

The Integrated Teaching and Learning Program: A Pioneering Learning Environment for 21st Century Engineering Education

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*“Tell me, and I forget.
Teach me, and I may remember.
Involve me, and I learn.”
— Benjamin Franklin*

Integrated Teaching and Learning Program
College of Engineering and Applied Science
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<http://itll.colorado.edu>

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Executive Summary

The College of Engineering and Applied Science is in the sixth year of a bold, College-wide program that models the real world of engineering where skills in communication, teamwork, and leadership, as well as the ability and self-confidence to define and solve open-ended problems, are demanded. A team of faculty and students defined and realized an ambitious vision for undergraduate engineering education reform:

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

The Integrated Teaching and Learning (ITL) Program integrates hands-on learning experiences throughout all four years and engages students in the design process from their first year. Cutting across all departments, the new curriculum vision demanded a new facility. The new ITL Laboratory, dedicated in April 1997, integrates leading-edge technology with the understanding and confidence borne of hands-on learning.

The ITL team designed, piloted, implemented and continuously refines a common *first-year design course* in which students work in interdisciplinary teams to design, build and test real products with real customers — products such as an assistive glove that a quadriplegic student uses to grasp a soda can. While experiencing the design process first-hand, students define customer needs, sharpen their presentation skills, manage their time and budget their own money. Preliminary retention figures indicate that a remarkably higher percentage of students who take this course remain in engineering into their third year.

The team transcended departmental boundaries and made theoretical concepts come alive, developing over 35 *experimental laboratory modules* to augment sophomore and junior theory courses. The “mysterious” mathematics of Fast Fourier Transforms are more compelling to students when an electric guitar generates the signal. Modules are key curricular components of new *interdisciplinary focus courses*, now offered in the ITL Laboratory. Simple “*hands-on homework*” experiments using basic household supplies put engineering science principles into real-world context. Keeping honey on a spoon illustrates the rate dependence of fluid viscosity more effectively than a “chalk and talk” lecture alone could ever do.

The team won legislative approval of the ITL project as well as state funding for one third of the cost. In partnership with our students, the rest of the \$17M ITL Program funding was raised by engaging alumni, industry and foundations sharing in our vision.

To support the curriculum reforms, a 34,400 sq. ft. Integrated Teaching and Learning Laboratory was created: a learning environment designed from the ground-up to support hands-on learning. The facility features first-year design studios, an active learning center, a computer simulation laboratory, an extensive computer network that integrates all the experimental equipment throughout two large laboratory plazas, capstone design studios to showcase student projects, group work areas to support student teams, shops where students turn their dreams into reality and interactive science-based kinetic sculpture galleries.

Unlike any other educational facility in the world, the ITL Laboratory *itself* functions as a *living laboratory* through exposed engineering systems and sensors integrated into the building, making its “pulse” accessible on the Internet as a technology and building systems resource.

Winston Churchill observed that “*first we shape our buildings, then our buildings shape us.*” During the 1997-98 academic year, 58 faculty taught 41 courses to more than 1,720 students — shaping their learning and our future in new and exciting ways.

in-te-grate (ɪn' tɛgrɪt') v. **1.** To make into a whole by bringing all parts together; to unify.

Imagine a Learning Environment...

- Where first-year students design a tracking system to keep an elderly person from wandering
- Where teams of sophomores “discover” dynamics by analyzing kinetic sculptures
- Where undergraduate students are so committed to completing an assistive technology design project for their disabled “customer” that they request lab access during spring break
- Where a team of aerospace, electrical and mechanical engineering seniors design and build an experiment that flies on the space shuttle, under their control
- Where students explore the innermost secrets of a building system in real time, on-line
- Where students actually enjoy the rigor of studying engineering
- Where students graduate with four years of hands-on, team-oriented problem-solving experience

The Integrated Teaching and Learning Program

All of these are happening today at the University of Colorado at Boulder as part of the College of Engineering and Applied Science’s Integrated Teaching and Learning (ITL) Program. The consensus among educators and practitioners nationwide is that engineering education must significantly change; the students, faculty and administration at CU agree. Through the College-wide ITL Program, CU has taken a bold approach to implementing systemic engineering education reform.

The engineering curriculum for the next century must be relevant to the lives of students and the needs of society. Reflecting the real world of engineering, we have expanded our teaching methods to exploit teaming, group learning, active learning and project-based design and problem-solving experiences in all four years of the curriculum. We have learned to value integration in addition to specialization.

The ITL Program is supported by the new Integrated Teaching and Learning Laboratory, a 34,400 sq. ft. hands-on learning facility that opened in January 1997. The architecture of this facility was driven *entirely* by curricular reform initiatives. It provides students with an interdisciplinary learning arena in which the principles of design are introduced during a student's first year; where theoretical engineering science courses in the middle two years are augmented with hands-on, open-ended discovery opportunities; and where interdisciplinary teams of seniors design, build and test real-world products.

College-Wide Curriculum Reform — The Process

Program Concept and Initial Planning — In early 1992, a small team of faculty, students and the Dean embarked on a bold venture — to completely revitalize the undergraduate curriculum by enriching it with hands-on, project-based learning, and to examine the traditional role of faculty. An interdepartmental *curriculum task force* solicited input from a broad customer base that included our own students, alumni and industry. Nearly 50% of the College’s 150+ faculty provided input; most of the original task force members are still actively engaged in ITL.

