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Hands-on Engineering: Learning by Doing in the Integrated Teaching and Learning Program*

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An integrated teaching and learning (ITL) program was initiated in 1992 by a team of faculty and students who articulated 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 ITL Laboratory was dedicated in 1997 to support this college-wide vision. This paper describes the development process of this new facility and its major features. The underlying educational value is also discussed. Outreach activities are described, including a unique on-line system where experimental modules are made available on the WorldWideWeb.

INTRODUCTION

'Tell me, and I forget.
Teach me, and I may remember.
Involve me, and I learn.'
Benjamin Franklin

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 a space shuttle, under their control;
- where students explore the innermost secrets of a building system in real time, on-line.

All of these are happening today as part of the 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 the University of Colorado (CU) agree. 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, the ITL program exploits teaming, active learning and project-based design and problem-solving experiences in all four years of the curriculum.

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.

The ITL Laboratory 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.

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THE DEVELOPMENT PROCESS

Program concept and initial planning

In early 1992, a small team of faculty, students and the Dean embarked on an ambitious venture—to 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 students, alumni and industry. More than 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) led a formal process to define the design requirements for the revised curriculum. Early and frequent dialog with Hewlett-Packard Company culminated in a $3 m 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 the Engineering Advisory Council, comprised of industry leaders who meet semi-annually to guide the college. An External Review Board, formed in 1994, meets annually to provide meaningful and objective critique.

Curriculum concepts

To illustrate the many components of the ITL program, a concept diagram emerged in late 1992, shown in Fig. 1. At its center are 2,400 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

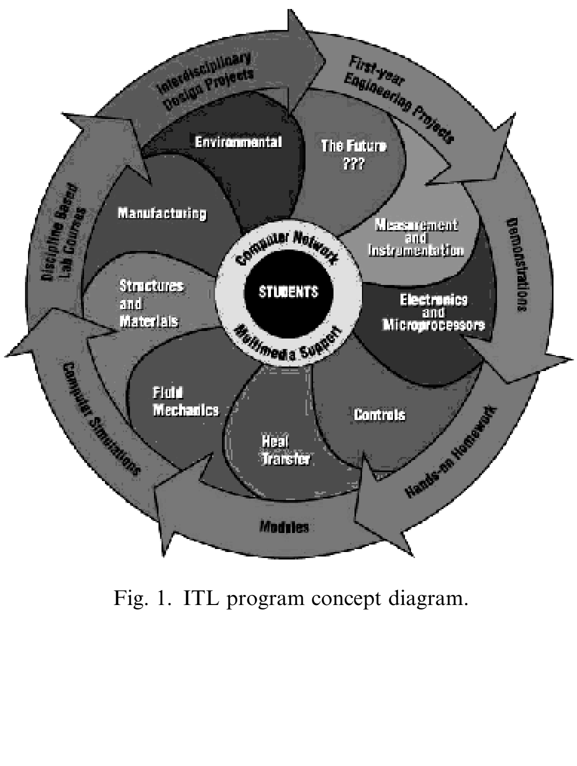

Fig. 1. ITL program concept diagram.

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.

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, an essential and unique source of financial and intellectual support has been provided by the student body. 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 fund generates $700,000 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.

Students were also 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 \$17 m ITL program funding. The team also led the project approval process through the state legislative system, which resulted in more than \$5 m in state support for the program. Foundations that have supported ITL include the David and Lucile Packard, US 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 co-operative 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 the architects and engineers engaged 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 co-ordination 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 under way, 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 was completed ahead of schedule and within budget.

