Development of a Multidisciplinary Engineering Design Laboratory at the University of Notre Dame

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Introduction/Philosophy

As technology has evolved, the primary challenges in engineering design have evolved from creating well-defined components to producing complex, interdependent systems. Furthermore, the design of such systems typically requires the combined talents of a team of engineers, often from different disciplines. Ironically, as design challenges have shifted from components to systems, engineering curricula in universities have become increasingly specialized. Whereas formerly engineering students in all disciplines could be expected to have a common foundation of courses such as mechanics, electronics, and thermodynamics, today's students are required to specialize in a major in the sophomore or even freshman year, with little opportunity to take courses outside of their field. While one disadvantage of this trend is that students have less of an understanding of the physical principles and techniques used in other disciplines, a more serious issue is that students are less familiar with the interfaces between disciplines. This leaves students unprepared to confront the most difficult problems faced by practicing systems designers: how to simultaneously meet all the constraints imposed by different concerns, and how to effectively make trade-offs between concerns to optimize system performance.

To address this issue, we have developed a *multidisciplinary engineering design laboratory* course for senior-level undergraduates. The main goal of this laboratory is introduce both faculty and students to interdisciplinary group design projects. Projects were implemented using Lego blocks and mechanical components, along with a variety of motors and sensors, that are controlled from personal computers. The course was initially offered in the fall semester of 1995, involving seven faculty and twenty-one students. In this paper, we will describe the organization of this course and discuss our experience and observations with the initial course offering.

Course Development and Organization

Goals

The primary goal of this laboratory course was to explore the educational benefits of having groups of faculty and students work together on interdisciplinary design projects. A secondary goal was to try to develop a set of interdisciplinary laboratory exercises appropriate for possible future use in an introductory engineering course.

In order to achieve these goals, two strategic issues were raised regarding project development and implementation:

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2. Department of Aerospace and Mechanical Engineering
3. Department of ChemicaJ Engineering
4. Department of Civil Engineering and Geological Sciences
5. Department of Electrical Engineering

- while projects should have an appropriately challenging level of technical sophistication, they should be defined to emphasize the “intangibles” of interdisciplinary design, such as planning, teamwork, and communication;
- in order to build and test projects of this complexity in a short time period, it is necessary to have hardware that is flexible, safe, reusable, and requires minimal tools for construction.

In response to the first issue, each team was given the task of developing an interdisciplinary laboratory assignment, suitable as a learning vehicle for freshman engineering students. By casting the design problem as such, participants in the course would be forced to analyze and distill the essence of what they’d learned as undergraduates in their respective disciplines, and to explore the range of systems that apply diverse technologies. Further, by having students develop a problem—as well as a candidate solution to that problem—they could rapidly focus on the heart of what makes interdisciplinary design so difficult. Specifically, the students would be challenged to look for problems that not only have interesting trade-offs in the individual disciplines, but at the system level as well. Ideally, these laboratory assignments would demonstrate to freshman engineering students the limits to empirical problem solving. A weakness of the traditional lecture format is that the value of analytical techniques may not be obvious to students, and exhortations are not convincing. An early laboratory experience could potentially allow students to run up against the limits of intuitive problem solving, and motivate them to consider how simple models or analyses might yield better problem solutions.

In response to the second issue, that of design kits, we explored the use of Lego-based products, which are described later in this paper. Thus another goal was to determine if Lego is an appropriate technology for use in a college-level interdisciplinary design course.

Teams and Mentors

Each design team for the course consisted of three students and a faculty mentor. Students were selected for the course through an application process, where they were asked why they wanted to participate in the course, and what level of commitment they thought was appropriate, as well as to describe a sample project. Prior academic performance was not considered in the selection process. An effort was also made to fairly evenly represent the five engineering departments at Notre Dame (aerospace/mechanical engineering, chemical engineering, civil engineering, computer science and engineering, electrical engineering) with both students and faculty. The original target size for the class was fifteen students and five faculty; this was increased to twenty-one students and seven faculty because of higher student turnout than expected. One faculty member, in addition to mentoring a student team, served as coordinator for the course.

During the first class meeting, students were randomly assigned to teams, subject to the constraint that no two students with the same major were on the same team. Faculty mentors were also randomly assigned. The role of the faculty mentors was to serve primarily as facilitators, to act as a “sounding board,” and to help remove unforeseen impediments, but otherwise not to actively participate in the project development process.

Resources

Laboratory space was provided by one of the engineering departments for the course, along with workbenches for each of the groups. Five personal computers (PowerMacintosh 7200s) and eight construction kits were purchased for the course, with funds provided from both the College of Engineering and the University. The total cost of equipping the lab was approximately $20,000.