Engineers from Martin-Marietta Corporation (now Lockheed-Martin) guided us in the use of a formal process to define the design requirements for our revised curriculum. Early and frequent dialog with the Hewlett-Packard Company culminated in a \$3M equipment grant, one of the largest grants ever awarded by HP to a public institution, to outfit the ITL Laboratory with high-end computers, instrumentation and networking. The emerging ITL concept was also shaped by input from our Engineering Advisory Council, comprised of industry leaders who meet semi-annually to guide the College.

Curriculum Concepts Emerge — To illustrate the multi-dimensional and multi-level components of our revamped undergraduate curriculum, the ITL Program concept diagram, shown in Figure 1, emerged in late 1992. At its center are 2,300 undergraduate students pursuing bachelor's degrees in ten degree programs in six departments: aerospace engineering sciences; chemical engineering; civil, environmental and architectural engineering; computer science; electrical and computer engineering; and mechanical engineering. The inner ring represents the information technology component of the ITL Program: a computer network linking computers that support electronic lab notebooks, control of experiments, data acquisition and analysis, graphics and report preparation. Interdepartmental areas that focus on common fundamental concepts of engineering were defined: measurement and instrumentation, electronics and microprocessors, controls, heat transfer, fluid mechanics, structures and materials, manufacturing, and environmental engineering. The outer ring illustrates the curricular components of the ITL Program. These curricular elements support students' progress in becoming independent learners and effective team members — skills vital for lifelong learning and professional success. The curricular components include a first-year design course, integration of hands-on experimental modules and hands-on homework components throughout theory courses, and interdisciplinary capstone design courses.

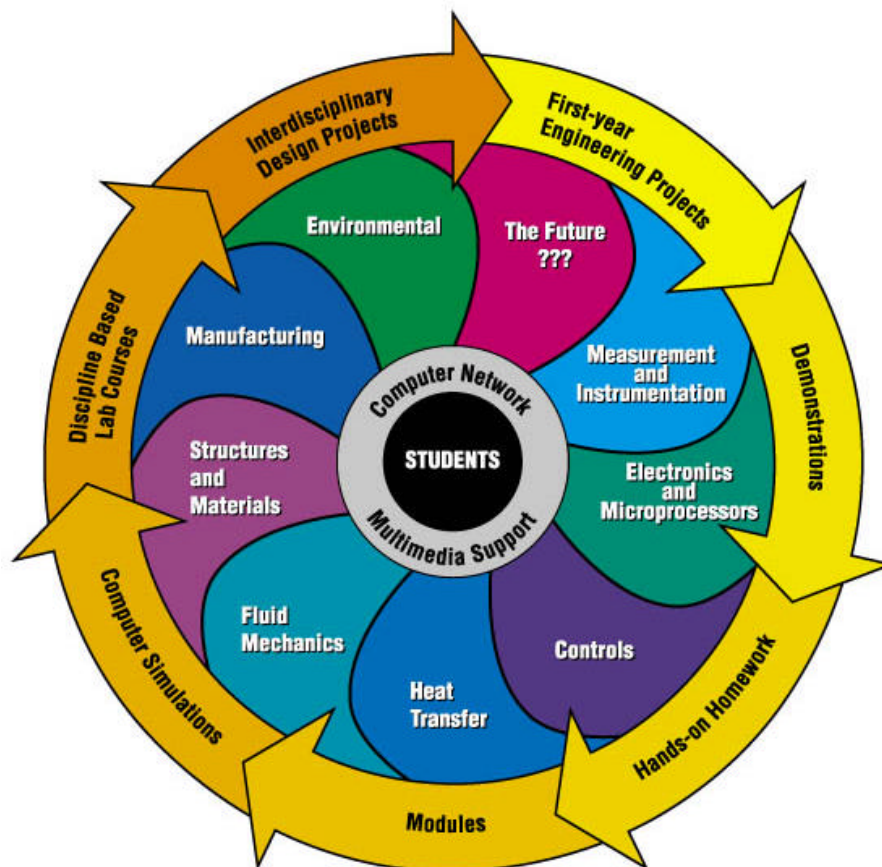


Figure 1. ITL Program Concept Diagram

Focus Areas Span All Departments — By late 1993, the work of the task force was augmented by the contributions of experimental focus area teams — groups of faculty from *multiple departments*

interested in common, specific topical areas such as fluid mechanics, controls and manufacturing. The focus area teams defined experimental modules that serve multiple departments by providing *hands-on experiences to augment theory courses*. For example, four departments teach courses in fluid mechanics. While retaining disciplinary specialization at advanced levels, the focus teams identified common underlying concepts and specified modules and equipment to support hands-on reinforcement of basic theoretical principles. The first two *interdisciplinary focus courses*, in fluid mechanics and electronics, inaugurated the new ITL Laboratory using in-class demonstrations and hands-on laboratory and homework experiences. Faculty throughout the College developed more than thirty-five experimental laboratory modules in various focus areas; all are exportable to other institutions.

