A FRESHMAN DESIGN COURSE USING LEGO NXT® ROBOTICS

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Civil engineering majors have their concrete canoes and steel bridges and the mechanical engineers have their solar cars. Certainly, the discipline of chemical engineering is no less visual—we just cannot haul a skid-mounted process unit into the classroom (without raising administrative eyebrows and inviting an immediate visit from the campus safety officer). What concrete, visible means do we have for giving our students a clear picture of chemical engineering? Pursing K–12 outreach and teaching freshmen for a substantial part of my career, I've journeyed through a maze of options for trying to help students understand what chemical engineers do in daily practice. Most attempts coalesced into a series of chemistry demonstrations accompanied by pictures of chemical processing equipment—leaving my audience with a conceptual gap between the two.

In the Swalm School of Chemical Engineering at Mississippi State University, the ideal opportunity to tackle this problem came with the revision of a three-credit-hour, junior-level course—Chemical Engineering Analysis and Simulation (hereafter referred to as Analysis). Originally designed to address the application of numerical methods to fundamental topics in chemical engineering, the course has pre-requisites that, over time, allowed a shift in class composition to a mixture of underclassmen taking the course "on time" and upperclassmen (typically co-op students) squeezing in the course among other requisite courses. This led to an unsatisfactory pressure on the course content (*i.e.*, too difficult for one set, too remedial for the other). A general curriculum review revealed an opportunity to strengthen our curriculum by moving Analysis to the freshman year—using it as a vehicle to incorporate teamwork, experimentation, and project design into the early stages of our curriculum.

LEGO® ROBOTICS—FOR CHEMICAL ENGINEERS?

The incorporation of problem-based or project-based learning strategies into the classroom has swept the educational scene from K–12[1-4] across multiple disciplines in higher education.[5-7] LEGO® robotics kits have proven to be widely adaptable to a variety of disciplines and learning styles in engineering education. Building on the work of chemical engineering educators such as Levien and Rochefort,[8] Moor and Piergiovanni,[9,10] and Jason Keith,[11] my students and I began a journey in the Fall semester of 2006 to incorporate this relatively inexpensive technology into the Analysis course. At under $300 per base set, the LEGO NXT® robotics kit offers tremendous versatility for designing model engineering apparatus and processes in the classroom. With modest additional cost for accessories (*e.g.*, valves, tubing, tanks) a number of units can be built to allow an entire class to be

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actively involved in the same design project simultaneously (in contrast to the traditional Unit Operations laboratory approach relying on the rotation of student groups through a single experimental apparatus sequentially). Coupled with the LEGO NXT® kits, we chose a series of sensors from Vernier (*e.g.*, pH, temperature, dissolved oxygen) that interface with the robotics kits for monitoring processes and performing simple control schemes. A significant factor in choosing the LEGO NXT® robotics kits is the use of an intuitive graphical interface for programming (based on National Instruments Labview® software). This user-friendly programming interface removes the focus from programming and places it on the broader objectives of problem analysis and design of engineering processes.

CHE 2213 Chemical Engineering Analysis is a required, three-credit-hour course, offered once per year in the second semester of the freshman year (after a one-hour orientation and before the sophomore-level Mass & Energy Balances course). A large number of students entering the chemical engineering program at Mississippi State University (MSU) are community/junior college transfers from an extensive two-year college system throughout the state. Analysis is among the courses required for their first year at MSU. Enrollment lies typically between 55-70 students. The course is conducted in a 160-seat auditorium, the adjacent Unit Operations laboratory, and, with some design competitions, in the connecting hallway for maximum exposure to passing students from other classes.

Through loads of laughter and enthusiasm, discovery and creativity, and precautions to avoid spending an inordinate amount of time on their robotics projects, teams of students have consistently pushed the course content forward in subsequent semesters—demonstrating the value of a highly visual, project-based approach to learning engineering fundamentals. Through several iterations we have constructed projects more directly oriented to chemical engineering for illustrating the importance of fundamental concepts including basic units and measures, materials balances, and the fundamentals of process control.

