Results & Lessons Learned from a Chemical Engineering Freshman Design Laboratory

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Abstract

A survey of United States chemical engineering curricula shows that a relatively small number of departments offer their first-year students a laboratory experience focused on core chemical engineering concepts using hands-on design projects. Furthermore, the first-year chemistry and physics laboratories taken by engineering students do not typically ask them to exercise the type of creativity that attracted students to engineering in the first place.

In order to bring more active, collaborative, and hands-on learning into our curriculum, we created a freshman chemical engineering design course and laboratory. This course is situated in the second semester of our curriculum, after a more traditional lecture-based introduction to chemical engineering course, which we have used as a benchmark for our results.

In the design laboratory, individual freshmen first use interactive browser-based simulations to familiarize themselves with the relevant theory and data analysis. They are then put into teams, which are given design goals and access to a wide variety of inexpensive materials and tools. Such design goals include, for example, building a process to automatically create homogenous alginate beads for drug delivery, or building a photobioreactor to grow algae effectively. Students then validate their designs and compare their data to that predicted by theory. Students are trained on the use of Arduino microcontrollers and MATLAB to enable them to collect data from a variety of sensors. The course also includes a collaborative assignment on our seniors’ final project, for which our freshmen create resumes and apply. The semester is then capped with a proposal and final project of their own design.

We have collected three semesters of results from student surveys, pre- and post-tests, and detailed usage data from online simulations. The data indicate the pedagogy used in this course has been greatly successfully on multiple fronts. Students report remarkably high levels of satisfaction when compared to control surveys from more traditional lecture-based courses. They indicate that the collaborative methods used have helped them make social connections within the department. Student learning has been demonstrably improved and their skill sets have broadened. The prototyping, teamwork, communication, and data-analysis skills that students have gained early in the curriculum have also greatly increased the value of our freshmen to faculty research programs and others who hire our students as interns.

Introduction

Intellectual creativity, experimentation and active inquiry are at the heart of a rewarding engineering career, but often this fact is obscured during the early years of a chemical engineering education. Teaching methods that promote such qualities in the classroom may not
only be more authentic; they have been shown to correspond with significant gains in student learning and satisfaction.

Active and collaborative learning environments, have repeatedly and consistently been shown to impart a variety of benefits to students and departments\textsuperscript{1–3}:

- gains in learning\textsuperscript{4–7};
- improved retention of course material\textsuperscript{8};
- higher student self-assessment of their educational experiences\textsuperscript{7,9};
- improved student retention, particularly in underrepresented groups\textsuperscript{5,10–12};
- aid in ABET assessments\textsuperscript{13}.

Given such benefits, STEM education reform recommendations have recognized the need for more authentic and active learning within core curriculum, from the K-12 to the undergraduate level\textsuperscript{14–16}. Furthermore, research has revealed that developing a sense of community and belonging within a department can also result in significant gains in retention\textsuperscript{17–20} and student learning\textsuperscript{21}.

Active and collaborative learning can be, and often is incorporated into courses that have been traditionally lecture-based. However, laboratory courses, due to their innately interactive and collaborative nature, present the most direct route to such learning. While most freshmen labs required for introductory chemical engineering students are general engineering labs\textsuperscript{22}, intended for all freshmen in the college, there are several examples of effective engineering labs in the literature that focus on chemical engineering and their numbers appear to be growing\textsuperscript{23–26}. We surveyed the four-year undergraduate academic plans of 50 randomly selected chemical engineering departments in 2012 and resurveyed the same departments in 2015 (Figure 1). At the start of our work, early curriculum laboratory experiences for aspiring chemical engineers were rare. Figure 1 shows lab courses for freshmen and sophomores have been gaining in popularity; however, such courses are still relatively rare and the best practices for managing such laboratories remain in need of investigation.

In general, laboratory courses require resources and instructor effort significantly beyond those required for traditional lecture-based courses, particularly when employed with freshmen class sizes.

Furthermore, freshmen enter our departments with a
wide range of technical and hands-on skills and need additional training, presenting distinct hurdles that are not as pronounced within, for example, senior unit operations labs.

