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Exploiting Design to Inspire Interest in Engineering Across the K-16 Engineering Curriculum*

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One approach to addressing the dilemma of poor mathematics and science performance of US students on standardized tests and lagging enrollment in US engineering colleges is engineering outreach to the K-12 community. Engineering outreach has been a core mission of the Integrated Teaching and Learning (ITL) program since its inception. Team-based design spans the entire K-16 hands-on learning curriculum, integrating math and science fundamentals through creative, self-directed learning. Experiencing design provides a context for undergraduates to develop advanced technical skills, and motivates youngsters to pursue an engineering path. This paper describes how design pervades the diverse ITL K-16 spectrum, including a variety of engineering curricula for K-12 students, as well as undergraduate engineering courses.

DESIGN AS A MOTIVATOR

I hear—I forget
I see—I remember
I do—I understand
(Confucius, c. 500 bc)

DESIGN IS the *raison d'être* for engineering, articulating the distinction between engineering and science. As Joseph Bordogna, Deputy Director of the National Science Foundation, states:

> Scientists investigate what is; they discover new knowledge by peering into the unknown . . .
> Engineers create what has not been; they make things that have never existed before . . .

Design is an ideal focus for hands-on learning, serving to anchor and provide context for theoretical foundation concepts. It is, by its very nature, open-ended and multidisciplinary, and forces effective teamwork skills, especially if the project is complex enough (in other words, realistic). By creating and implementing designs, students come to appreciate that *engineering is about creating things for the benefit of society*, a premise that has broad appeal to a diverse population.

We believe that a great way to increase the quality and diversity of young people pursuing careers in engineering and technology is to expose students to the joys (and frustrations!) of engineering early in their academic pursuits. And, because design projects are both fun and creative, they inspire students from a broad spectrum of ages. This paper presents an overview of the many design-based activities offered by the Integrated Teaching and Learning (ITL) program, where the spirit of discovery learning spans the K-16 continuum.

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GIVE THEM TOOLS

He worked so slowly for the dullness of his tools that he had not time to sharpen them.
(Cormac McCarthy)

The physical home for the ITL program is the ITL laboratory, a learning environment designed to support team-oriented, hands-on learning across all engineering disciplines [1]. The facility features team study rooms, design studios, large shared laboratory plazas with powerful data acquisition and analysis capability (Fig. 1), and an active learning center. A dedicated technical staff helps students create what they dream, particularly in the two fabrication centers. The Electronics Center allows students to simulate, design, prototype and test electronic circuits. The Manufacturing Center features CNC and conventional machine tools, CNC laser cutters and a '3D printer' rapid prototyping system for creating physical prototypes directly from CAD models.

In addition, numerous interactive exhibits dispersed throughout the ITL laboratory's contemporary architecture are captivating for 'children of all ages,' and illustrate many intriguing facets of engineering, technology and science (Fig. 2). In this sense, the ITL laboratory resembles a science museum and is, therefore, an appealing venue for K-12 outreach activities.

A HANDS-ON INTRODUCTION TO ENGINEERING

First-year engineering students arrive at the university eager and creative, anxious to get their hands dirty. Like other institutions [2], CU satisfies

Fig. 1. One of two hands-on laboratory plazas in the ITL laboratory.

this desire with a First-Year Engineering Projects course as a counterpoint to the large, impersonal lecture classes in core mathematics and science classes [3]. In this one-semester course, which is required of some, but not all, engineering majors, students work in teams to design, build and test functioning prototypes, while honing valuable oral and written communication skills. About 14 sections serve more than 400 students annually.

As opposed to schools where all students create different solutions to the same design challenge, each section has a project focus that varies with the instructor. Each team of up to five students, however, experiences the entire open-ended challenge of the design process. In other words, we standardize on the design *process* throughout the many course sections, as opposed to the *product*.

For example, one or more sections will usually focus on assistive technology projects to aid people in the community with disabilities. In addition to solving a challenging problem, students gain a deeper insight into engineering design by working with real clients with real needs. The satisfaction a recent team gained by building a complete cosmetic prosthetic arm for an Afghan refugee child could not come from a textbook. Other examples of products include a powered gripping glove for a paralytic child, improved 'sit-skis' for paraplegic skiers, a pulley system to allow a child with muscular dystrophy to safely navigate stairs, a bowling ramp for a child with cerebral palsy (Fig. 3) and electronic communication devices.