TABLE 1
CHE 2213 Analysis
Learning Objectives & Outcomes

Learning Objectives:
At the end of this course, you should be able to…
• Brainstorm a problem quickly within a team setting (or working alone) listing a number of possible solutions over a broad range of ideas
• Describe the Engineering Design Cycle as used in this course and steps/tools involved in engineering design
• Take an idea for solving an engineering problem and bring it to a complete, functioning prototype using the LEGO NXT robotics system and accessories
• Use Microsoft Excel® tools to collect and analyze data from your engineering designs
• Describe the importance and basic elements of conducting a material balance for and maintaining control of a chemical process.
Learning Outcomes:
Upon completion of this course, you should be able to…
• Employ the Design Cycle for both originating an engineering design and for making performance improvements in an existing design
• Explain to someone in your family (a non-engineer) what chemical engineering is all about—giving some very practical examples.

LEARNING OBJECTIVES AND OUTCOMES

Table 1 describes the learning objectives and outcomes for the Analysis course. Defining a learning objective as a specific, targeted description of acquired knowledge or skill and a learning outcome as a broader response to particular situations requiring use of that acquired knowledge or skill, these course objectives and outcomes are being affirmed over time in coordination with our overall chemical engineering program objectives.

THE LEARNING ENVIRONMENT AND COURSE STRUCTURE

Offered Tuesdays and Thursdays for two 2-hour-and-20-minute sessions, Analysis comprises one credit hour of laboratory and two credit hours of lecture. The learning environment is patterned after a studio setting. I provide instruction on specific topics or skills as needed in a dynamic, laboratory environment that allows students to immediately put that knowledge or skill to practice on the current project. Projects are structured to require use of accumulated knowledge over the course of the semester. Class discussions center around knowledge and skills needed for use on a timely basis. Homework problems are assigned to allow practice of key tools. Grades come primarily from individual quizzes and the final exam (evaluating their understanding of skills and concepts learned during design exercises). Some portion of the grade is derived from team participation in oral and written reports (in varying percentages over the semesters since the course's inception). No grade has yet been assigned for the quality or performance of designs.

Table 2 (next page) describes the flow and content for Analysis. Up to six in-class quizzes are given at appropriate junctures, evaluating students' comprehension and use of the concepts, skills, and tools learned to date. Beginning with Team Challenge #2, all designs require quantitative data acquisition and analysis and are accompanied by team written reports, team self-evaluations, and oral reports.

Over the eight semesters we have offered Analysis in its current format, a surprising number of students have expressed little past experience playing with LEGOs®. To put everyone at ease at the course outset, student teams construct the LEGO® NXT robotics kits and build a mobile robot of their choice, using as a guide the "Taskbot" design included with the kit (Figure 1). This enables students unfamiliar with LEGO structural elements and the various sensors included in the kit to quickly learn something about the capabilities and limits of both the building components and the available sensor technology.

Key aspects of the course content are shown in Figure 2. The Analysis course was placed in the second semester of the freshman year to engage our chemical engineering students in team-oriented, "real engineering" projects at a critical stage of their collegiate (and chemical engineering) experience, thereby strengthening their communication and working relationships among one another, while giving them insight into the importance of their preparatory mathematics and science courses. Students have commented on the timeliness of design projects requiring use of topics just covered in math and chemistry.

Through the introduction of increasingly complex "team challenges" students are engaged in an integration of communication skills, engineering topics, and engineering design principles. Introduction of the Design Cycle (Figure 3) provides teams a guide for iteratively approaching an optimal solution for the problem they are tasked with solving.

Figure 1. *Students becoming familiar with the LEGO NXT® kit.*

TABLE 2
Course Structure

ChE 2213 Analysis comprises approximately 28 studio sessions over 14 weeks.
• Course Orientation—one studio session (2 hrs. 20 min. per session)
a. Brainstorming
b. Using the Engineering Design Cycle
c. Data acquisition and analysis using Microsoft Excel®
d. Exploration of LEGO NXT® robotics kits
• Team Challenge #1 Taskbots & Sumo Wars—four studio sessions
a. Learning to use the LEGO NXT® system
• Team Challenge #2 Free format Design using LEGO NXT® sensors—five studio sessions
a. Teams design an experiment of their choosing using one or more of the sensors provided in the LEGO NXT® kit (*i.e.*, rotational, pressure, light, ultrasonic, or sound sensors)
b. Constraints require clear establishment of an independent/dependent variable with elimination of extraneous parameters (where possible)
c. Brainstorming, critical thinking, teaming skills emphasized
d. Data acquisition and analysis using Microsoft's Excel®
• Team Challenge #3 Level Control Experiment—five studio sessions
a. Interfacing the robotics kits with a tank/submersible pump/valve system assembled in-house by the student teams
b. Level control experiment
c. Explanation of fundamental control concepts
d. Level control is measured over time by control valve deflection from an established setpoint
• Team Challenge #4 Mixing tank/Continuously stirred tank reactor (CSTR) design—eight studio sessions
a. Case 1—Two feed tanks supply two separate components for mixing in a third tank (*e.g.*, deionized water and a salt solution to be mixed to a specified salinity)
b. Case 2—Two reactant tanks supply reactants to a CSTR from which a specific product quality must be obtained (*e.g.*, pH, coloration, dissolved oxygen level)
• Individual quizzes—five studio sessions
• Final exam