Vital Student Support — since the inception of the ITL Program, the student body has provided an essential and unique source of financial and intellectual support. In 1991, forward-thinking undergraduate engineering students, with a referendum support vote from their peers, chartered the Engineering Excellence Fund (EEF) to sponsor College-wide curriculum innovation. Every engineering student now contributes \$100 each semester to the EEF, managed by a group of students, with the advice and approval of the Dean. This nationally unique *educational excellence fund* generates \$700K annually; half of that is committed to operational support of the ITL Program. The other half is competitively awarded annually to faculty and students for curricular and laboratory innovations throughout the College, much of which is complementary to ITL.

Our students have also been intellectual partners in the evolution of the ITL Program. They lobbied both the Colorado Commission on Higher Education and the state legislature to support the ITL Program and to change the state legislative rules to allow a portion of EEF funds to be used for capital construction costs. Several students served on the curriculum task force, and numerous students provided input into the conceptual design of the ITL Laboratory.

Successful Fund-Raising — The curriculum task force was instrumental in helping to privately raise two-thirds of the \$17M ITL Program funding. The team also led the project approval process through the state legislative system, which resulted in more than \$5M in state support for the program. Foundations that have supported ITL include the David and Lucile Packard, U S WEST, Hewlett-Packard, AT&T, and Gates Family foundations. The Hewlett-Packard Company, Quantum Corporation, National Instruments and Lockheed-Martin Corporation also were significant contributors to the implementation of the ITL Program.

The Vision Takes Shape — 1994 marked the offering of pilot ITL curriculum components, most notably the First-Year Engineering Projects course, as well as architectural design of the ITL Laboratory, which was entirely curriculum-driven. The ITL Program's emphasis on cooperative teamwork and active learning formats demanded spaces different from traditional laboratory and classroom configurations. The initial design meeting was held at the San Francisco Exploratorium to inspire project architects by experiencing the thrills of people of all ages engaged in open-ended discovery. Design of the laboratory was conducted as a College-wide, participatory process. All students and faculty were invited to a number of open-house-style design charettes to provide input. The potential to make the building *itself* a learning opportunity evolved as we engaged the architects and engineers in creative brainstorming sessions.

From the earliest phases of facility design through construction, the ITL co-directors provided strong project leadership, working collaboratively with Facilities Management and the external design and construction teams as *partners*. An all-day partnering session was held with the designers, contractors, and all major subcontractors to kick-off the construction phase. Imbuing them with the ITL vision and negotiating a process for collaborative and productive resolution of inevitable project conflicts, an environment for collaborative decision-making was established. In particular, the extraordinary complexity

of making the building itself a learning tool required an unprecedented level of creativity and coordination between faculty, architects and contractors. Unquestionably, the exciting hands-on laboratory facility that emerged from this intense process reflects the collective creativity of dozens of students and faculty.

By late 1995, ITL Laboratory construction was underway, the First-Year Engineering Projects course was refined and gaining acceptance by faculty throughout the College, and the Hewlett-Packard equipment grant was secured. A College-level curriculum revision in spring 1996 guaranteed that the First-Year Engineering Projects course fits into all majors.

The process and investments paid off: the ITL Laboratory building — with more capabilities than we ever imagined possible — was completed ahead of schedule and within budget.

External Review — To provide meaningful and objective critique, beginning in 1994 the ITL team invited faculty from a number of forward-thinking institutions, including principal investigators from four NSF engineering education coalition institutions, to serve as external reviewers of the ITL Program. Annual meetings with this group provide valuable feedback and mutual exchange of ideas, many of which have been incorporated into the ITL curriculum and facility. For example, a portion of the University of Maryland's Introduction to Engineering Design course provided inspiration for the design project portion of the First-Year Engineering Projects course. Likewise, the reverse engineering component of that course was adapted from Stanford's mechanical dissection concept. Unanimously, our external review panel applauds the value of the mutual exchange of ideas.

Celebrating Diversity in Learning Styles — CU's Engineering College has long-standing programs to support diversity in gender, race and culture in its student body. The ITL Program now enables us to celebrate diversity in learning styles as well. Women students make up approximately 20% of the student body and 23% of entering first-year students. Underrepresented minorities account for 8%. The College has a clearly articulated goal of improving the recruiting and retention of women and people of color into our engineering program. The nationally acclaimed Women in Engineering and Minority Engineering programs serve as advocacy organizations for both groups of students. The average retention rate (first to second year) for underrepresented minority students in engineering is a remarkable 70-80%, placing CU-Boulder among the top ten of all universities in the nation. The ITL Program, with curricular components that capitalize on group learning, experiential self-directed learning, and small group active-learning techniques, is designed to have a positive impact on retention of all students and should especially aid students who historically have felt isolated in the engineering education experience.

Tour the ITL Curriculum and Laboratory

Because the design of the ITL Laboratory was curriculum-driven, a tour of the facility provides an excellent way to describe the curricular elements that define the ITL Program. To realize the ITL curricular dream, several fundamental design concepts were incorporated into the laboratory design. *Flexibility* was vital to accommodate future, and unknown, teaching and learning methods. Because much of engineering is visually interesting, *visibility* was a key element in the design to stimulate students to study engineering by watching other students in action. Finally, the laboratory needed to be *interactive and stimulating* in order to function as a learning environment for our students, as well as its many visitors. The interior spaces showcase engineering in ways very different from traditional laboratories.

