Abstract: This paper describes the Integrated Teaching and Learning Laboratory (ITLL) of the College of Engineering and Applied Science. Not only does the building support and drive our curriculum but the design of the building was curriculum driven. In fact, the building itself serves as a laboratory instrument with more than 280 sensors embedded throughout the building, and the opportunity to perform experiments on the building itself. All the sensor data are available on the web. The ITLL is truly an example of Winston Churchill's quote: 'first we shape our buildings and then our buildings shape us.'

Introduction

The College of Engineering and Applied Science has recently built a new laboratory facility designed to enable hands-on, team-oriented learning across all of its six departments. The three-story, 34,400 sq. ft. Integrated Teaching and Learning (ITL) Laboratory opened its doors in January 1997 with full scale operation in August of 1997. Its curriculum-driven design accommodates a variety of learning styles and features two first-year design studios, an active-learning arena, a computer simulation laboratory, a computer network integrating all the experimental equipment throughout two large, open laboratory plazas, capstone design studios, group work areas and student shops.

Designing this facility from the ground up has given us a unique opportunity to use the building itself as an interactive teaching tool to give students, as well as the public at large, an appreciation of the variety of engineering concepts and systems implicit in any modern building. Included in the "building-as-learning-tool" (BLT) concept of the laboratory is the capability to expose, monitor and manipulate the facility’s many complex engineering systems.

In this paper we will review the pedagogical background of the integrated teaching and learning initiative, some the curriculum changes which have been developed and then concentrate on the use of the building itself as a living laboratory.

The Integrated Teaching and Learning Laboratory

The Integrated Teaching and Learning Laboratory (ITLL), a 34,400 sq. ft. hands-on learning facility that opened in January 1997, is the visible manifestation of a significant shift away from lecture based engineering education. The ITL Laboratory supports the new hands-on engineering curriculum in innovative and creative ways. CU has also become more involved in expanding engineering education to reach into the critical elementary through high school years.

The unique design and architecture of the ITLL facility was driven entirely by curricular reform objectives. It provides K-16 students with an interdisciplinary learning arena. K-12 learners experience the joys of learning in summer workshops. The principles of design are introduced during a student's first year in engineering. Theoretical engineering science courses in the middle two years are augmented with hands-on, open-ended discovery opportunities. Finally, interdisciplinary teams of seniors design, build and test real-world products.
II. Integrated Teaching and Learning
The vision statement articulated by a team of faculty and students in 1992 continues to drive College-wide curriculum reform: To pioneer a multidisciplinary learning environment that integrates engineering theory with practice and promotes creative, team-oriented problem solving skills. The ITL curriculum integrates hands-on learning across all six engineering departments and throughout all four years of undergraduate study, beginning with First Year Engineering Projects. This College-wide course introduces students to the excitement of engineering and to the practical considerations of the design process including experimental testing and analysis, oral and written communication, multidisciplinary teamwork, and project management [1,2]. Two dedicated design studios in the ITL Laboratory, shown in Figure 1, provide the capacity to teach this course to all first-year students. The major component of this course is a design project through which students experience the complete design-build-test cycle that attracts many students to engineering in the first place. The design project is especially rewarding and more challenging when the student teams are meeting the needs of real customers from outside the University.

Figure 1: First Year Project Design Studio

Past client-based assistive technology projects include a page turner for an adult with cerebral palsy, a talking backpack that answers "yes" or "no" at the push of a button by a mute child, and an assistive glove that allows a quadriplegic classmate to grasp a can of soda. Another client-based design project theme is interactive learning exhibits: CU students learn while designing and building projects that help younger children learn basic concepts of science, either formally in a middle school class, or informally in a museum setting. Examples include a system of levers and pulleys for a middle school class studying simple machines, and a children’s museum display that illustrates concepts of gravity and momentum when children race tennis balls down different tracks.

In their middle two years, undergraduate students encounter the difficult theoretical courses that define them as engineers. To cement the abstract concepts, interdepartmental faculty teams developed interdisciplinary focus courses that capitalize on the state-of-the-art equipment in the two large, open laboratory plazas in the ITL Laboratory, shown in Figure 2. Students gain hands-on reinforcement of the fundamental principles of fluid mechanics, electronics, controls, measurements, structural mechanics, materials and thermodynamics. These are open design labs that allow first year students to watch the upper-class students doing experiments at the lab stations below. In addition, all students get further exposure to the process of engineering design by watching senior design
projects unfold in the visible capstone design studios. Examples of these projects range from building a racecar to building a human-powered submarine.

