A MULTI-DISCIPLINARY DESIGN ENVIRONMENT

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ABSTRACT
Design projects provide an ideal focus for hands-on learning, serving to anchor and provide context for theoretical concepts. Product design is inherently open-ended and multi-disciplinary, 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. This paper discusses the design resources of the Integrated Teaching and Learning (ITL) Program, the design curricula it supports, and lessons learned.

INTRODUCTION
In 1992, a dedicated task force of faculty, from all engineering departments, and students, with full support of the dean, embarked on an ambitious quest, as articulated by the vision statement engraved in the entry lobby of the ITL Laboratory:

To pioneer a multidisciplinary learning environment that integrates engineering theory with practice and promotes creative, team-oriented problem-solving skills.

This vision statement served as a guiding beacon, against which myriad decisions were tested. Always, the path of action chosen was the one that best supported the vision. Atypical of most new buildings on a state campus, the task force was intimately involved in all details of the project: fundraising, selection of the architectural design team and construction contractors, architectural design and project management. In other words, we did everything from helping raise millions of dollars to choosing the color of the bathroom tiles! The 34,400 sq. ft. ITL Laboratory opened in January 1997, ahead of schedule and under the total $17.5M budget [1].

A HANDS-ON LEARNING ENVIRONMENT

“I hear – I forget
I see – I remember
I do – I understand”

Confucius c. 500 B.C.

Figure 1. The contemporary architecture of the ITL Laboratory

The physical cornerstone of the ITL Program is the three-story ITL Laboratory (Fig. 1), connected to the Engineering Center by bridges lined with 18 highly-used team study rooms that support small team interaction. Each conference-style room is equipped with white boards (some interactive, although students seem to prefer traditional white boards) and a PC connected to a high speed network, supporting teams to easily access files and data.

Two large, open laboratory plazas each contain 30 custom LabStations with powerful data acquisition and analysis
Lab plazas are flexible spaces that are quickly configured by rolling up mobile modular experiments or specialized testing equipment, attaching a pre-wired connector and loading the appropriate LabVIEW virtual instrument application. Two smaller — and often dissimilar — lab classes are often scheduled simultaneously in a plaza, and two LabStations are always left unscheduled for drop-in student use, even during scheduled classes. As a result, Lab Plazas are usually vibrant spaces bustling with interdisciplinary activity.

Hands-on design activities are supported by two dedicated design studios (Fig. 3), whose design was shaped by pilot offerings of the First-Year Engineering Projects course (described below). Each studio features oval tables for team activities, a PC for each team’s use, work benches for fabrication and assembly, team-based storage lockers stocked with toolboxes for use throughout the semester, and an assortment of specialized tools ranging from hand grinders to a sewing machine. A podium with a PC, AV equipment and video projector support student and faculty presentations.

Two fabrication centers, each staffed with technical experts, allow students to create what they dream. The Electronics Center supports 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 ABS plastic prototypes directly from SolidWorks CAD models. A separate Tool Shack contains pneumatic hand tools that are accessible at all times the laboratory is open (until 11:00 PM most weekdays, with 12 weekend hours as well).

For safety reasons, each student wishing to use the Manufacturing Center must first complete a one-hour safety workshop and pass an on-line quiz. Subsequent technical workshops provide training on specific tools. Upon entering the Manufacturing Center, students swipe their ID cards, which prints an adhesive label they wear to show which tools they are trained on and authorized to use.

LIKE A SCIENCE MUSEUM

By design, the open contemporary architecture features many gallery spaces that are perfect for display of numerous interactive learning exhibits that appeal to “children of all ages (Fig. 4).” These exhibits are entertaining for engineering students and their children and parents alike. And they create an appealing venue for our many K-12 engineering activities, intended to stimulate students to pursue futures in engineering at an early age.

Another unique feature of the laboratory’s design is the building-as-a-learning-tool (BLT) concept [3]. Much of the building’s structure and building systems are exposed to show how buildings are constructed, succinctly explained on interpretive signs. And more than 300 sensors integrated into

Figure 2. Two hands-on laboratory plazas support hands-on experimentation

Figure 3. Two design studios encourage open-ended design activities
the building monitor its pulse regularly, with the data posted on the Internet, (http://blt.colorado.edu).