Bridging to the Future — An overhead bridge links the Engineering Center to the ITL Laboratory. Flanking one side are ten *group study rooms* that students reserve for teamwork. Each space contains round tables and white boards, with a computer connected to the ITL network for access to data as student teams analyze experimental results and prepare presentations.

A Place for Art in Engineering Education — A gallery of *interactive science-based sculptures* provides both intrigue and educational opportunities for students. One audio-kinetic piece features a fascinating maze of spiraling tracks with balls zooming down, seemingly at random. Sensors incorporated into the sculpture allow students to measure aspects of dynamics such as velocity and acceleration, and compare them to computer simulations. Using a video camera and a computer, students track the repetitive bounces of a ball on a steel plate, measuring the coefficient of restitution. This experiment, and several others, is also available on the Internet as a virtual experiment accessible for distance learning (<http://itll.colorado.edu>). A Taylor column provides a captivating display of rolling cells in a pearlescent fluid. All the sculptures possess this multiple level for learning potential and are targeted to expose elementary-age children, as well as college students, to the challenges and excitement of science and engineering.

First-Year Students Try On Engineering — Just past the gallery with its commanding view of the laboratory plaza below, students enter one of two *design studios* dedicated to the First-Year Engineering Projects course where they experience the engineering design process in a hands-on way [1]. The design of the studios was based on two years' experience piloting the course, and represents a significant departure from the conventional classroom. Small tables facilitate team communication, while work benches and hand tools support product design and construction. A computer with a myriad of software is available for each team. These spaces are two of six *smart classrooms* throughout the building that use network connectivity and high-resolution video projection to capitalize on the growing role of educational technology in the learning process.

During the last 4½ years, 36 sections of the First-Year Engineering Projects course have been successfully offered. The course is available to all first-year students in the College. In contrast to the often large, impersonal math and science courses, each section is limited to 30 students. The course goals include introducing students to the excitement of engineering and to the practical considerations of the design process, experimental testing and analysis, project management, oral and written communication, and working in multidisciplinary teams. Workshops on team dynamics, social style profiles, learning styles, and group communications progressively develop students' awareness and skills. Design reviews, presentations, written communications, cost considerations, and engineering design journals are key components of the first-year projects experience. The course also serves to cement the concepts first-year students concurrently learn in core physics, chemistry, and mathematics courses. Three main components characterize the course:

Mystery Artifact Challenge: In the first “ice-breaker” challenge, student teams deduce the function of six unusual “*mystery artifacts*.” Although valid scientific or engineering devices, their function is not immediately obvious. To solve the enigmas, students become resourceful and reach out to the engineering world and beyond, in part through the World Wide Web; they increase their knowledge and draw this knowledge into engineering. For example, a small steel cylinder studded with sharp trapezoidal projections turns out to be a hob for manufacturing spur gears. The student teams present their research and conclusions to the rest of the class.

Design Project: In the main eight-week *design project*, students experience the complete design-build-test cycle of product prototype development. Past project themes include:

- Rube Goldberg contraptions to perform ordinary functions in surprising ways;
- “Green” designs to make it easier for the campus recycling center to collect materials;
- Sensors that accurately measure a physical quantity, such as the amount of fuel remaining in a vehicle's tank, regardless of its orientation; and
- Assistive technology devices, e.g. a page-turner for an adult with cerebral palsy [2].

- Interactive learning exhibits aimed at teaching an engineering or scientific concept to children, either in a middle school class, or as an exhibit in a youth museum.

Reverse Engineering: A three-week *reverse engineering project* encourages student teams to learn about real-world design by dissecting and analyzing a product of their choosing. Past examples include:

- Measuring the release force on automatic release ski bindings & correlating it with published data;
- Making an old rusty internal combustion engine breathe new life;
- Successfully creating light bulbs in the laboratory; and
- Dissecting rock-climbing hardware and engaging the designer via e-mail.

The *outcomes* of this course are tremendous. Entry-level students are introduced to tangible experiences in engineering that stimulate further exploration and demonstrate the context and need for further study in advanced topics such as electronics, fluid mechanics and materials. Students learn to work cooperatively in teams, significantly improve their written and oral communication skills, and gain confidence by completing challenging yet attainable creative projects. Most importantly, students are exposed to the challenging, integrative, and fun nature of engineering early in their college experience.

Preliminary retention figures indicate that nearly 80% of students who took this course during their first year have remained in engineering into their third year, a remarkably higher rate than our 55% average. Students overwhelmingly report that this demanding design course gives meaning to their physics and calculus courses, and frequently cite it as their initial reason for selecting CU, and then for remaining in engineering. Individual students have said, “the applications aspect of the course has kept me in engineering,” and “it’s using your mind, not plug and chug.”

Recognizing the importance of hands-on experience, coupled with the large number of students who transfer into engineering after their first year, we are piloting a new sophomore version of this course in fall 1998. With financial support from the National Collegiate Innovators and Inventors Alliance, *Innovation for the Community* will focus on the invention and product development process. Students will design, build and test interactive learning exhibits for clients in the local educational community, experiencing first-hand the satisfaction achieved from meeting the needs of real customers with real products of societal value.