![Figure 2: ITLL Laboratory Plaza](image)

**Students**

The commitment of CU to ITL begins at the grass roots—with student support. Since the inception of the ITL program, our students have provided essential and unique intellectual support. Engineering students have also been financial partners in the evolution of the ITL program since its beginning, and they continue to play a vital role in the success of the entire ITL program. In 1991, engineering students voluntarily imposed upon themselves an annual $200 differential in tuition and fees to underwrite the nationally unique Engineering Excellence Fund. The fund generates $700K annually, half of which is committed to operational support of the ITL program. The balance is competitively awarded for curricular innovations throughout the College, much of which is complementary to ITL. In 1994, students lobbied the Colorado State legislature to support the ITL program and change traditional funding practices so that $478K of their funds could be used towards capital construction of the ITL Laboratory. Several students served on the original student/faculty curriculum task force that shaped the program, and dozens of students provided input into the conceptual design of the ITL Laboratory.

Students continue to hold critical decision-making roles in the ITL Laboratory: upper division undergraduates serve as coaches in the First Year Engineering Projects course, teams of student "patrollers" ensure after-hours security in the facility, and students are helping to develop ethics case studies for incorporation into the first-year design experience. Faculty solicit, respect, and respond to student input. From the beginning, the ITL program was conceived to be by, and for, students.

**III. Building as Learning Tool**

The Integrated Teaching and Learning laboratory was used for teaching as it was constructed and it is currently used as both a home for lab experiments and an experiment in itself. The various building-as-learning-tool (BLT) features can be grouped into four main levels of complexity:
Exposure
Showing, through example, the various engineering systems required to make a building function. Virtually everything required to make the building function is exposed and incorporated as design elements.

Measurement
Sensors permeate the ITLL facility to allow real-time monitoring of the "pulse" of the building, including air flow and temperature, structural strain, electrical demand, soil moisture and temperature, etc. These data are available in real time on workstations located in gallery spaces, and the data from these sensors is continuously monitored and posted on the Internet at http://blt.colorado.edu. As data are accumulated over months and years, clear trends should develop, giving a big-picture look at actual building behavior.

Manipulation
Students are permitted to control the climate of one of two identical side-by-side classrooms, and also to experiment with a high-speed, parallel computer network throughout the building.

Documentation
The construction process was documented with video, still images, AutoCAD drawings, structural calculations and a real-time image of the site posted every 15 minutes on the World Wide Web (http://itll.colorado.edu/Chronology/index.html). A time-lapse video shows the complete construction sequence in a few seconds.

III.1 EXPOSURE

BLT Interpretive Tour
We have developed a self-guided tour of the many BLT features of the ITL Laboratory using interpretive signs. Text and graphics are located throughout the facility to explain the design of the building and its systems. The goal is to effectively communicate complex technical features in language understandable by children and non-engineers. Examples of visible BLT features on the interpretive tour are described below.

Exposed Building Systems
In the ITLL, portions of building systems that are normally hidden above ceilings or behind walls are exposed. These include:

   Mechanical
   Usually hidden out of sight, the air handling unit is prominently located on the upper level, accessible to the public. The supply air leaving the air handling unit passes through a single, five-foot diameter duct on its way through the maze of ducting that is an architectural design element throughout the building. View windows in the air handling unit reveal moving fans, and at a later date, a window placed into the side of an air duct will reveal streamers placed inside to help visualize air flow.

   Mechanical equipment, such as pumps, compressors, heat exchangers, etc., is normally hidden from view, but in the ITL Laboratory it is visible through large windows, and students may walk through the two mechanical rooms unsupervised. Signs and system diagrams explain the equipment, and various pipes are color-coded for easy identification (Fig. 3). Piping is also visible throughout much of the building. The Mechanical Room also houses one of the Andover computer workstations that graphically display the functional status of the building systems. Plexiglas on the underside of a variable air volume (VAV) box in one of the classrooms allows students to see damper actuation and the usually-hidden components of this standard piece of HVAC equipment.
**Electrical**
Although not accessible to students without supervision, the electrical distribution panels are prominently visible behind windows, and feature transparent panels to show their inner workings. Elsewhere in the building, dummy electrical and motor control panels adjacent to functional ones may be manipulated without affecting lab operation. Much of the electrical conduit is visible throughout the building, intentionally designed and carefully crafted to become an architectural design element.