Two different types of construction kit were used in the initial course offering: the Control Lab package, manufactured by Lego Dacta [1], and the MIT 6.270 kit [2], which was developed at MIT for their popular robot design course/competition. For both types of kit, the primary building technology is Lego blocks and compatible mechanical components. In addition to mechanical components such as gears and axles, both kits also provide a variety of actuators and sensors such as motors, lamps, switches, and temperature, light, and rotation sensors, as well as software for controlling these. The most significant difference between them is that the Control Lab package provides software for building graphical user-interfaces using the Logo programming language, while the MIT kits have a remote 681l-based processor board that is programmed using Interactive C. While projects built using Control Lab must be tethered to the personal computer, the MIT 6.270 processor software is edited and debugged from the host via the serial interface, but then the processor board may be detached to allow construction of autonomous robots. The Control Lab kits come ready-to-use and have a standard, modular interface to sensors and actuators, but the addition of new devices is relatively inflexible. The MIT 6.270 kits require some construction, but are more flexible to adding new devices. Student teams were allowed to decide which kits they wanted to use for their projects.

The course also had a modest budget for groups to purchase additional parts outside of the kits. In order to obtain outside parts, students had to justify the purchase to their faculty mentors.

Schedule and Deliverables

The main organization for the course was that the semester was divided into three phases, each approximately one month in length: system familiarization and concept definition, project development, and project validation and assessment. To ensure that the groups stayed on track, project independent deliverables were scheduled on approximately a weekly basis. Each group was to meet with their mentor once per week, while the class met as a whole five times during the semester. Table 1 summarizes the primary milestones for each phase of the course, which are discussed in detail below.

Table 1: Summary of course milestones

Phase I: System Familiarization and Concept Definition	
week 1	Class meeting: team formation, organizational overview
week 2	Class meeting: technology familiarization demo/presentation due
week 3	Individual project concept studies due
week 5	Team project concept studies due
Phase II: Project Development	
week 6	Class meeting: presentation of project concept studies, project schedules due
weeks 7-8	Status reports due
week 9	Draft of project description and sample solution due
week 10	Final project description and sample solution due
Phase 111: Project Validation and Assessment	
week 10	Class meeting: presentation of Phase II project descriptions and demonstration of sample solutions, selection of new teams for Phase III
weeks 11-12	Project implementation
week 13	Class meeting: project demonstrations, validation study report and critique due
week 14	Course assessment due

Phase I: System Familiarization and Concept Definition

The goals of the first phase of the course were for students to meet their team members, become familiar with the basic construction and programming techniques of their kits, and to develop a proposal for their projects. During the first class meeting, the newly-formed teams were assigned “canned” projects to complete by the following week. In general, these were simple control systems that required monitoring the output of a sensor, making a control decision, and then activating a mechanical device.

Having thus become acquainted with the building technology, students were then given one week to each write a brief concept study for a proposed project, that was to address the following points:

- description of the project;
- discussion of how project would integrate different engineering technologies;
- specific educational goals that the project would meet;
- feasibility of completing project with given equipment in the allocated time frame.

Given the individual concept studies as "seeds," each team then had two weeks to produce a detailed team project concept study as a major document. These were presented for discussion and review at a class meeting.

Phase 11: Project Development

The goals of the second phase of the course were for each team to formally develop a detailed project description (assignment handout) that would be suitable as an educational activity for freshman engineers, as well as to construct a prototype implementation of the project and write a sample lab report. To aid the teams in . . completing these diverse tasks in one month, they were required to submit a schedule with assigned responsibilities during the first week of this phase, and status reports for each week thereafter. Teams were also required to submit a draft of their project description for critique to their faculty mentors one week prior to the final due date.

Phase III: Project Validation and Assessment

The goals of the third and final phase of the course were to validate and assess the projects. This was done by forming new groups to act as "virtual freshmen," where each new group was to do one of the laboratory assignments developed during Phase H. To begin Phase III, a class meeting was called where each of the Phase II teams presented their project descriptions and demonstrated their prototype implementations. The new teams were then randomly selected, subject to the constraints that no student was to evaluate his or her own project, and that no Phase II teammates were again on the same team. Faculty mentors remained with their Phase II projects to answer questions regarding requirements.

Deliverables for the validation and assessment phase included a project lab report (as would be submitted by freshmen), a demonstration of the implementation, a critique of the project, and a critique of the course.