Another recently added section focus is appropriate technology—finding 'low-tech' solutions to challenges in developing countries. Taught by a civil engineering faculty member who started 'Engineers Without Borders', this design project topic has proved to be popular, because it allows students to make an impact on society. Examples of projects include a Filtron system to purify drinking water, a floating water turbine, a photovoltaic water pumping system and a banana digester. A biodiesel processing project was judged 'best of section' at the end-of-semester Design Expo. This project subsequently received substantial campus-wide funding in a student referendum to convert used cooking oil from campus food services to diesel fuel that powers a campus shuttle bus.

Like other engineering colleges, we are focused on student retention—45% of our entering first-year students leave the college before their senior year. This loss is even more pronounced among populations typically under-represented in engineering. Numerous reasons are cited for early

Fig. 2. The Pythagorean Fantasy ball machine by kinetic sculptor George Rhoads is one of many interactive learning exhibits in the ITL laboratory.

Fig. 3. A child with cerebral palsy tries out a bowling ramp created for him in an assistive technology section of the First-Year Engineering Projects course.

departure from engineering, including lack of early exposure to both hands-on learning environments and the 'real world' of engineering, coupled with limited cultivation of personal relationships with instructors due to large class size.

Retention rates for 2581 CU engineering students who either did or did not take the First-Year Engineering Projects course as first-year students during a five-year period were examined, tracking students into their senior year [4]. Results show an overall retention improvement (all values statistically significant at $p < .05$) of 19% for students who completed the course during their first year. This retention gain was even more marked among women and students of color; the study revealed a 27% retention differential for women who took the course and a 54% retention improvement for Latino student 'takers' (Fig. 4).

Invention and innovation

The Invention and Innovation course, co-taught by the authors, bridges the gap between widgets that work but would never sell and abstract entrepreneurial enterprises with little grounding in physical reality. In this junior-level technical elective, students design, build and test products that could succeed in the marketplace [5]. In the applied context of their own team invention, they study a range of entrepreneurial topics, including intellectual property and patent issues, customer demographics and product pricing, how to generate financial support for inventions, and estimating fixed, direct and variable costs to produce their product. As part of a feasibility study, they calculate the break-even point in product sales they would need to achieve to turn a profit.

Example projects from the most recent semester include a ratcheting open-end wrench, variable brightness brake lights to signal braking rate, a portable solar-powered wireless access point, improved manual wheelchair propulsion and theft-resistant quick-release bicycle components. Many students go on to receive funding from the National Collegiate Inventors and Innovators Alliance to develop their products further, conduct more in-depth marketing studies and file for US patents.

THE K-12 ENGINEERING INITIATIVE

To impact the 'pipeline' of students who study engineering, the ITL program has emphasized K-12 engineering since its inception [6]. Our goal is to help prepare and attract a student population whose diversity is representative of society at large. Design is woven throughout the pre-engineering curricula, and all programs are evaluated for continuous improvement.

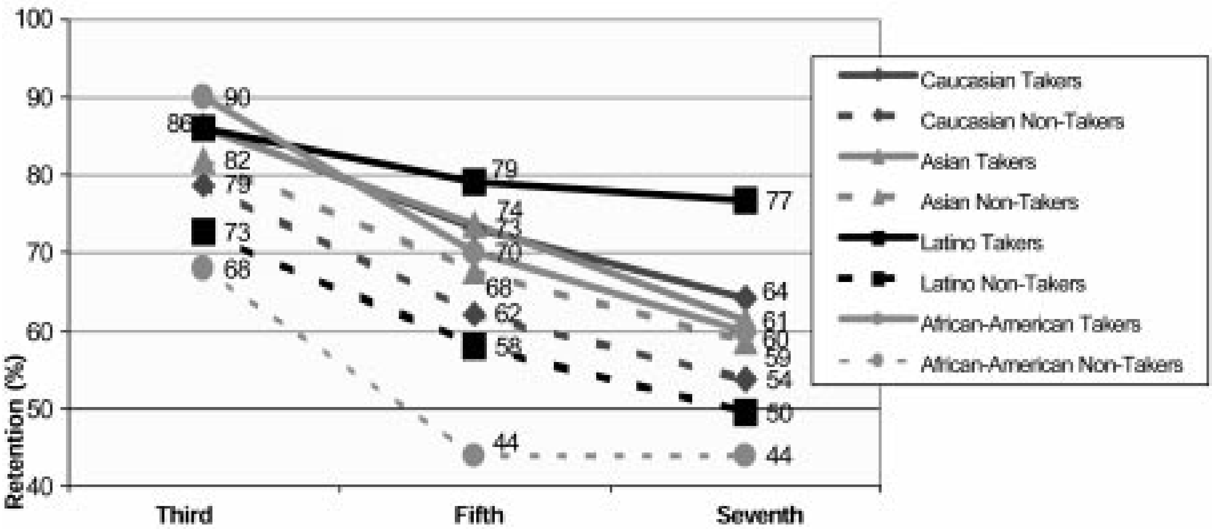

Fig. 4. Increased retention for students of color who took the First-Year Engineering Projects course as freshmen, vs. their colleagues who did not take the course.