Figure 2. *CHE 2213 Analysis—Course content.*

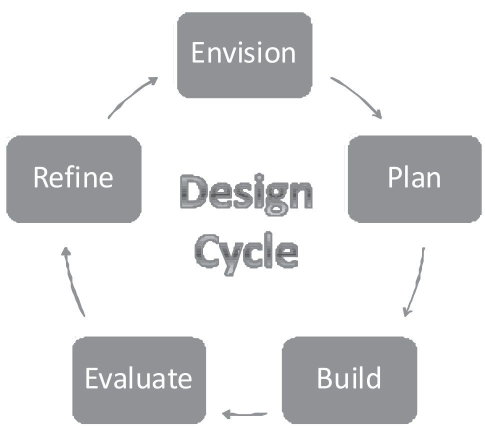

Figure 3. *Design Cycle.*

TEAM DYNAMICS

On the opening day, students self-assemble into teams of three members and begin familiarizing themselves with the robotics kits. In some semesters, I have allowed groups to remain constant over the course of the semester; in others, group members were reassigned approximately at mid-term. Through frequent, informal interviews and anonymous surveys, the feedback has been roughly constant for both approaches (*i.e.*, most class members favoring staying in their self-selected teams with one or two teams wishing for anyone other than their current team members). I interact with individual teams throughout the class periods, coaching and exchanging ideas, and watching for problems that crop up with group dynamics. Additionally, this interaction is an excellent opportunity for getting an idea of the broader issues that arise among our chemical engineering students. During this first studio session, we also cover key tools they will be expected to put to use early in the course including brainstorming for initial problem solving, using the Engineering Design Cycle, and use of Microsoft Excel® for data acquisition and analysis.

Team Challenge #1: Taskbots and Sumo Wars

The team challenge announced to the class is a "Sumo war" requiring teams to build a robot capable of staying within a defined circle while attempting to push the opposing robot out of the ring (Figure 4, next page). A "contest" environment motivates a high-energy response. I have used this team challenge to bring in upperclassmen and, with loud music and the AIChE chapter providing food, the result was a memorable social event.

Team Challenge #2: Free-Format Design

After the dust settles and emotions subside, a second team challenge opens the door to a more fundamental, and methodical, approach to engineering problem solving. Teams are tasked with designing an experiment and constructing a robot (not necessarily mobile) to demonstrate the performance of one or more LEGO NXT® sensors of their choice—acquiring data from a set of independent/dependent variables. Using available computational tools and the course text,[12] teams report raw and processed data in graphical form with appropriate oral and written reports. Student designs have included measuring the volume of liquid dispensed from a soft drink can as a function of robot "tipping velocity"; the angle of projection by a ball hit in a robotic batting machine; and colorimetric sensitivity of the light sensor as a function of varying shades.

Team Challenge #3: Level Control

The importance of process control in chemical engineering is emphasized in the next team challenge by requiring teams to adapt the LEGO® NXT system with a bench-scale fluids handling system (Figure 5). A submersible pump delivers water to a tank through a small needle valve operated by a LEGO motor which in turn is controlled by programming the NXT robotics "Intelligent Brick" (*i.e.*, a 32-bit microprocessor).

Teams must design the system to maintain a prescribed fluid level in the tank. A sonar sensor, analogous to one type of level-control technology used in industry, detects the fluid level feeding the signal through the NXT brick to the controlling motor. Small adjustments in the liquid level are "amplified" and observed by noting changes in rotational displacement of the valve stem with an affixed adhesive rule applied to the valve/motor coupling. Students record, as a function of time, +/– displacements from an established set point. Recorded data is then plotted in a simplified control plot for qualitatively evaluating system control performance. A manual valve on the tank outlet (lower right in Figure 5) allows teams to investigate the capacity of their system (*i.e.*, pump/valve/controller) to maintain adequate control under varying dynamic conditions. While relatively simple in construction, this team challenge allows students to gain an intuitive sense of the importance of controls. Class discussions focus on the importance of automatic control for safety and operability of systems and on basic controls concepts. Additionally, this challenge touches, to some degree, on each of the course objectives.