Opportunities for Open-Ended Discovery — In the past, sophomores and juniors studied heat transfer without feeling heat, or fluid mechanics without getting wet. The two 4,000 sq. ft. *laboratory plazas* at the heart of the ITL Laboratory change that. Dispersed throughout each plaza, designed to accommodate 60 students at a time, 15 custom-designed LabStations [3] — each an experimentalist’s dream — can access and analyze data from mobile experiments (see Figure 2). Standardized connectors allow pre-wired portable experiments to quickly connect to the LabStation. Each LabStation features an oscilloscope, signal generator, counter, multimeter and signal analyzer, all controlled by two PCs running LabVIEW software [4]. Each plaza features a 260 sq. ft. “smart” *breakout space* where students gather with the instructor for a short, stand-up discussion of an important nuance, then retreat to their LabStations to continue their experiments. The key experimental and curricular ingredients that provide effective use of these lab plazas include:

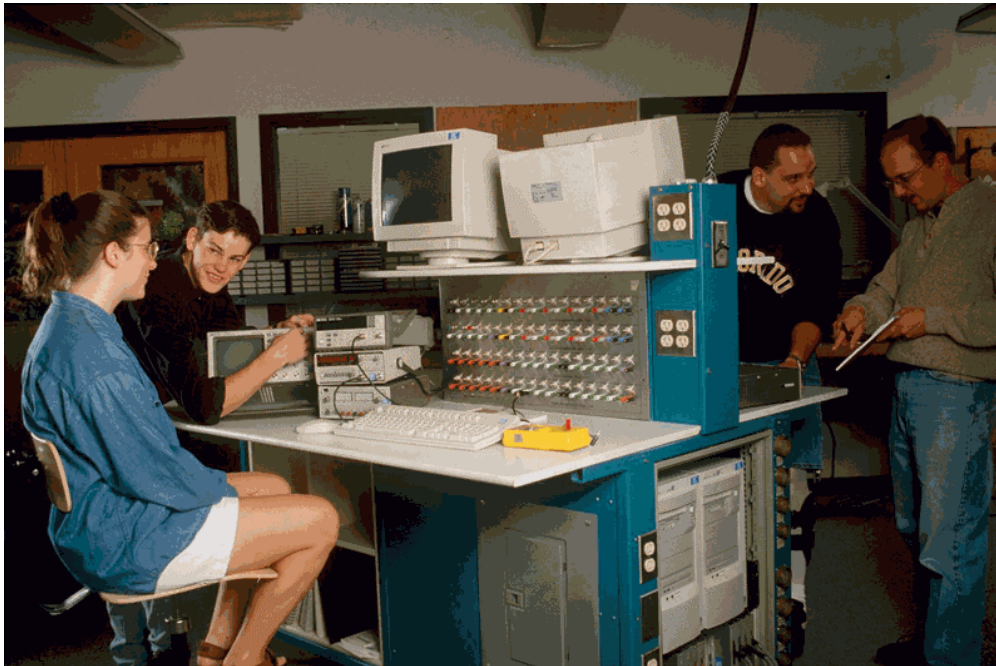


Figure 2. ITLL LabStations provide powerful computer and data acquisition capabilities for two teams of students to conduct hands-on experiments.

Experimental Laboratory Modules: Experiential learning is the cornerstone of the ITL Program. Recognizing that the undergraduate curricula cannot accommodate a traditional laboratory component in every course, *experimental modules* provide enhancements to traditional theory courses. Modules are small experiments mounted on carts that are wheeled to a standardized LabStation. These portable, modular experiments were developed for the interdisciplinary focus areas shown in the concept diagram (see Figure 1) by faculty teams that span multiple departments; many were developed by undergraduate students as senior design projects. Modules are open-ended to encourage learning by discovery. For example, a functioning model of an automobile suspension with variable mass, spring rate and damping, controlled with LabVIEW software, allows students to design, model and observe optimum response characteristics.

More than 35 experimental modules are in various stages of development. They are designed to be:

- Of multidisciplinary interest, crossing traditional departmental boundaries;
- Suitable for open-ended exploration;
- Stand-alone experiments requiring minimal supervision; and
- Sequence-independent.

Examples of modules already piloted in courses include:

- Dynamic strain analysis of a mountain bike — a bicycle instrumented with strain gauges allows students to measure stresses in real time.
- Compressible flow modeler — uses water to simulate supersonic flow conditions in air.
- Photoelastic stress — visualizes stress patterns in complex structures.
- Remote sensing — simulates the way satellites sense the earth from space.

Interdisciplinary Focus Courses: Interdisciplinary courses combine hands-on experiences into core engineering theory subjects. One such offering is a junior-level course in basic fluid mechanics coordinated

between civil and mechanical engineering. Fifteen experimental modules are utilized; some were developed at CU while others use commercially available fluid mechanics equipment. Fluids courses in aerospace and chemical engineering also use some of the experimental modules. Most of the experiments are open-ended, encouraging students to *discover* and *understand* fundamental fluid mechanics concepts by applying them. The College-wide Electronics for Non-Majors course relies heavily on the HP computers and electronic instrumentation.