Targeting young children

Upper elementary and middle school children are particularly good candidates for engineering outreach, because they are naturally inquisitive and still have plenty of opportunities to acquire the math and science skills they will need to successfully pursue higher education in engineering and technology.

Kids Invent Toys: In this weeklong, full day 4th–6th grade workshop, students explore first-hand the fun and ingenuity of the invention process as they design and build prototype toys, prepare business and marketing materials, and create a web page. The 24 'junior engineers' who attend each weeklong summer class present their inventions and business plans during an 'Invention Fair' to an audience of their peers, parents and instructors.

Sweet Machines: This more gender-neutral version of its 'Kids Invent Robots' predecessor still attracts predominantly boys. Working in teams, the 7th and 8th graders work for almost 40 hours during a weeklong workshop to design and build autonomous robots from kits, write programs to control them and show off their creations at an end-of-workshop design fair. This summer, the class name was changed to 'Sweet Machines' to hopefully appeal more to girls. However, early registration statistics still show an overwhelming appeal to middle-school boys. Apparently, robots do not appeal to young girls, regardless of what they are called.

How *Do* Things Work?: Twenty-four rising 6th–8th grade students take apart and reassemble household appliances, tools, toys and computers to gain an understanding of how things are built and evaluate how they might re-engineer them. Under the guidance of a female engineer, teams work together for a week to design and build their own projects from a building set that includes motors and sensors for light, sound and weight. In some years, enrollment is high enough to support both mixed-gender and girls-only workshops.

A focus on under-represented populations

A growing emphasis of our K-16 engineering outreach program is the preparation and guidance of middle- and high-school students towards the university engineering and technology pipeline—especially those with backgrounds typically under-represented in engineering. During the course of these initiatives, students are introduced to the world of engineering and the iterative design/build process, including use of technological tools and software.

Girls Embrace Technology (GET): Concurrent to society becoming increasingly more technology-driven, the representation of women prepared to contribute to the technological revolution is shrinking. In 2002, girls made up only 14% of the high-school students who took AP computer science exams, down from 17% in 1999, and by far the lowest percentage of girls' participation in all AP tests given [7]. A profound and growing gender distinction pervades the information technology (IT) world: 'boys invent things and girls use things boys invent' [8]. Girls shun being the creators of the very technologies that shape their lives. This void of women as technology creators is disconcerting. Girls begin to lose interest in computers during middle school, just as boys are getting deeply involved in computer games. Research has found that the rules of engagement for most games are not interesting to girls, prompting them to relate to the computer more as a tool for wordprocessing and homework than as a puzzle that may be a source of creative enjoyment in itself [9].

Thirty-six high-school girls explore their potential for a career in engineering and technology through developing educational interactive multimedia software during a six-week 'Girls Embrace Technology' summer internship [10]. The intent is to help girls get past social and stereotype hurdles so they can envision themselves in an engineering or technology career. 'Techno-neutral' girls are targeted—those who do not envisage themselves pursuing a career in high tech, yet have the academic preparedness, curiosity and commitment to complete the internship and produce a successful multimedia product. The girls are paid a nominal $50 per week stipend and work in four-person teams to create multimedia educational software to teach elementary or middle-school children basic science principles. The interns develop technical skills in graphic design, user interface development, visual programming, digital image manipulation, multimedia authoring and user testing while working on a fun and creative open-ended group project (Fig. 5). Thirty-eight percent of last year's participants returned this year.

Design Experiences for Under-Represented Students: While women are outnumbered by approximately five to one in engineering colleges, students of color and first-generation college-bound students comprise even smaller fractions of engineering student populations. African-American and Hispanic students combined received only 11% of the Bachelor's degrees in engineering in 2002 [11]. We have partnered with several local industries and organizations, including the college's Multicultural Engineering Program and Women in Engineering Program, to offer workshops to attract these students to careers in engineering and technology.