Figure 4. The Catenary Arch is one of many interactive learning exhibits that are both entertaining and educational.

DESIGN THROUGHOUT THE CURRICULUM

General Engineering Design Courses - First-year engineering students arrive eager and creative, anxious to get their hands dirty. The First-Year Engineering Projects course is a counterpoint to the large, impersonal lecture classes in core math and science classes [4]. In this one-semester course that is required of some, but not all, engineering majors, students work in teams to design, build and test functioning product prototypes, while honing valuable communication and teambuilding skills. About 14 sections, with maximum enrollment of 32, serve more than 400 students annually.

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 emphasize the design process throughout the many course sections, as opposed to the product. Example themes include assistive technology for outside clients with disabilities, appropriate technology – “low tech” solutions to challenges in developing countries, interactive learning exhibits similar to museum exhibits intended to teach K-12 students engineering concepts in an engaging, hands-on way, or Lego robots – where students build and program robots to compete on a challenge course.

Creating product for clients has the added benefit of helping students come to understand that engineering is a helping profession. The satisfaction a team gained by creating a cosmetic prosthetic arm for an Afghan refugee boy could not come from a textbook. A biodiesel project in an appropriate technology section led to substantial campus-wide funding in a student referendum to convert used cooking oil from campus food services to diesel fuel that powers campus shuttle buses, and the student that spearheaded this effort and is now pursuing a career in alternative energy.

As shown in Table 1, First-Year Engineering Projects has had a significant impact on retention of students studying engineering [5]. While retention gains are significant among all student “takers,” they are even more marked among women and other underrepresented groups. This is particularly important because one of our strategic college-wide goals is to improve the diversity of both students and faculty.

<table>
<thead>
<tr>
<th>Student Demographics</th>
<th>Retention Improvement Into Senior Year (compared with non-takers of FYEP course)</th>
<th>Number of Students</th>
</tr>
</thead>
<tbody>
<tr>
<td>All student “takers”</td>
<td>+18% 1</td>
<td>5,070</td>
</tr>
<tr>
<td>Women</td>
<td>+26% 1</td>
<td>1,015</td>
</tr>
<tr>
<td>Latino</td>
<td>+17%</td>
<td>290</td>
</tr>
<tr>
<td>African-American</td>
<td>+31%</td>
<td>80</td>
</tr>
</tbody>
</table>

Table 1. Retention gains for students who took First-Year Engineering Projects, compared with non-takers. Total sample size 5,070 from students entering in 1994-2002.

The Invention and Innovation course co-taught by the authors bridges the gap between gadgets that work but would never sell and virtual entrepreneurial enterprises with little grounding in physical reality. In this junior-level technical elective, students design, build and test products that might succeed in the marketplace [6]. In the context of their own team invention, they explore 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 analysis, they calculate the break-even point in product sales they would need, at a given price point, to turn a profit.

1 Statistically significant at p < .05
Example recent projects include a home biodiesel system, a retractable dog leash integrated into the collar, a battery-free tent illumination system powered by the motion of hiking, a heads-up display inside winter goggles to display information such as lift line status, temperature, etc., an automatic animal deterrent system to keep deer from destroying gardens and a novel skateboard brake. Many projects 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 U.S. patents.

Supporting Departmental Design – The Aerospace Engineering Sciences department has capitalized extensively on the resources of the ITL Laboratory. In 1997, they drastically reformed their department-wide curriculum, particularly at the sophomore level. In a college with essentially a common first year, the sophomore year is typically the first significant exposure for students to specific programs. The Aero department combined various topics that were previously covered in traditional three-hour predominantly lecture courses into four comprehensive five-hour courses; two are taught each semester of the sophomore year, thus comprising the bulk of sophomore students’ schedules.

Each course mixes theory, design and experimentation in intensive hands-on labs [7]. For example, when studying solid mechanics and materials, students learn beam theory, and are introduced to composite structures. Working in teams, they design an optimal mix of fiber/matrix for a truss beam. Using the fume hood in the ITL Laboratory, they fabricate their beam, which they then test to failure using a universal testing machine controlled by LabVIEW software.