**Communications**
Much of the network wiring runs in cable trays suspended from ceilings. While the primary function of the cable trays is to allow easy network access, they also help visitors visualize the extensive computer
network. View windows into telecommunications closets and the building computer machine room expose
the various wiring systems, boards and equipment necessary to support extensive computer networks

**Structural**

**Variety of Structural Systems**
For educational demonstration purposes, the building has been designed with four different structural types used in
more than ten different applications; all are exposed. This includes:

- Wide flange steel columns;
- Long and short span beams;
- Tube steel bar joists and a 40-foot truss;
- Composite steel and concrete decking;
- Pre-cast concrete;
- Cast-in-place concrete;
- Load bearing masonry

**Visible Re-Bar**
Steel reinforcing bars are integral to the design and construction of concrete structures, but they are only visible
during construction. In one location, representational "re-bar" has been applied to the outside of the column to
visualize what’s embedded inside (Fig. 4). A section of the steel deck attached with anchor studs has been welded
onto a prominent steel beam to create a permanent display of the composite floor construction that is hidden from
view elsewhere under the concrete and floor tile.
General

Cut-Away Walls
The building features cut-away walls enclosed in plexiglas to expose interior wall construction, plumbing, conduit, etc. Other transparent "slices" into the building include glass plumbing pipes in a roof drain, a plexiglas cover on a fire alarm panel, as well as a window into the elevator shaft to show the hydraulic piston and machinery required for door operation. However, the window into the wall between the men’s and women’s restrooms reveals plumbing and wiring, but little else!

Acoustical Panels
Sound absorbent acoustical panels are a design feature in the ITLL, as well as a very functional one. Ground-face concrete masonry not only protects the walls, it includes sound absorbing material behind open slits.
Light Shelves
Horizontal light shelves and vertical fins on the south and west faces of the building serve to shade the interior from harsh direct light, and also provide indirect daylighting. Students can track and study solar angles.

III.2 MEASUREMENT
A wide array of sensors located throughout the building connects to the Andover control system used to control building climate. Computer workstations located in several locations feature graphical building layouts and displays of current values of all sensor points, as well as allowing trending of the data. As mentioned earlier, this information is also made available on the WWW (http://blt.colorado.edu).

Structural
Vibrating Wire Strain Gages
To introduce students to the workings of structural building systems, vibrating wire strain gages were installed in the foundation and column system within the ITL Laboratory. The vibrating wire instruments were attached to the reinforcing steel and the concrete was poured around them. Data was gathered showing strain in a caisson as load was built up during construction. Using this BLT project, students are able to make measurements in a setting in which they can literally put their hands on the column in which the strains are being measured. They will have the opportunity to make a comparison of theoretical and actual loads. Gages have also been welded to the 40-foot steel truss in the upper Lab Plaza to allow students to see the distribution of tensile and compressive forces (Fig. 5). Finally, vibrating wire gages have also been attached to structural beams and columns supporting the upper Lab Plaza; students can track loads as they are carried horizontally across beams and vertically into columns. Systems are being designed to allow students to apply live loads to both the floor of the upper Lab Plaza and the flange of the truss.
Fiber Optics Cast in Concrete
This pioneering project is a good example of the BLT work that was done during construction. In order to instrument the ITLL building to measure structural strain (from occupant load, wind, snow, etc.), a scaled mock-up was built to test and research use of fiber optic technology. With 220 meters of fiber donated by Corning, 48 fibers were embedded in three levels of columns and two levels of beams of the building structure as the concrete was poured. Ultimately, the fiber optic leads will be connected to an optical time domain reflectometer developed for monitoring by undergraduate students in the ITL Laboratory.

Electrical
The ITL Laboratory is equipped with a state-of-the-art power monitoring system that allows engineering students to obtain data on building energy use and energy patterns. Power Logic software, by Square D Electrical, connects to
the Andover system to track large scale (building) power consumption and small scale (designated circuits) usage, as well as power characteristics. Students can monitor the building’s electrical distribution system, from main electrical feeders to branch circuits that feed computer classrooms. On screen, or on display panels in various locations throughout the building (Fig. 6), they can see the building’s electrical system "come alive," and gain valuable insight into the way technology is currently being used in private industry.