At the resident Success Institute (SI), about 65 high-school students are welcomed each year to a research university and are exposed to the possibilities of pursuing careers in engineering and technology at multi-day residential engineering workshops, with an opportunity to return each summer throughout their high-school years [12]. Through hands-on, team-based activities and design projects, teams solve engineering challenges and learn how engineering, mathematics and science affect their everyday lives.

Fig. 5. High-school girls design the storyboard for their interactive multimedia presentation.

Reflecting input from the local community, SI is not just a one-time workshop, but rather a graduated series of summer opportunities for students in each of their high-school years. Open-ended design challenges pervade the curriculum for 11th- and 12th-grade students, following introductions to technology and a wide range of engineering fields in 9th and 10th grades. In a recent summer, students were challenged to design and build stereo speakers from scratch (Fig. 6). As the teens learned content theory and delved into their design/build project, they were concurrently engaged in team-building and creative-thinking activities. Hands-on engineering skills were developed, as they used digital cameras and color scanners and participated in soldering, hand tools, machining and software mini-workshops.

Of our 1998 pilot Success Institute, attended by 14 inner-city middle-school students and their parents, 10 first-year African-American students who graduated from high school in 2002 entered CU that fall, seven of them in engineering.

We also collaborate with other CU programs that target under-represented populations, offering high-tech design and build experiences in the state-of-the-art ITL laboratory. For example, the CU Pre-Collegiate Development Program engages 6th- to 12th-grade first-generation college-bound students, grooming them to attend the university. The older students (half female) tackle open-ended engineering design challenges, creating stereo speakers, rockets and airplanes during the five-week design-build experience. In the latter project, for example, students study aerodynamics and build paper study models before fabricating and testing balsa wood airplanes. Hands-on engineering design experiences are also a valuable component of the six-week American Indian Upward Bound residential program for high-school seniors from 13 reservations.

CONCLUSION

It *always* works on paper! This is one of the main reasons why hands-on design, as opposed to abstract theoretical design, is critical to gaining an

Fig. 6. Students work in the Manufacturing Center to create their stereo speaker team project.

understanding of the many challenges that present themselves in integrated design/build projects. A full design/build experience teaches students of all ages much more than they learn from textbooks. Such experiences underscore the need for in-depth analytical skills, while at the same time revealing that mathematical models of real-world phenomena also have limitations.

There is no substitute for fabricating working (or not!) prototypes of conceptual designs, and learning first-hand that designing within constraints and through iteration unleashes creativity and motivates deeper understanding. Furthermore, solving challenging problems is satisfying to learners of all ages and inspires further study and inquiry. What could be more gratifying for any educator?

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L. E. Carlson received his B.Sc. degree in Mechanical Engineering from the University of Wisconsin in 1967. Moving west, he earned an M.Sc. degree from the University of California at Berkeley in 1968, and a D.Eng. in 1971, both in Mechanical Engineering. His first teaching position was at the University of Illinois in Chicago and he joined the University of Colorado at Boulder in 1974. Dr Carlson has research interests in the application of mechanical design to rehabilitation engineering, primarily to artificial arms, and also to designs for crutches. He has been heavily involved in the ITL project since 1992, and currently serves as its co-director. His activities in this capacity include curriculum development, teaching the First-Year Engineering Projects course, fundraising, public relations and amateur architecture. In addition, he has helped develop a new course, Invention and Innovation, which explores the world of entrepreneurship through hands-on design and build projects. Many students from this course have received E-team grants from the National Collegiate Inventors and Innovators Alliance (NCIIA) to pursue their inventions further and file for patents. He team-teaches this course annually with Jackie Sullivan, the other ITL co-director. Dr Carlson claims that working on ITL has been more work, and is much more enjoyable, than anything he has ever done.

Jacquelyn Sullivan is founding co-director of the Integrated Teaching and Learning Laboratory and Program, focused on integrating hands-on learning throughout the undergraduate engineering experience. She co-led the development of a First-Year Engineering Projects course, and co-teaches Innovation and Invention and a service-learning Engineering Outreach Corps elective. Dr Sullivan initiated the ITL's K-12 engineering program, which makes engineering come alive to K-12 teachers and students through

professional development workshops, summer children's classes, and a summer resident program for under-served high-school students. She also leads a multi-institutional NSF-supported initiative to create a searchable, web-based, digital library of K-12 engineering curricula. Dr Sullivan has 14 years of engineering experience in industry and served for nine years as the director of an interdisciplinary water resources decision support research center at the University of Colorado. She received her Ph.D. in environmental health physics and toxicology from Purdue University.