Hands-on Homework: The assignment of laboratory experiments as homework problems provides students with an alternative mode of learning that permits practical reinforcement of theoretical concepts. Supported by a grant from NSF, hands-on homework (HOH) experiments augment theoretical courses. They are characterized by the use of relatively simple apparatus and materials that are typically available in the home. They generally involve solving a problem analytically, recreating the effect with a simple experiment, describing the experimental results qualitatively, or in an approximate quantitative way, and contrasting observations and analysis. Examples of concepts and simple materials used for exploration in HOH exercises in the area of fluid mechanics include:

- Instabilities of viscous flow down a sloped surface *using salad oil and a cookie sheet*
- Buckling flows *using liquid detergent poured onto a flat plate*
- Standing hydraulic jump *in the kitchen sink*

Thus far, 27 HOH are developed, 9 are in progress, and 16 are in planning stages. These experiments, because of their “low threshold, high ceiling” nature, are highly transportable to other institutions.

Seniors Struttin’ Their Stuff — Capstone design projects form the ultimate integrating educational experience, allowing seniors to apply the knowledge they have acquired to open-ended design projects with no “right” answer. Adjacent to the lower lab plaza, four *capstone design studios* provide a highly visible environment for long-term, in-depth projects with visual appeal. Observing seniors working on intriguing projects stimulates the interest of lower division students and makes them eager for their own design experiences. Each studio is equipped with a full complement of electronic instrumentation and a computer. Student teams compete for the limited space, which becomes their secure working environment for an entire term, or year, depending on the project.

Use of these design studios during the ITL Laboratory’s inaugural year was diverse, including:

- “Things That Think,” an interdisciplinary Computer Science course in which students created and tested small intelligent devices
- A racecar powered by a motorcycle engine that competed in the national Formula SAE competition in Detroit in May 1998.
- The Robotic Autonomous Transport (RAT) – a robotic vehicle that can navigate an outdoor course delineated by two white lines and avoid numerous obstacles in its path. This unique vehicle won second place overall in a national competition in May 1998.
- Human-powered submarine
- Remote micro surveillance airplane

Modeling the Real World — Analysis characterizes engineering design, allowing numerical models to accurately predict the behavior of a complex design before it is built. The *Simulation Laboratory* features 25 high-performance UNIX workstations with simulation software that students use to predict stresses in a complicated structure, estimate heat transfer behavior or model complex fluid flow phenomena. Moreover, students learn that simulation is an integral part of the engineering design and manufacturing process that goes hand-in-hand with testing in the laboratory. Three high-resolution color monitors face out from the lab allowing students to showcase their simulation and animation work.

Active Learning: An Alternative to Lectures — More effective than the traditional “chalk-and-talk” lecture format is the active-learning approach in which lecture is minimized and replaced with intense team-based student interactions. Students stay alert, are engaged, and learn more. The Active Learning Center is designed to support the needs of a more student-centered learning approach. Serving 65 students at a time, this reconfigurable “smart” space features oval tables to accommodate small-team interactions.

In fall 1996, the active-learning format was piloted in an Applied Data Analysis course. This required statistics class, with a reputation of being dry and boring, has historically yielded poor course evaluations. In the active-learning format, each 75-minute class period opened with a short Q&A period followed by a mini-lecture introducing new material and a brief example problem. Students then spent about 30 minutes in teams of four conducting hands-on workshops designed to reinforce the statistical concepts being studied. For example, students measured water temperature from drinking fountains, obtaining real data to subsequently compare and analyze with other teams' data to discover trends and correlations. They timed auto traffic outside the Engineering Center and compared their results to a Poisson distribution.

Another difficult required Chemical Engineering controls course was taught using the active-learning format last year. The professor, who had taught this course 19 times previously, received the highest student evaluations (A+) he had ever received. The professor's assessment was that, in addition to being significantly more engaged, students learned at least as much as prior classes.

Create What You Dream — “It *always* works on paper.” But, as any practicing engineer can attest, the proof is in the fabrication and implementation of a design. Included within the ITL Laboratory is the capability to build mechanical and electrical components and systems. The *Manufacturing Center* contains a wide variety of computer-controlled and conventional machine tools for metal, wood and polymer fabrication, including rapid prototyping with engineering polymers directly from a CAD model. The *Electronics Center* allows students to breadboard and test electronic circuits. Technical staff helps students learn to safely fabricate their designs. These shops restore a hands-on manufacturing capability once prevalent in engineering education.

A Living Laboratory — A modern building is an ideal example of the integration of multiple complex engineering systems. A one-of-a-kind educational facility, the new ITL building *itself* is an interactive teaching tool, with the capability to *expose*, *monitor* and *manipulate* the many engineering systems inside. In a hands-on, real-world way, this capability helps to educate both engineering students and the general public about the multidisciplinary science and engineering technology found in today's structures, as shown in Figures 3 and 4 [5].

To *demonstrate* engineering principles and practice, building elements that are usually hidden above ceilings, behind walls or in equipment rooms are *exposed*. Interpretive signs highlight these features for the self-guided visitor. For example, the air-handling unit that ventilates and cools the entire building is



Figure 3. The machine room is color-coded and visible behind a glass wall.