Fig. 6 Square D Power Logic monitors electrical system performance

**Mechanical Systems**

**HVAC System**
Like most modern buildings, the ITL Laboratory has a well-engineered central heating, ventilating and air conditioning (HVAC) system. However, several things distinguish our system. While most buildings are only monitored to provide effective system control, our building has more extensive monitoring of individual components and the complete system. At the component level, individual equipment is monitored to allow engineering analysis of its performance. This equipment includes heat exchangers, fans, pumps, and duct and piping systems. For example, two fin-tube heaters are equipped with temperature sensors to measure inlet and outlet water temperatures, and air temperatures above and below the heater, allowing measured performance comparisons with theoretical
predictions of free and forced convection in heat exchangers. At the system level, the monitoring promotes an understanding of the interactions among the system components. For example, an increase in room temperature will cause a cascade of other system changes, all of which can be traced through the air distribution system, the air handler (Fig. 7), and the chilled water system.

![Fig. 7 Video screen image from the Andover system showing the real-time performance of the main air handling unit in the ITL Laboratory](image)

**The ITLL "Swamp Cooler"**

Another interesting feature is that the bulk of the building is evaporatively cooled (with the exception of the conventional refrigeration system in the Simulation Lab to ensure the reliability of the high performance UNIX workstations). In the dry Colorado climate, most summer air conditioning requirements can be economically satisfied by evaporating water into the building air, cooling and humidifying the space. However, at times of high outdoor temperature and humidity, the indoor temperature and humidity are likely to be higher than usual. Using the monitoring in the cooling tower and air handler and fundamental psychrometric relationships, students can quantitatively link their indoor comfort to outdoor conditions and system operation.

**Thermal Environment**

**Air Stratification**

Temperature sensors are arrayed vertically approximately every eight feet throughout a three-story space to track air stratification.

**In-situ Heat Conduction**

Temperature sensors are embedded one inch apart through north, east, south and west facing, solid pre-cast concrete walls to study the effects of solar orientation and thermal characteristics of concrete. Sensors are also located at each change of material throughout a composite exterior wall. Knowing inside and outside temperatures, students can compare the actual thermal gradient with the predicted one.

**Soil Temperature**

Sensors along the exterior of the foundation wall enable students to monitor soil temperature, track freezelines, study thermal characteristics of soil and correlate this data to climatic data.

**Thermal Performance of Windows**

In accordance with current energy conservation principles, most of the glazing in the ITL Laboratory is double-pane insulated windows. However, in one area of the lower lab plaza, students can compare the thermal performance of several different glazing systems using temperature sensors connected to the Andover system (Fig. 8). This includes conventional, 1/4 inch single-pane tinted glass (as used on the 30-year-old Engineering Center), as well as more "high tech" double-pane glass with Low-E coating (as used throughout the new ITL Laboratory), double-pane fritted (patterned) glass, and triple-pane Heat Mirror® glass.
General

ITL Weather
The equipment included in a meteorological data acquisition system mounted on the roof includes a data logger, temperature and humidity probes, barometer, rain gage, and anemometer. The meteorological instruments are used to teach basic engineering science concepts relating to fluids, thermodynamics, pollutant transport and aerodynamics, and techniques for analyzing time series of data.

Ambient Air Quality
Students investigate operating principles and practical aspects of ambient monitoring with EPA reference methods, and gain experience in using regression and time series analysis to better understand relationships between pollutant concentrations and meteorological conditions.

Hydrological Information
An automated hydrologic monitoring system surrounds the ITLL building. The system consists of soil moisture probes, and surface runoff and drain flow measuring equipment. The continuously collected data, combined with data from the weather station, can be used to teach fluid flow, engineering hydrology, groundwater engineering, water resources engineering and transport processes. Handling the information provides students with experience in data acquisition, data synthesis, data analysis and use of data in model simulations and engineering design.

III.3 MANIPULATION

Climate Controls
The two identical first-year project classrooms have different climate control systems. One has conventional pneumatic controls, while the other has separately operable, direct digital controls (DDC) which students can manipulate (within reason!) and measure the effect of changing different variables, such as temperature and air flow. A mechanical VAV box with a plexiglass view panel is installed so that students can see the equipment in operation.

Experimental Computer Network
In the ITL Laboratory, all computers and data acquisition instrumentation are linked via high speed networks. The Production Network, using 100 MBit/sec-based technology, allows students to take data at any location and access it from any other location for analysis, simulation, printing, etc. To provide further BLT experiences, a second limited network, called the Experimental Network, using 500 MBit/sec-based, fiber optic technology, allows students to experiment with the latest in network technology without jeopardizing the integrity of the Production Network.