Documentation and Communication

Because this was not a regularly scheduled course, with a fixed meeting time and place, a variety of methods was used to ensure that faculty and students were informed of course requirements and developments. All course handouts were developed, reviewed, and compiled prior to the start of the semester and distributed as a packet at the first class meeting. Because the course involved faculty and students from each of the engineering departments, it was not possible to schedule a time during regular class hours for all participants to meet as a group. The full-class meetings for the semester were thus scheduled for the evening, during the first class meeting.

Electronic media were used extensively for course documentation and communication. All course documentation was published on the World Wide Web (http: //www.nd.edu/-lego). Each team had a link to its own home page off of the main course home page, where they were to submit all deliverables, including reports, presentations, schedules, and graphic and video images of their projects. In addition to the use of WWW, email lists for faculty and students were used to send routine information and reminders, while broader discussions were held on a local newsgroup created for the class.

Evaluation and Feedback

Evaluation of work in this course took on several forms:

- *Evaluation of student projects by faculty:* Faculty met twice during the semester to discuss grades for the course, once at the end of Phase II, as well as at the end of the semester.

- *Evaluation of student work by other students:* Each Phase III group submitted a critique of a Phase II project.
- *Student self-evaluation:* Students were required to submit a memo to their mentor stating what grade they felt they had earned following Phase II. Criteria to consider were the extent to which they had achieved objectives, quality of written work, presentations, and project implementation, and effort expended relative to other three-credit-hour courses.
- *Student evaluation of course:* Students were required to comment on course strengths and weaknesses at the end of the semester.

Projects

Taken together, the seven projects developed by the student teams spanned a broad range of topics in engineering. While each of the projects were successfully implemented, they varied in the extent to which they satisfied their educational objective, and in some cases, the final version of the project diverged significantly from the teams' original concepts. A capsule summary of each of the projects is given below.

Automated Stale

The challenge for this project was to develop a system that would automatically weigh an object and display the result on the screen of a computer. While one of the conceptually simplest of the projects, it also gave rise to a broad range of possible implementations and many subtle engineering problems, such as precision in positioning and determining convergence in the control algorithm. Designs were to be evaluated according to an objective function that considered both speed and accuracy of the measurement. Both the development (Phase H) and validation (Phase III) teams implemented balance schemes, one in which the fulcrum was moved, and the other in which the balance arm was extended.

Heat Transfer

For this project, the goal was to automatically bring a water bath to a given temperature, transferring heat to and from cooled and heated baths without transferring any mass, in the fastest possible time. Both the development and validation teams used a system of rotating arms and pulleys to move metal slugs to transfer the heat. A temperature sensor was used to setup the controller. The students encountered some subtle implementation issues, such as discovering the need to agitate the water bath to obtain accurate measurements. Faculty and student opinion of this project varied greatly, some feeling that the project was an excellent simple introduction to control systems and heat transfer, while others felt that the project was boring. Many of the faculty felt that the project could have benefitted greatly from more engineering analysis; formal optimization and prediction techniques could have been applied to improve the speed of the system.

Drag Racing

The goal of this project was to design an autonomous vehicle, using only parts from the autonomous-processor kits, that would run a straight, hilly track in the fastest time. For their implementations, both the development and validation teams designed transmissions that would change gears under programmed conditions. The development team built a shaft encoder to shift according to motor speed, while the validation team used a mercury switch to determine if the vehicle was heading up or down hill.

Real-world engineering considerations figured heavily into the success or failure in implementing this project: transmission designs that worked on the lab bench would sometimes fail under actual weight and friction conditions, resulting in drive trains that came apart, as well as stripped gears and burned-out motors. The development team was able to produce a design with a shifting transmission that could outrun a fixed-gear competitor; the validation team did not.

Factory Line: Electroplating

The objective of this project was to design a factory line that would automatically take zinc plates and copper-plate them. Both the development and validation teams experienced difficulties with this project, generally resulting from the fact that it was not well-suited to the available technology.

Walter Purification Plant

The goal of this project was to take acidic water from an available "stream," neutralize it, and then transport it uphill to a nearby "town." Tasks for this project included designing a pump, interfacing and calibrating a pH sensor, building the control system for neutralizing the acid with a basic solution, and an exercise in path planning for routing the pipeline across a contoured terrain. Both the development and validation teams produced working implementations of this project, with significant differences in the pump design and the means for regulating the flow of the basic neutralizing solution. The original team used an Archimedean screw built from worm gears to transport the water uphill, while the validation team modified a Lego pneumatics kit to work- with water.