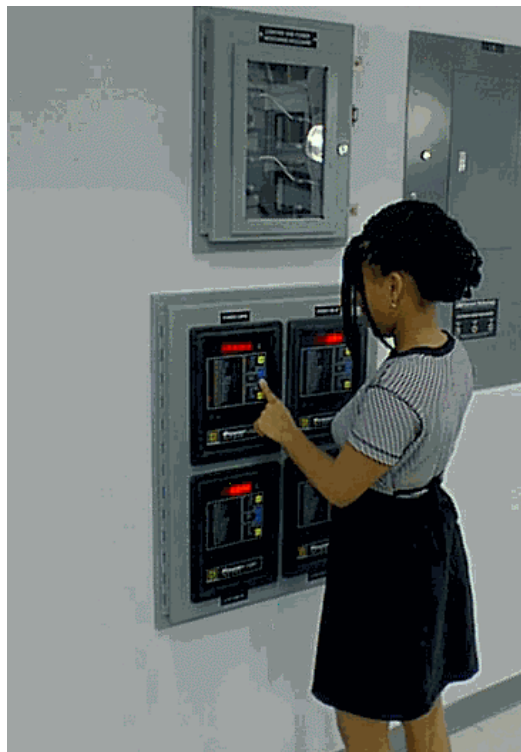


Figure 4: Square D Power Logic monitors electrical system performance.

visible behind a glass wall. A prominent design feature of the laboratory is a five-foot diameter duct and its myriad of branches that carry the HVAC air supply throughout the three-story facility. Several types of concrete and steel structural framing are conspicuous, including a yellow 40-foot truss spanning a large bay. Even before its completion, the truss and large exposed ductwork have inspired many such questions from visitors. Numerous transparent “slices” reveal the building’s infrastructure, including water flowing in a transparent pipe, the elevator shaft and equipment room, dampers inside a mechanical VAV box, etc. A peek into the wall separating the bathrooms reveals...plumbing, but little else! Reinforcing steel on the *outside* of one concrete column and beam illustrate and mirror the maze of re-bar hidden inside, making the building itself a tutorial in construction engineering.

From instrumentation placed in building components, more than 200 precise *measurements* are taken in real time to monitor the status of the building systems, thermal environment, structural loading and electrical load profile. An extensive digital network controls the HVAC system and reveals its “pulse” on computer workstations in several locations. Also measured are temperature stratification in a three-story atrium, temperature distribution through five different wall sections, thermal performance of several different types of window glazing, outside soil temperature along the foundation wall, fin tube heater performance, etc. Steel framing and concrete caissons are equipped with strain gauges to measure stresses, and the use of optical fibers embedded in concrete to measure building strain is being pioneered. These data are sampled every minute, and will be accessible on the World Wide Web beginning fall 1998 in a variety of formats.

Manipulation of building systems presents unique learning opportunities. One of the two first-year design studios has conventional pneumatic temperature controls, while the other uses separately programmable direct digital control. Students testing different control algorithms can experimentally manage the climate in the second room. A parallel experimental computer network provides students the opportunity to experiment with network management without jeopardizing the laboratory’s main network.

It is clear that, in addition to its important role in engineering education for CU students, the ITL Laboratory will serve a broader role as a technological museum. In addition to *educating* visitors about engineering, it will hopefully *motivate* young people towards careers in engineering. Many “building-as-learning-tool” concepts were utilized in civil engineering courses during construction of the ITL Laboratory, and many courses throughout the College will use this rich capability as they come on-line.

ITL Program Assessment

The College is committed to assessing the total qualitative and quantitative impact on student learning of the tightly coupled facility, equipment, and curricula that represent the ITL Program. Assessment initiatives underway include:

- In-depth surveys, with in-person follow-up if requested, of the 58 faculty who taught in the ITL Laboratory during its inaugural year. Response was overwhelmingly positive, and many suggestions for improvements are being implemented to continuously enhance the learning environment. Students will also be surveyed during the coming academic year.
- Mid-semester group consensus feedback approaches are employed in all sections of the First-Year Engineering Projects course to better understand student needs and to provide input for mid-semester corrections.
- Students who took the First-Year Engineering Projects course are interviewed two years later through focus groups to assess the longer-term value of the course.
- The College engaged the expertise of Elaine Seymour, Ph.D., to evaluate College-wide plans to assess the effectiveness of the ITL Program. Author of the renowned study *Talking About Leaving: Factors*

Contributing to High Attrition Rates Among Science, Mathematics and Engineering Undergraduate Majors, Dr. Seymour is regarded as a national expert in this area.