MAJOR PROGRAM FEATURES

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 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 team work. Each space contains a round table 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 (Fig. 2). This experiment, and several others, is also available on the Internet as a virtual experiment accessible for distance learning (http://bench.colorado.edu). All the sculptures

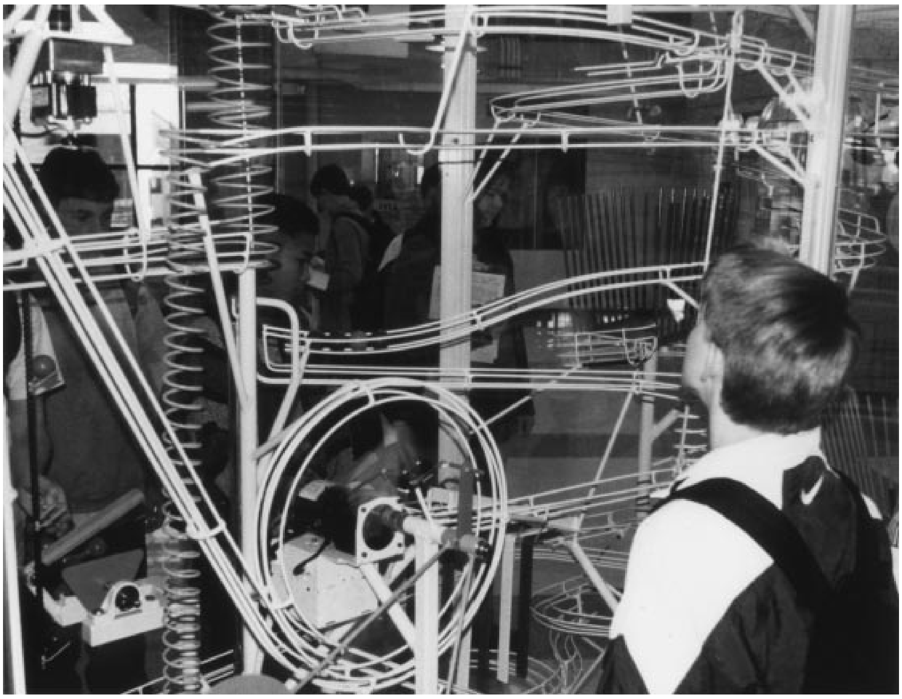

Fig. 2. This kinetic sculpture intrigues all visitors to the ITL Laboratory, and is used for quantitative experiments in dynamics by engineering students.

possess this multiple level for learning potential and are targeted to expose elementary-age children, as well as college students, to the excitement and discovery 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* (Fig. 3) 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.

Fig. 3. Design studios support the first-year projects course.

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 past $4\frac{1}{2}$ 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.

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.
- 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.

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 the college's 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, the co-authors piloted a new sophomore version of this course in fall 1998. With financial support from the National Collegiate innovators and inventors Alliance, innovation and invention focuses on the invention and product development process.

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* (Fig. 4) at the heart of the ITL Laboratory change that. Dispersed throughout each plaza, designed to accommodate up to 90 students at a time, 15 custom-designed LabStations [3] access and

Fig. 4. Large, open laboratory plazas showcase engineering education in action.

analyze data from mobile experiments. Standardized connectors allow pre-wired portable experiments to quickly connect to the LabStation (Fig. 5). 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 *break-out space* where students gather with the instructor for a short, stand-up discussion of an important nuance, then return to their LabStations to continue their 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 Fig. 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;
- standalone experiments requiring minimal supervision;
- 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.
- Musical signal analysis—students study dynamic signal analysis using inputs from various musical instruments and computing Fast Fourier Transforms.

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.

Seniors struttin' their stuff. Capstone design projects form the ultimate integrating educational

Fig. 5. LabStations provide flexible data acquisition capabilities for a diversity of experimental modules.

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 an international competition in May 1998.
- 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 20 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.

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 re-configurable 'smart' space features oval tables to accommodate small-team interactions.