In this work we developed a new freshman design laboratory at the University of Utah, to introduce hands-on chemical engineering projects and evidence-based teaching methods as early as possible into our curriculum. Our goal was to improve our students’ learning, community, retention, and satisfaction with their educational experience. After three semesters, we now have evidence to indicate this change to our curriculum has been greatly successful.

Methods

The course developed as part of this work is entitled Chemical Engineering Design and Innovation and is situated in the second semester of our curriculum’s freshman year,27,28; positioned after a traditional lecture-based introduction to chemical engineering in the first semester. Our undergraduate population is roughly 22% female, and 37% belong to a racial or ethnic minority group. Each lab section contains between 25 and 40 students, and is overseen by a professor, a teaching assistant (TA), and the department’s lab manager. Three sections are now taught each year.

The course requires a $50 lab fee to cover project consumables, but no textbook is required; information that would traditionally be delivered by textbook is delivered through screen casts, simulations, and web pages developed specifically for the course. Each lab module requires approximately 1 m² of bench space per student team. Most teams consist of three students. The course is split into 1. a weekly one-hour discussion in a classroom setting in which the students are oriented to the upcoming design project and 2. a three-hour laboratory portion which occurs within our teaching laboratory space, which is about 6,500 ft².

Homework is split into individual and team assignments. Individual assignments consist primarily of student use of online simulations that model the physics involved in upcoming design projects. The simulations generate random constants and unknowns for each student and require virtual experimentation, data collection, and analysis; students are able to and must alter experimental parameters that would be alterable in reality. Individual students are tasked with determining unknowns using virtual data from simulations before they come together as a team to build a physical device to collect and analyze similar data. For example, students may be asked to run a virtual reaction in a spectrophotometer simulation to determine a reaction order and rate constant before they do the same, as a team, with data from a physical spectrophotometer that their team designed and built. The goal with individual assignments is to assure all students enter their team projects understanding both the relevant physics needed to inform their design decisions, and the mathematics needed to analyze their real-world data.

Each team assignment follows a flexible design cycle (Figure 2). New student teams are created for each project, to maximize social connections and avoid semester-long persistence of dysfunctional teams. Teams are given design goals and a wide assortment of material and tools with which they might meet those goals. Projects are given in memo form and students return assignments in the form of memos or presentations, mimicking the workplace. The labs are designed to build on each other — the skills gained in validating a sensor are used to make a
spectrophotometer, which is then used to monitor mass transfer in a drug delivery module and cell growth in a bioreactor module. As such, creative invention and reinvention are exercised. Each module and the associated discussions are coupled with online simulations of related systems. These simulations are used in homework assignments to familiarize freshmen with complicated theory, prepare for hands-on assignments, compare real-world data to theory, and track student usage to inform iterative improvement of curriculum material.

After the introductory week students begin a series of projects. **Basic Sensors (Week 2):**

**Purpose:** Students develop the skills needed to assemble a simple circuit and acquire data that would be useful to a chemical engineer. Basic concepts of physical measurements, and data analysis are introduced.

**Procedure:** Teams are asked to pick one sensor from a list of low-cost sensors (e.g. thermistors, CO sensors, photometers), collect data from them with Arduino Uno microcontrollers, and evaluate the sensor’s performance. A list of the sensors used, their model numbers, and vendors may be found online. Teams find the sensor’s datasheet, assemble an appropriate circuit, devise...

*Figure 2: Example of a hands-on Design Module.* Simulations are used in the research phase, during class discussions and individual homework. Students then plan their designs, using the theory they have learned, and then build their device using a variety of miscellaneous materials. Finally, they evaluate their designs using collected data and comparing results to theory.
and execute a means to introduce a step change in the sensor’s response, and record the response. In the end, each team member will go on to different teams carrying with them the ability to collect a unique measurement (temperature, pressure, humidity, and more).

**Homework:** Teams create five slides to communicate their work: title, introduction, methods, results, and discussion. Individual students watch a screencast on spectrophotometry and use an online spectrophotometer simulator to prepare for the following week’s design project.

**Spectrophotometer (Week 3 & 4):**

**Purpose:** Students experience the full design cycle, and learn the basics of calibration and line fitting. They obtain hands-on experience with reaction kinetics.