III.4 DOCUMENTATION

ITLL On-Line
Information regarding the construction process was posted on the ITL web site http://itll.colorado.edu from groundbreaking in October 1995 until landscaping was complete in December 1996, including photos of the architectural model, construction schedule, information regarding touring the construction site, and the latest image...
of the site from a video camera mounted on the Engineering Center. This image was updated every 15 minutes and the stored images formed the basis for a time-lapse video showing the building rising (magically!) from the ground.

**Educating Construction Engineers**
The College’s Construction Management Program has taken advantage of the ITLL construction project to capture on-site construction lessons to enrich its curriculum for future students. This real-world resource features the principles and practice of construction, and will be available for students for years to come. This includes:

- A collection of real-time and time-lapse video tapes of the construction progress;
- All construction documentation (AutoCAD drawings, contracts, calculations, memos, meeting minutes, change orders, field clarification requests, etc.); and
- A construction engineering video library (a user-searchable library on CD-ROM of short digital video clips of construction processes, materials and equipment).

**IV. Building as a Learning Tool (BLT) System**

Figure 9 shows the architectural of the BLT System. Data from over 280 sensors distributed throughout the ITLL building are collected on a small number of data-collection computers. On arrival, the data is e-mailed to a central UNIX computer that stores them in a relational database. Users issue requests for data through their web-browsers. The browsers send the requests to a web-server (http://blt.colorado.edu) which, in turn, triggers the required programs necessary to retrieve and format the requested data.

![Figure 9. Architecture of BLT system](image-url)
To facilitate easy location of data, users can search for data from different perspectives. For instance, sensors can be searched by dimension (e.g., temperature, flow, insulation, etc.) or by location (e.g., the air handling unit, the weather station, the cooling tower, etc.). Similarly, any list of retrieved sensors can be sorted according to any of its attributes (e.g., name, number, manufacturer, sensor type, etc.).

Data are available as line graphs (Figure 10) or as table-formatted ASCII (text) files (Table 1). Whereas the former facilitates easy comparison of the trajectories of variables over time (note the relationship between outer and inner wall temperatures during a 24-hour period in Figure 10), the latter allows inspection and use of the actual, numerical data. Once retrieved, data can be interactively re-scaled, zoomed, re-plotted with different plot types, saved to the local computer, etc.

Figure 10. Example of graph available from BLT system
The following table shows an example of the ASCII data that are available on the web from the BLT system.

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<th>DATE</th>
<th>TIME</th>
<th>S0</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
<th>S4</th>
</tr>
</thead>
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<td>13.8</td>
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<tr>
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<td>13.2</td>
<td>14.1</td>
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<tr>
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<td>14.5</td>
<td>14.1</td>
<td>15.1</td>
<td>16.1</td>
</tr>
</tbody>
</table>

S0->Wall.Temperature.24 (degrees C), S1->Wall.Temperature.23 (degrees C), S2->Wall.Temperature.22 (degrees C), S3->Wall.Temperature.21 (degrees C), S4->Wall.Temperature.20 (degrees C), S5->Wall.Temperature.19 (degrees C)

Table 1. ASCII data available from BLT system

In addition to the provision of ITLL sensor data, the BLT system contains a large collection of texts and graphics explaining the functions and workings of the various building components such as the air conditioning, the building’s structural components, the air handler unit, the glazing, etc.). These overviews are partly interactive in that whenever the text refers to a quantity or variable actually measured by one or more sensors, these references are “hot” links which, when clicked, automatically display a graph of the last 50 observations.

**VIRTUAL TOUR OF THE ITLL**

As their senior design project in Computer Science, a group of four students is constructing a virtual tour of the ITL Laboratory that will be accessible through a VRML browser on the Internet. "Visitors" will be able to navigate the interior spaces of the ITLL, and access sensor data by clicking on flashing icons that indicate the location of the various sensors throughout the building.

**CONCLUSION**

The various "building-as-learning-tool" features of the ITL Laboratory provide unique opportunities to learn about a variety of engineering principles as utilized in a modern structure. The concepts are being included in the curriculum in a variety of classes, ranging from construction management to a digital signal processing class utilizing the various pieces of sensor data. The capability to make this information available on the World Wide Web offers the potential for a truly worldwide learning opportunity.