Create what you dream. 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 help 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 Figs 6 and 7 [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 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. 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 280 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

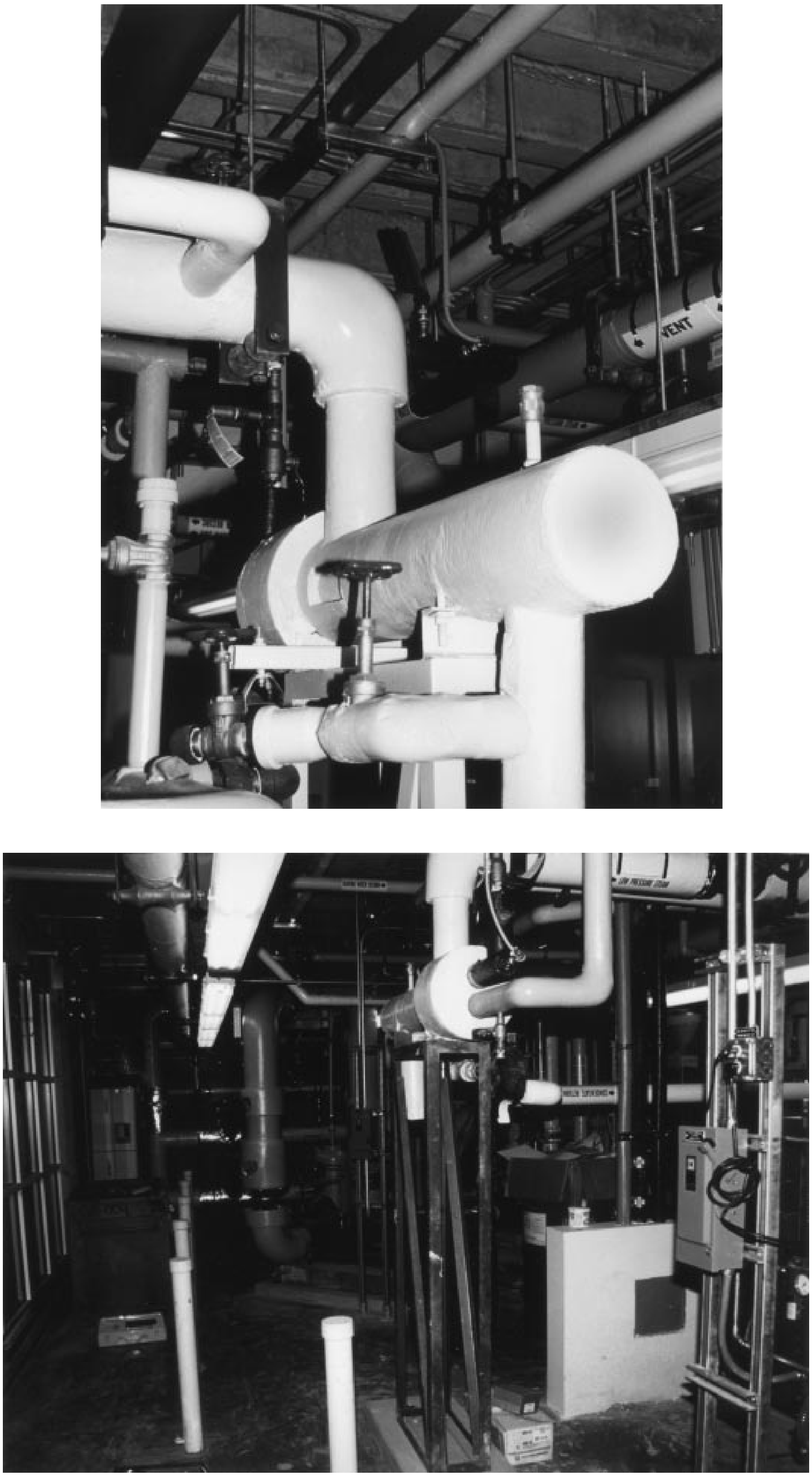

Fig. 6. Exposed features of the building demonstrate how buildings function. In this case, the mechanical room is exposed, with color-coded piping.

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 are accessible on the WorldWideWeb at http://blt.colorado.edu 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

Fig. 7. More than 280 sensors integrated into the ITL Laboratory monitor its pulse, such as the electrical system.

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.

In addition to its important role in engineering education for CU students, the ITL Laboratory serves 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.