Many programs have moved to yearlong capstone senior projects. This allows their students more significant, in-depth design experiences, many industrially sponsored. However, it also increases the resources needed to be successful. Senior student teams increasingly capitalize on the design, fabrication and experimental capabilities of the ITL Laboratory. Students have the capability, for example, to design a part in SolidWorks CAD software, perform stress analysis and optimization using Cosmos Works, build a scale model using the “3D printer” rapid prototyper, test the part to failure, and finally machine the final product using CNC milling machines and/or lathes. The ability to experience such modern engineering tools in a hands-on way not only enhances the quality of their final product, it gives them invaluable skills to take into their budding careers in engineering and technology.

Attracting Pre-college Engineers of the Future - To impact the “pipeline” of students who study engineering, the ITL Program has emphasized K-12 engineering initiatives since its inception [8]. Our goal is to help inspire, prepare and attract to our engineering college a student population whose diversity is representative of society at large. Design is woven throughout the grades 3-12 pre-engineering curricula, and all initiatives are evaluated for continuous improvement. The emphasis of our extensive K-12 engineering program is the exploitation of engineering as a vehicle for the integration of science and mathematics learning — capitalizing on engineering design for exposing grades 3-12 students to the excitement and creativity of engineering and technology. Through partnerships with seven public schools, over 1,800 K-12 students explore engineering in 65 classes weekly for the entire school year. The schools are selected for their high representation of students from backgrounds typically under-represented in engineering, and for their progressive implementation of a four-year high school engineering academy. Through hands-on, inquiry-based learning, students internalize the excitement of engineering through the iterative design/build process, including use of technological tools and software.

An example of one of our many summer “deep dive” workshops is the resident Success Institute (SI), where about 60 high school students are welcomed each year to a research university where they experience the possibilities of pursuing futures in engineering and technology at multi-day engineering workshops, with an opportunity to return each summer of their high school years [9]. Through hands-on, team-based activities and design projects, teams embrace engineering challenges and learn how engineering, math and science affect their everyday lives.

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 9th through 12th grade students. In a recent summer, students were challenged to design and build Mars rovers using remote control trucks and adding their own servo-driven mechanisms. As the teens learned content theory and delved into their design/build project, they were concurrently engaged in team-building and creative-thinking activities. Students learned to use basic machine tools, CAD software, laser cutters, digital cameras, color scanners and gave quality PowerPoint presentations to their parents. For seniors who participated in SI from 2001 to 2004, 25% of them are now attending CU, with 15% studying engineering. The primary challenges of recruiting these students into engineering include the selective admission criteria for engineering and the competitive scholarship offers that are being awarded from other universities.

We also collaborate with other campus-wide 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's 6th – 12th grade first-generation college-bound students attend the university. The older students (half female) tackle open-ended engineering design challenges, creating stereo...

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1 Aerospace Engineering Sciences, Chemical and Biological Engineering, Computer Science, and Mechanical Engineering

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speakers, rockets and airplanes during a five-week design-build experience. 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 multiple reservations.

Showcasing Student Projects – When motivated, students spend tremendous amounts of time and energy on design projects. At the end of each semester, our students proudly showcase the fruits of their labors at the Design Expo, held on a Saturday and always highly attended by the public. At the most recent Expo, 104 projects were judged, ranging from high school senior design projects through senior university capstone initiatives. Teams of judges from local industry or scientific laboratories evaluate all the projects, and “best of section” prizes are announced. Anyone attending also casts a ballot to select the Peoples’ Choice from all projects on display. Experience has shown that this public exposition clearly leads to high standards of performance. Amazingly, it seems that the quality of projects steadily rises.

LESSONS LEARNED

Some of the lessons we have learned – sometimes the hard way – since the ITL Laboratory opened its doors in January 1997, include:

Assess – Assess – Assess – If it’s worth doing, it’s worth measuring. Although our students occasionally complain of “death by assessment,” we thoroughly assess all facets of the ITL Program. Surprisingly, we continually garner new insights, even for well-worn initiatives.