**Procedure:** Teams are tasked with building a low-cost spectrophotometer prototype to track a reaction for an industrial process. They are given sensors and materials similar to those described in previous published work, but are given no further instruction. Teams design and build their spectrophotometers and a flow cell over a lab period and have them ready to calibrate and track a batch and CSTR reaction during the following week’s lab period. The model reaction used is the alkali bleaching of a triphenylmethane dye (e.g. malachite green, crystal violet, or fuschin). To calibrate and track the reaction, teams may use whatever concentrations they determine to be reasonable. Typically, concentrations of dye around $10^{-4}$ M are used with $0.01$ M NaOH, resulting in a reaction that takes place over 15 min. The data collected are used to determine the reaction rate constant.

**Homework:** After this project’s first lab period, teams write a one-page memo with a design schematic, circuit diagram, and parts list, with all costs. After the following week’s calibration and data collection, teams write a short memo with an introduction, methods, results and conclusion section. Individual students complete a homework using an online simulation to determine an unknown reaction’s order and rate constant, as they will with the data they collected as a team.

**Process vs. Product Design for a Drug Delivery System (Weeks 5 & 6):**

**Purpose:** Students learn the difference between process and product design. They become familiar with fittings, pumps, and piping and instrumentation diagrams (P&ID). They are introduced to concepts of mass transfer, and empirical models through a hands-on project.

**Procedure:** Teams are tasked with creating a device to mass produce uniform, spherical, alginate beads to be used as a drug delivery system. Alginate beads are formed using the methods described by. The student’s process must use two solutions (an alginate and CaCl$_2$ stream) to form at least 10 mL of beads and separate them from the recycled process streams, without human intervention. To accomplish this task they are given a variety of fountain and aquarium pumps, tubing, fittings, and various containers. In this project’s first week, students build their system, produce their beads, and load them with a model drug over a week (fuschin). On this project’s second week, they use MATLAB’s Image Processing Toolbox to obtain the distribution of bead major dimensions and eccentricities. Finally, teams place a known volume of their beads into DI water and track the dye concentration over time to characterize the mass transfer by an
empirical model, as described by Farrell and Vernengo. Students may use the spectrophotometers they built earlier in the course for this task.

**Homework:** After this project’s first week, students turn in a single-page memo with a P&ID and standard operating procedure for their process. After the project, the team creates a series of slides that detail their design and results, along with the calculations needed to compare their rate of mass transfer to the Peppas empirical model for drug release. Individual students use an online simulation to determine the relationship between diffusivity and bead diameter and the rate of drug release. In their team slides, they use the simulation to estimate the model drug’s diffusivity in the bead by inputting their measured bead radius and release data, and altering diffusivity to best match their data to a 1-D Fickian diffusion model in spherical coordinates.

**Algae Photobioreactor Design (Weeks 7 & 10):**

**Purpose:** Concepts of biochemical engineering, phases of batch microbial growth, and growth kinetics are introduced to students. Students are to experience the importance of fluid dynamics to mixing considerations.

**Procedure:** Teams are given the goal of creating a bench-top photobioreactor to grow a particular strain of cyanobacteria as quickly as possible, in order to supply oil for our biodiesel research. The strain of algae used is Synechococcus Elongatus, though most any strain should suffice. Each team begins with the same stock solution of algae (about 20 cells/μL) and 500 mg/L Miracle-Gro® in city water, and each reactor is allotted a similar 0.5 m by 0.5 m area of bench top in front of a standard two-bulb fluorescent light. As such, the teams must focus on maximizing the algae’s access to light and dissolved gasses, typically by airlift mixing, while limiting their water evaporation rate. Teams build a wide variety of photobioreactors from any assembly of containers, tubing, and pumps they desire. They track microbial growth over 3 weeks, and may use their spectrophotometers to track microbial growth. In the 10th week of the course, teams collect their last data, and the algae are collected for use in ongoing research.

**Homework:** After the first lab session, teams turn in a single-page memo with an illustration of their photobioreactor, noting each component and the streamlines of flow they anticipate within their reactor. At the end of this module, students turn in a memo report with an introduction, a materials and methods section, a results section with their growth data and calculated maximum growth rate, and conclusions about the performances of various reactor designs in the class. Individual students use an online simulation to calculate the maximum growth rate of a microbe in a browser simulation similar to the one used in the spectrophotometer module.