INITIAL STATISTICS

In its initial year of operation during the 1997–98 academic year, 62 faculty (out of 150 in the college) taught 49 separate courses, with a total of 79 sections, to 2,580 undergraduate students. As shown in Fig. 8, all six engineering departments utilized the new facility, in addition to the applied mathematics department, and general engineering projects courses. Also, approximately 8,000 school children visited as part of the ITL outreach mission.

Modeling teamwork

While the new laboratory facility has exceeded everyone's expectations, it is the team of professional and student assistant staff that makes the ITL Laboratory a world-class learning environment. Seven technical staff members, assisted by more than 20 student assistants, are imbued with the high quality, service-oriented attitude that pervades the organization. Weekly staff meetings focus on meeting the needs of ITL's primary customers—the students.

Students are a key part of the ITL team. All students who want after-hours access to the laboratory or a computer log-in must first take a half-hour orientation tour conducted by students. They each sign a contract agreeing to expected standards of conduct while using the ITL Laboratory. Student employees also serve as after-hours security patrollers. Wearing purple vests to identify them as ITL Laboratory staff, they not only monitor after-hours use of the laboratory, but they answer questions students may have, and provide useful data on after-hours usage patterns.

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 satisfaction surveys, with in-person follow-up if requested, by 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.

- Group consensus feedback approaches are employed in all sections of the First-Year Engineering Projects course to obtain in-depth information.
- 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.
- College-wide questions were added to all the faculty course questionnaires to assess the course content for design, computing, communication, and teamwork components.
- Students' attitudes, beliefs and knowledge are assessed before and after taking the client-based sections of the First-Year Engineering Projects course. This helps to fine tune the class and determine if students are gaining the experiences expected.
- 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 to evolve the curriculum to make it more relevant to needs in the 'real world' will be solicited.

K-16 INTEGRATED ENGINEERING OUTREACH

Preparing children with the skills necessary to flourish in an increasingly technological world becomes more challenging every day. Our model for an integrated K-16 engineering community is designed to demonstrate, through doing, that engineering is about building things to help people and society. Beyond the pipeline issue—nurturing enough motivated students to study engineering and technology—lingers a growing concern for general technological literacy. The more members of society who understand the nature of technology, how it transforms social systems, and the ramifications of technology on culture, the greater likelihood we as a nation will continue to prosper.

The K-16 Engineering Outreach Vision is:

> To create a K-16 learning community in which students, K-12 teachers and the college of Engineering explore, through hands-on activities, the role of engineering in everyday life, and, to apply and appreciate the art of engineering through designing and building solutions to meet the needs of society.

To meet today's challenges, the ITL program is reaching beyond the campus walls and deep into the K-12 community. The ITL program was recently awarded a prestigious Program of Excellence grant from the Colorado Commission on Higher Education to foster outreach activities and model the integration of engineering principles and practices into a seamless K-16 community. Arbitrary barriers of age and grade level fall away as students acquire and integrate first-hand knowledge in mathematics, engineering and technology. University engineering students are enriched as they:

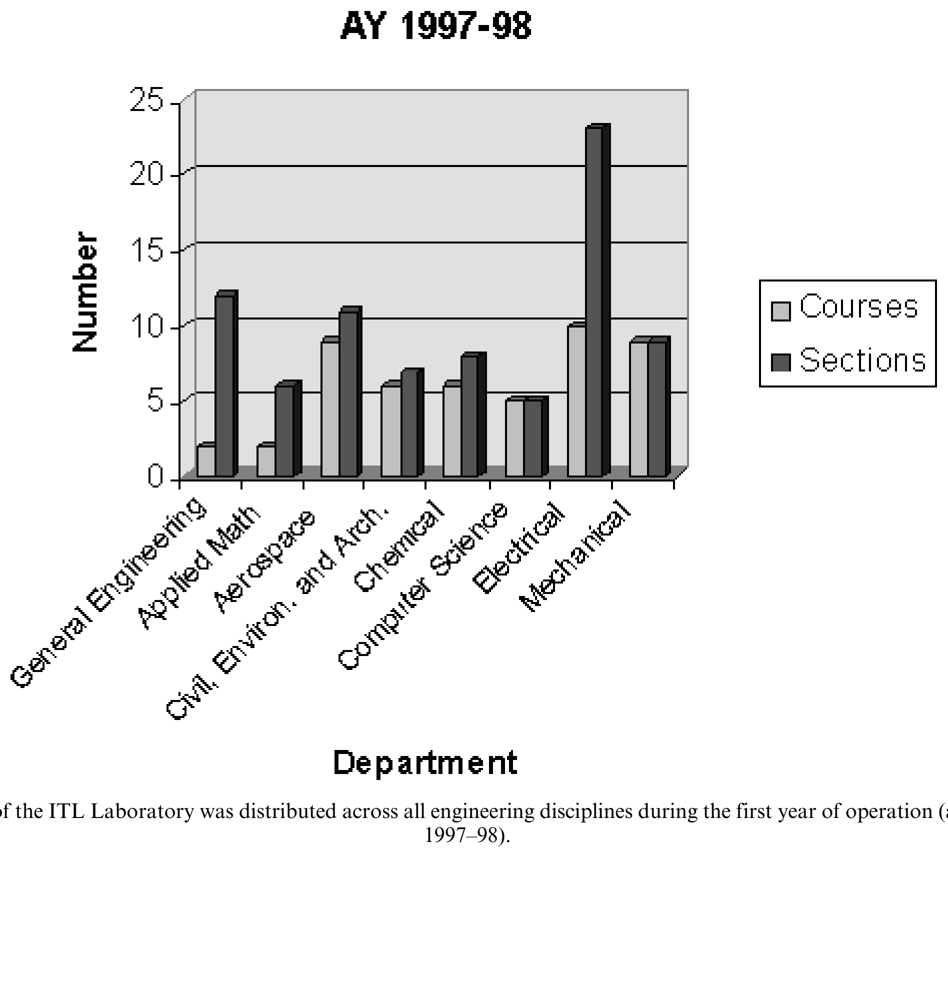

Fig. 8. Usage of the ITL Laboratory was distributed across all engineering disciplines during the first year of operation (academic year 1997–98).

- design and build devices to serve the broader community;
- help develop and teach summer K-12 engineering workshops;
- participate in design initiatives throughout their undergraduate experience;
- create a comprehensive on-line technology education resource;
- mentor K-12 students, especially those from traditionally under-served populations.

The three interrelated K-16 outreach program components are:

- Design for the community
- Engineering in everyday life
- Advancing under-served audiences.

Design for the community. Engineering students in several sections of the projects courses described earlier design and build sophisticated client-based projects that anchor their learning experience while creating useful engineering products for the community:

- Assistive technology—custom products to aid people with disabilities.
- Museum exhibits—for science and youth museums.
- Interactive learning exhibits—for elementary and middle school classrooms.

Projects from recent semesters include a specialized bed for a child with Down's Syndrome, a portable desktop tornado, an interactive bubble exhibit that illustrates varying gas densities, and a demonstration of the ability of soils to buffer acid rain. These client-based projects promote university/community collaborations while benefiting individuals and institutions locally.

Engineering in everyday life. This initiative promotes technological literacy by developing interactive, hands-on pre-college engineering workshops, based on the K-12 educational standards developed by the state of Colorado. The two primary elements of the program are: *workshops* for students and teachers, and *websites* and *networking* opportunities.

Engineering faculty and students team with middle and high school teachers to develop hands-on pre-engineering activities, curriculum modules and resource guides. These materials form the basis for week-long summer workshops: 'Engineering in everyday life' workshops for K-12 children, and design and build workshops for teachers. Examples for summer 1999 include:

- Go With the Flow—fluid mechanics for middle school.
- Kinetics for Kids—dynamics and chemical kinetics for 10–12 year olds.
- Too Hot to Handle—thermodynamics and heat transfer for 11–14 year olds.
- How Do Things Work?—dissection of electronic and mechanical components for 11–14 year olds.