The total assessment package of the First-Year Engineering Projects course consists of:

- Faculty/TA meeting prior to each semester
- Pre-survey of engineering skills at course beginning
- Weekly faculty/TA meetings to coordinate sections and maintain consistency
- Post-survey of engineering skills at course end
- One-hour mediated student focus group interview at course end
- Standard faculty course questionnaire at course end
- Several-hour faculty/TA debrief at semester end

This provides a wealth of data that we use to continually improve the course. We also administer surveys in all technical workshops offered in the ITL program, using student responses to inform future workshop offerings. We solicit feedback from ITLL users through annual surveys which form the basis for an extensive summer action list. And we recently launched a regular ITLL users’ group, which consisted of a focus group soliciting potential improvements to ITL course offerings and services. This is followed up by email progress reports to attendees to let them know that their input was both valued and acted upon.

People Make the Difference – Even though the ITL Laboratory is a modern, technology-rich learning environment, it would be ineffective without outstanding staff who thrive on helping students learn hands-on skills. We recruit to this goal, and we manage staff with this in mind, including the most thorough and comprehensive yearly goal setting and performance reviews in the college. We also make heavy use of student assistants, ranging from technical staff to help students during evening hours to specialized TAs who aid students with specific engineering skills such as SolidWorks CAD modeling.

Customer Service is our ONLY Policy – A significant portion of the ITL operations budget comes from student fees in the form of an Engineering Excellence Fund. Since our students are therefore literally our customers, we stress pervasively to our staff that our number one priority is providing the best service possible. Our students appreciate the ITL learning environment; they work with us to keep it clean, and we strive to keep the technology base fresh and functioning. For example, we are currently running the third generation of PCs throughout the ITL Laboratory since opening in 1997, and will do a facility-wide upgrade again in 2007.

Engage Students – If we truly consider students as our customers, then shouldn’t we solicit, respect and listen to their input? Early in the planning stages when we were articulating our emphasis on teamwork, students pointed out that there were very few places in the 500,000 sq. ft. engineering center where students could meet and work. This led to the successful team study rooms described earlier. When the laboratory plazas were shown in one of several design “charettes” open to all students and faculty, some students reacted negatively to the “fishbowl” aspect of such open, visible space. This led to breakout rooms adjacent to each plaza where small groups of students and/or faculty can convene in a more intimate setting. And students even visited the state legislature to lobby (successfully) for the ability to use student fees to support this type of capital construction project.

Everyone Needs a Garage – In our quest for a flexible, highly interactive learning environment, we sought to maximize programmable space that could be constantly used by students. Although we did include team storage lockers in each design studio to provide secure space for students to store tools and project supplies, many projects are simply too large to fit. As a result, we are always searching for places to store large projects in labs in the adjacent engineering center. Large, flexible-ball-designed secure storage areas would facilitate large projects, although care would have to be taken to avoid the inevitable clutter and chaos that characterize many garages.

Architectural Design Can Stimulate Creativity – The architectural design concepts of visibility and flexibility informed most design decisions. Design details to stimulate
student learning — such as maximizing day lighting and creating “vicarious learning” environments — were also high priorities in design of the ITL Laboratory. Starting with a building footprint, walls could only be added if they could be justified. Faculty and students report that they find the environment stimulating and engaging, and the facility is the most highly rated item on college-wide senior exit surveys.

**A Clear Vision Can Generate Resources** — As described earlier, one of our first tasks was to craft a concise vision statement. We spent many hours on the road articulating that vision to generate financial and intellectual support from potential donors, primarily industry and alumni. Our audience responded, and two-thirds of the $17.5M total project cost was raised, the first such funding structure for our campus.

**Every Successful Project has a Champion** — While a project of this scope requires the synergistic power that only an effective team can generate, it also needs someone to dedicate his or her entire energy and focus — like a laser — on its success. The co-authors of this paper assumed that role, and have continued since as its co-directors, a very successful leadership-sharing collaboration.

**CONCLUSION**

A comprehensive design/build experience can teach students at many levels much more than can be learned from textbooks. Hands-on design is an empowering way to gain an understanding of fundamental engineering concepts — and the manner in which engineers create things for the benefit of society. However, hands-on design is also resource-intensive, requiring continual investments in up-to-date facilities and equipment, and perhaps even more important, qualified staff committed to hands-on learning. The rewards of self-directed student learning and satisfaction — where students create their own knowledge real-time — are well worth it.

**REFERENCES**