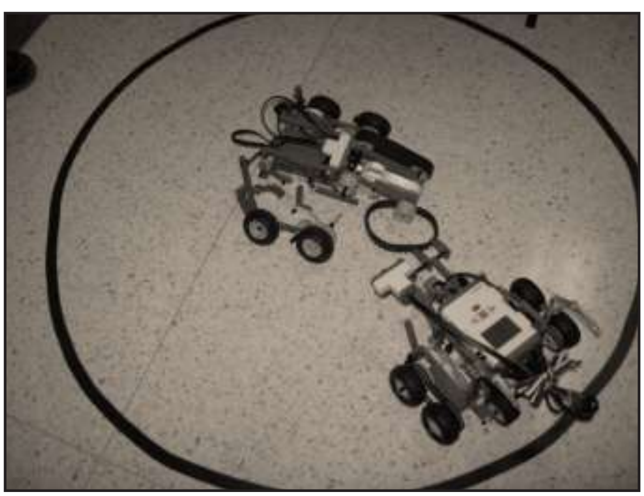

Figure 4. *Sumo Wars using LEGO "Taskbots."*

Team Challenge #4: Mixing Tank/Continuously Stirred Tank Reactor (CSTR) Design

In the latest course iteration, we have strengthened emphasis on chemical engineering process variables (*e.g.*, concentration, pH, temperature, pressure) and material balances. Student teams conduct team challenges using these measures as indicators of product quality. For example, one challenge requires feeding de-ionized water and a salt solution from two separate reservoirs to a mixing tank—maintaining a prescribed salt concentration in the outlet stream (as indicated by a conductivity sensor). Another challenge allows students to feed dilute acid and base solutions (typically vinegar/sodium bicarbonate) to a mixing tank, maintaining a particular pH as an indicator of the product quality. Students are required to conduct calculations using basic stoichiometry and mass balances to predict their system behavior and to assess actual performance.

In some semesters, we have engaged in "free-form" challenges—each team deciding on a design depicting some process of their own choosing with certain guidelines/goals. Creative design projects have included building a robotic device for titration and assembling a multi-step station for simulating the application of photo-resist to a silicon wafer, spin coating, and wet etching (Figure 6).

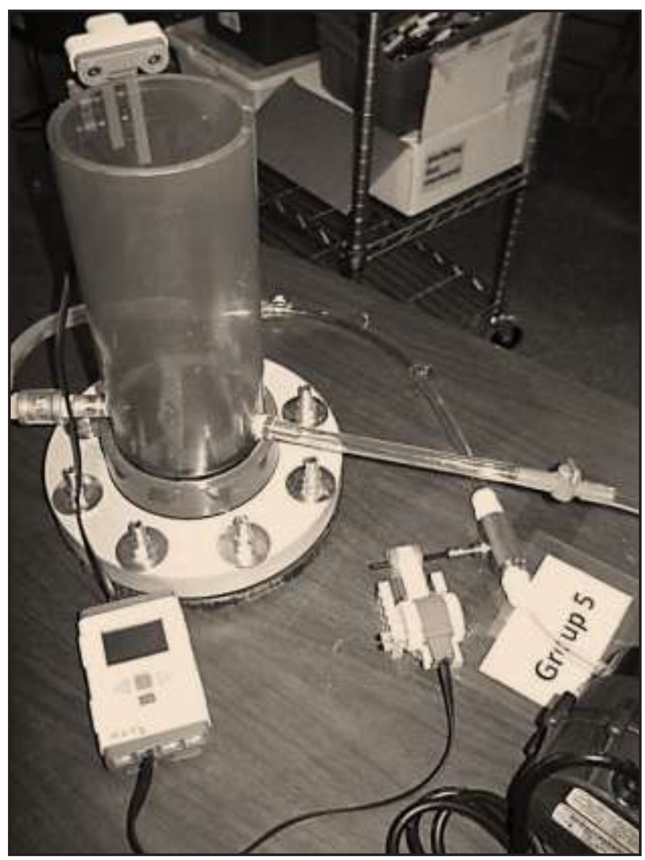

Figure 5. *Elements of level-control system.*

OUTCOMES AND ASSESSMENT

Figure 6. Silicon-wafer treating station.