Shape Drawing

Like the mass measurement system, this project had a simple specification with a broad range of possible solutions. The goal of this project was to design a machine that could draw a square, a triangle, and a circle. Design quality was evaluated by a simple objective function that combined speed and accuracy.

Development and validation teams produced two very different, working designs: the first with an arm that would rotate and extend, and the second with a transverse beam mounted on a vehicle which would drive across the paper in one direction, and move the pen along the beam in the perpendicular direction. The two designs clearly favored different shapes in their scoring.

As an aside, the original concept for this successful project was to develop a gyroscope that would stay in a given region. This idea was abandoned midway through Phase II when it was determined to be more complicated than originally envisioned. A similar change occurred with one of the other projects.

CD Player

The goal of this project was to encode the first line of the Notre Dame Victory March onto a paper disk six inches in diameter and play it back through a piezo sound element, Both the development and validation teams developed a black/white coding scheme that could encode the information in a single track. The development team did not produce a working implementation of their design, having experienced difficulties in time-sampling the rotating disk. The validation team, however, corrected the problem and did produce a working design by adding a synchronization track.

Observations and Conclusions

In evaluating our experience with the initial offering of the multidisciplinary engineering design laboratory, three factors should be considered: the success of the educational experience, the effectiveness of the course organization, and the appropriateness of the projects and building technology.

In general, the student response on the experience of working in interdisciplinary teams was uniformly very positive. While many students commented on the value of domain-specific expertise that different members brought to the team, such as designing a linkage or writing computer programs, others noted the positive impact of diversity on group problem solving. Examples of student comments include:

- "In my other classes we do a lot of group projects, but there, we all have the same skills and similar strong points, and we are limited as to what we can design. Having the opportunity to use the collective knowledge of classmates allowed me to be more creative."
- "When I discussed my project with my fellow chemical engineers, I discovered that I generally viewed

things the same way as them. When I discussed with other engineers, however, they expressed viewpoints that were completely different from my own. I learned the importance of having all those different viewpoints."

- "... you have to be able to explain things you have accomplished to someone who may not be well-versed in your discipline. In this respect, it is an incredible learning experience."

The educational experience of the students-in terms of the extent to which they were *taught* interdisciplinary design methodology y—varied from group-to-group depending on the faculty mentor. Some of the faculty taught their groups planning and brainstorming techniques, while others had more of a hands-off approach. An important consideration is that each of the faculty volunteered their time for this course above and beyond their regular teaching load, and as a result, the level of faculty commitment to their groups did vary. The administrative load of the course for the organizer was also very significant, approaching that of a typical teaching assignment.

Overall, the three-phase course structure (familiarization/development/validation) worked well. Having a regularly-scheduled set of deliverables was critical to keeping the students focussed on the course. This became particularly evident during the validation phase, when there were few deliverables before the end of the semester. As a result, there was more of a tendency for groups to procrastinate, and some of the projects suffered for this.

A significant issue in administering the course was maintaining cohesiveness, given that the class did not have a fixed meeting time and place. To these ends, the use of electronic media, in particular the WWW for posting student deliverables, was crucial. By allowing students to view other students work in this manner, healthy competition encouraged them to improve the quality of their work and to submit it on time. One complaint voiced by students and some faculty was the lack of a regular meeting time for the course. In particular, some of the groups had difficulty finding times when they could meet together in the lab for several hours at a time when they could work on their projects. Several of the groups kept lab books available on their workbenches, so that teammates could note their progress when working alone. Although the projects could have been undertaken in separate, distributed facilities, we found that having dedicated laboratory space for the course greatly improved the cohesiveness.

Several of the projects developed in the course could, with modification, serve as the core for freshman design projects. Weaknesses in two areas, however, would need to be addressed before the projects could be used in that manner. First, the technology requirements for some of the projects would need to be better adapted to the available kits. Both types of construction kit though, with some limitations, proved to be generally acceptable for a course of this type, and provided adequate technical challenge for seniors. The second area for improvement would be to strengthen the link between engineering analysis and design. While several of the projects did establish a tie with underlying physical phenomena, they in general failed to exploit opportunities for modeling, simulation, or optimization. This would be crucial for extending classroom learning to the solution of real-world problems.

In summary, both students and faculty found the initial offering of the Multidisciplinary Engineering Design Laboratory at Notre Dame to be a rewarding experience. The course is expected to be a springboard for future activities in this area.

References

[1] LEGO Dacta Control Lab, LEGO Systems Inc., Enfield CT.

[2] P. Oberoi, et. al. *The MIT LEGO ROBOT Design Course; 6.270 Course Notes.* EECS Department, Massachusetts Institute of Technology, Cambridge, MA.