering faculty access to a plethora of tested, affordable, standards-based lessons that will facilitate using *engineering as a vehicle for the integration of science and math* fundamentals.

Assessment shows that using hands-on, minds-on engineering curricula to teach science and math in context makes a difference. As the *TeachEngineering* curricula continues to evolve and engineering faculty and college students nationwide strive to impact young learners, the engineering profession hopes to see an increase in the flow of students who enter the engineering and technology pipeline.

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