All learning materials developed during summer 1999 teacher workshops will be posted on a website to encourage networking among workshop participants and dialogue with others interested in the subject matter, as well as to ensure that teachers are comfortable with use of the World-WideWeb. When the teachers return to their classrooms they will be encouraged (and coached) to stay connected to each other via the website to share successes, trouble-shoot problems, and maintain contact with CU content specialists.

Advancing under-served audiences. The goal of equity/equality is to ensure that broad ranges of students have access, opportunity, participation and success in mathematics and pre-engineering. The successes of the college's Women in Engineering and Minority Engineering programs are enhanced by providing hands-on learning experiences through the ITL Laboratory that expose students to the challenging and fun world of engineering at critical points in their K-12 careers, when they can still make pivotal academic and life choices. Upcoming outreach initiatives targeted at under-served audiences include:

- Pre-college experiences for girls and children of color to capitalize on diverse learning styles.
- Development and piloting of a summer design/build engineering course for high school students between their junior and senior years.
- Pre-college workshops for rural students that motivate technology-based careers.
- Development, piloting, and refinement of a concentrated summer First Year Engineering Projects course designed to 'jump-start' first-year engineering students considered 'at-risk'.

ON-LINE LABORATORY EXPERIMENTS IN MECHANICS

In order to make the ITL Laboratory more accessible both on-campus and beyond, a unique on-line experimentation program was developed to capitalize on the latest in information technology: virtual instrumentation, high-speed networks, and the WorldWideWeb. Many permutations of an ITL Laboratory experiment are run to create a large experimental database. Engineering students from community colleges and other universities connect from a remote site to 'run' experiments that randomly access the stored data. As a result, they have access to hands-on experience to supplement their existing courses, without the tremendous cost associated with these experiments. They generate and analyze real data to supplement existing engineering courses, just as students do inside the ITL Laboratory.

Experimental modules

At present, ten on-line experimental modules are available to users at http://bench.colorado.edu.

A summary can be found at http://bench.Colorado.EDU/presentation. The modules are:

- Mechanical Behavior of Materials—the mechanical properties of aluminum using a tensile test.
- Heat Treatment of Aluminum: the effects of heat treatment on the mechanical properties of aluminum.
- Coefficient of Restitution: determination of the material type for three different balls by analyzing their bounce characteristics in a unique kinetic sculpture.
- Dynamics of Fluid Flow: the behavior of a transient fluid flow system.
- First-Order Systems—the Thermocouple: an introduction to first-order modeling response.
- Sound Experiment: an introduction to Fourier transforms and sound frequency analysis.
- Torsion Test Experiment: determine the shear modulus, shear stress, and strain using a torsion test.
- Beam Deflection Experiment: an introduction to the theory and application of beam deflection.
- Statistical Similarity: a laboratory that introduces statistical testing methods for variance and mean similarity.
- Composite Testing: a two-part laboratory that demonstrates the fabrication and tests the elastic response of a composite specimen.

The strengths of the on-line program include:

- By utilizing modern computer and communication technology, the state-of-the-art ITL Laboratory facilities are available to students off-campus at a minimal cost.
- The hands-on experience supplements existing courses at other institutions.
- Students access real data, not computer simulations.
- The technology is readily accessible to students and faculty 24 hours a day.
- On-campus students benefit as well, by having after-hours access to reinforce concepts learned during actual experiments.
- Once in place, experiments can be run for years with minimal maintenance.

The plan is to continually expand the available modules/experiments, creating a growing library. Universities worldwide can add their own state-of-the-art experiments to exponentially expand the resource base. Future experiments from industry will help students 'simulate' their roles in industry before actually getting there.

CONCLUSION

The new Integrated Teaching and Learning Laboratory culminates the vision and years of planning and risk-taking by a dedicated team, beginning with the concept of a revitalized curriculum. Both the curriculum and the laboratory are dynamic, evolving entities. Now that the laboratory is in its second year of full-time operation, the driving force for all of those involved continues to be same as for the students—*the excitement of learning by doing.*

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