- Two semesters ago, College-wide questions were added to all the faculty course questionnaires to assess the course content for design, computing, communication, and teamwork components. We are using the results of these questions to chart and assess the flow of each of these elements through the four years of each of our major curricula. This information will next be used to guide departments in revising curricula, as needed, so that all students experience a steady stream of design, computing, communication, and teamwork experiences in each semester of their undergraduate program.
- A \$20K “seed money” grant was recently secured for planning and instituting a longitudinal assessment plan to better understand the outcomes of the ITL Program.
- We assess students’ attitudes, beliefs and knowledge before and after taking the client-based sections of the First-Year Engineering Projects course. This will help us to fine tune the class and to learn if students are gaining the experiences we expect.
- Mid-semester and end-of-semester qualitative and quantitative assessment are performed on those theory courses that incorporate hands-on, open-ended, experimental modules and hands-on homework to assess the added value of the experiential components.
- Three to five years after graduation, alumni will be surveyed to assess the relative value of various components of the ITL Program on their undergraduate experience. Suggestions will be solicited to evolve the curriculum to make it more relevant to needs in the “real world.”

K-12 Outreach: The Pipeline

The ITL Laboratory is used by University students primarily during the nine-month academic year. This leaves opportunities for summer outreach programs that extend hands-on learning experiences to K-12 schools in order to excite students and teachers about the future of a career based on a technological education. The ITL Program was recently awarded a prestigious \$1.4M Program of Excellence grant from the Colorado Commission on Higher Education to foster outreach activities.

We exploit the ITL Laboratory during the summer months for K-12 outreach purposes to:

- Develop and implement week-long hands-on *science and math workshops* for K-12 teachers (using the program design from the San Francisco Exploratorium as a starting point);
- Offer a series of hands-on *science and math summer camps* for fifth, seventh, ninth and eleventh grade children throughout the state;
- Develop and pilot an age-appropriate and fun week-long *fluid dynamics curriculum* — “Go with the Flow” — for middle school students, and train teachers to implement it;
- Develop and offer a “Kinetics for Kids” workshop, capitalizing on the stimulating and engaging kinetic sculpture exhibits throughout the laboratory; and
- Pilot the Success Institute, an intensive two-day introduction to engineering opportunities for 20 African-American middle school students (and their parents) from Denver.
- Offer an Upward Bound program for 50 Native American high school students, a six-week long program of computer skills, science, English composition, and traditional beliefs, in collaboration with the American Indian Science and Engineering Society (AISES)
- Conduct ongoing field trips and special tours for summer camps and science programs throughout the region.

The intent of the teacher workshops is to develop and export low-budget yet creative and integrative hands-on science and math experiments that can be replicated at low cost in local school districts and applied throughout the K-12 curriculum. Improving the knowledge and confidence of K-12 teachers in hands-on

math and science impacts many impressionable youngsters. The technology-rich ITL Laboratory serves as an excellent environment for exposing teachers and children to the possibilities that a technological-based future offers, and to make the world of science and technology seamless and approachable to learners from age five on.

The College is committed to developing this outreach program as an effective way to impact the “pipeline” of future scientists and engineers. School children, beginning with kindergarten, will enjoy the ITL Laboratory as a hands-on science museum as they explore the challenges presented by the myriad of museum-quality science-based sculptures.

Lessons Learned

The planning and implementation of a new undergraduate engineering program, and a state-of-the-art facility to support it, has been a tremendous learning opportunity for all of those involved. In order that what we have learned might help others, we offer some tips to bring about change:

Tips for Change

- THINK BIG!
- Make it a team effort – practice teamwork
- Find passionate advocates and reward them for incremental change
- Commit for the long haul
- Demonstrate a passion for change
- Pilot curricular aspects early
- Assess impact and advertise early results
- Continuously improve
- Solicit external feedback
- Stay positive – believe that change *is* possible

Provide Resources – People

- Broaden faculty horizons (e.g., ASEE, FIE, NCIIA)
- Treat curriculum reform as scholarly activity, and reward it financially
- Provide staff “enablers”

Provide Resources – Equipment

- Force collaboration – e.g., equipment must be used by at least three departments
- Encourage departmental cost-sharing
- Require curriculum development *and documentation*
- Let faculty determine priorities (within clear constraints)

Provide Resources – Culture

- Solicit feedback
- Act on suggestions
- Continuously improve

Provide Resources – Moral Support

- Recognize *and value* risk-taking
- Create a safe, trusting environment
- Share the success - give faculty visibility to Chairs and Deans
- Give praise and say thanks... often!

Overcome Inertia

- Make progress *every day*
- Be clear about what you intend to accomplish
- Focus – like a laser
- Don't confuse effort with results
- Have fun!

Conclusion

The new ITL Laboratory culminates the vision and years of planning and risk-taking by a dedicated team. We first revitalized the curriculum, and then made our dream of a magnificent hands-on learning laboratory to support that curriculum become a reality. Both the curriculum and the laboratory are dynamic, evolving entities. We eagerly look forward to continuing what has driven us — *the excitement of learning by doing*.

The ITL Program continues to be a leader in undergraduate engineering education reform. The program and laboratory are well planned, well supported, and well understood. The ITL Program prepares students for meaningful engineering careers, both today and tomorrow. At a time when knowledge doubles every seven years, our graduates are better prepared to face the challenges of a diverse economy based on technological progress, international economic competitiveness, communications, and sustainable development. CU will continue to lead the way, and to demonstrate that, given a clear vision of the need and direction for change, a large public institution *can* take a national leadership role in engineering education reform and thus prepare students to build things that benefit society. We have just begun to tap the possibilities.

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