Mechanisms for teaching and learning and the effects on student motivation have received wide attention in higher education.[13,14] Students in a project-based, studio environment face both challenges to their social and learning "centers of security" and opportunities for growth beyond their level of comfort. When conducted in a supportive/collaborative environment, this approach to student learning can significantly positively impact student self-efficacy[15] and preparation for advanced learning.

Using a Service Quality approach,[16] a multi-semester study of Analysis was conducted to assess variances between desired expectations and realized perceptions with a resulting "gap score." The gap score is the difference between what a customer expects from a service and what the customer perceives as being delivered. A negative quality gap score indicates the service is not meeting expectations, while a positive score indicates the service exceeds expectations. Scores are weighted according to students' relative expectations from certain characteristics of the course. The study was structured to examine whether or not an individual student's efficacy was impacted by realistic expectations, perceptions of the course, preparation, and team experiences.

Multiple surveys were given over the course of each semester—in weeks 3, 8, and 15. Surveys were structured to measure efficacy (the capacity or power to accomplish a desired effect or goal) in three areas—academics, team performance, and career. The service quality surveys, modified from a previously validated survey instrument, SERVUSE,[17,18] were structured to evaluate student expectations, their ratings of the importance of various factors, and their perceptions of various service quality dimensions as related to the course. Responses, using a 7-point Likert scale, were then correlated to respondents' academic preparation in high school and personal goals and expectations. Examples of survey questions included: "In excellent courses, instructors listen carefully to their students," and "In ChE 2213, instructors listen carefully to their students."

As anticipated, students with positive gap scores (*i.e.*, the course met or exceeded their expectations) scored higher in academic-, self-, and career-efficacy[16]—an indication of self-confidence needed for moving forward in an increasingly challenging chemical engineering curriculum. A close match between student perceptions and expectations served as a primary hypothesis for the study. This hypothesis was supported by the survey results. Team efficacy increased over the span of the semester while academic and career efficacy decreased slightly. While this requires more study, a contributing factor to lowered self-efficacy related to academics and career must be the delivery of the final survey during week 15, at the end of the semester when multiple exams and projects were due across all of their courses. Changes in efficacy and satisfaction, perceived quality, and behavioral intention (*i.e.*, how well a student believes he/she can perform in this chosen field) were significantly correlated in the study.

A perhaps intuitive but valuable and statistically valid implication of the study is that making changes to the course content to positively influence self- and team-efficacy can lend a positive influence to student satisfaction, perceived quality, and behavioral intention.

Changes made to the course over its multiple offerings include a significant increase in feedback (formal and informal) beyond structured quizzes. Additionally, the instructor provides opportunities for frequent, informal discussions across far-ranging questions about the curriculum, co-operative education, and general academic issues.

An equally valuable outcome has been the clarification among some students that chemical engineering "isn't for them." While we believe EVERYONE should be a chemical engineer (well, not exactly), the earlier a student realizes that a change of major may best serve their interests, the better for all concerned. A distinct advantage I have as the instructor for this course is that I also serve as the undergraduate coordinator for our chemical engineering program. As a result, I can also maintain ongoing academic/career advisement—regularly discussing with individual students their academic progress, interest, and preparation for participating in cooperative education, etc. We generally maintain an open, free-flowing communication that allows students to readily express concerns or doubts about their major—sorting out critical decisions before too much "time on task" has elapsed before switching fields of study.

Additional improvements include informal team surveys and individual interviews to assess the impact of projects. Through this process, and with enthusiastic inventiveness of many students, the team challenges have continuously improved. In several instances, students returning from their co-op experience have reported that the work with spreadsheets and the design approach have had a significant impact on their job preparation and performance. Additional feedback from co-op students has been re-invested into the course for making continual improvements.

SUMMARY

The placement of CHE 2213 Chemical Engineering Analysis in the second semester of the freshman year has enabled our program to maintain a steady, continuous contact with our freshmen throughout that critical first year. The significant numbers of transfer students taking the course benefit by being immersed in teamwork and engineering design, thereby solidifying their working relationships with others in their class and adapting to engineering problem solving. Project-based learning proves to be a worthy vehicle for integrating seemingly disjointed concepts studied in calculus, chemistry, and physics into practical problem solving— and it is much more fun than merely lecturing!

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