**Biodiesel (Weeks 8 & 9):**

**Purpose:** Students are given experience with a wide range of analytical equipment, and conduct an organic chemistry reaction with a clear industrial use. They are introduced to the importance of energy research and concepts of process economics and scale-up.

**Procedure:** While the students’ oil-producing algae are growing in their photobioreactors, each team is asked to select a competing oil for analysis: canola, vegetable, peanut, olive, coconut, or corn oil. Each team creates approximately 50 ml of biodiesel by mixing 10 mL of methanol, in which they dissolve 0.2 g NaOH, with 40 mL of their oil, at 60 °C for 30 min. During the
following lab period students analyze their starting oil and biodiesel using FTIR (Thermo Scientific, iS10), UV-Vis (PerkinElmer, Lambda 35), and refractometers (Bausch & Lomb, ABBE-3L). Teams also measure their biodiesel’s density, relative viscosity by measuring its flow rate through a 1/32” hole, and burn rate and flame temperature using a thermal camera (FLIR, T300) by burning their fuel in a 0.5 ml glass scintillation vial, using a 0.5” wide cotton wick. Data from each oil are collected and shared with the class on a cloud drive.

**Homework:** In the first week of this module teams compose a memo in which they estimate the costs involved in operating a continuous 1,000 gal algae oil per day conversion to biodiesel, using values from their bench-top reaction as a starting point. They are asked to find and consider only the material costs going into and out of the plant and are asked to estimate the total left for other daily operating costs, such as utilities, pay, and maintenance. In the second week, teams produce a memo evaluating each oil with its biodiesel product, and ranking each analytical method for its effectiveness in determining the difference between biofuels, the presence of unreacted material, and how near the biodiesel will behave to traditional diesel.

**Collaborative Project with Seniors (Weeks 10 - 12):**

**Purpose:** Students are to develop inter-year social connections between our students. Freshmen will learn about internships, research, and job opportunities, and better plan their curriculum. Seniors are meant to gain managerial skills; up to this point all their team working experiences in courses have been in teams of peers, though they will commonly be in leadership or support positions in the workplace. Another aim is to allow seniors to view job application process from the employer’s perspective, which may give them insights into editing their own resumes.

**Procedure:** At the beginning of the semester each freshman turns in a resume. This resume is edited by the professor and returned. In our senior projects laboratory, students pitch proposals for a capstone lab project, projects are selected and then a list of them is presented to the freshmen. Freshmen then rework their resume to apply to be part of the senior project they most desire. Senior teams then receive the resumes and choose four to eight freshmen they wish to “hire”. In weeks 10 through 12, freshmen arrange times to join senior teams to aid in the laboratory tasks needed to complete the senior team’s final project.

**Homework:** Individual students are required to turn in an initial resume, and a resume incorporating the professor’s changes and tailored to the job they want. At the end of the collaboration, freshmen teams compose a memo detailing their work with the seniors.

**Final Project (Weeks 12 - 14):**

**Purpose:** Students are to exercise their ability to develop and propose simple projects for a client, using the laboratory and prototyping skills gained throughout the course. Students are to develop confidence and demonstrate to themselves their ability to learn independently.

**Procedure:** Teams are told they may spend the final weeks of the course on a project of their own design. They are asked to propose this project to their client, the Department of Chemical Engineering, and told they must fit their project within department’s goals of education, service, and/or research. This module is meant to be radically open-ended; it must only be valuable work to their client. Proposal ideas are honed with TA’s and professors in a proposal workshop class
period. Resulting projects were primarily 1. teaching modules for outreach purposes, 2. improvements on existing lab modules in this same design lab, or 3. manageable projects from faculty research programs.

Homework: Each individual student prepares a one-page proposal which is graded and brought to the proposal workshop. A final team proposal is created during the workshop. At Week 13 a progress report is written by the team and submitted. During the class period’s final exam time (Week 15), a final memo report on their project is due and each team gives a 9 min presentation on their work to the class.

Results

Student Survey Responses – Many questions were asked of students in pre- and post-course surveys. Questions focused on both on the students themselves and on their regard for the new pedagogy. Answers were given on a 5-point Likert scale from “Strongly Disagree” to “Strongly Agree.” Figure 3 shows post course results from selected survey questions for three semesters (of the three bars shown for each question, the bottom bars represent more recent semesters). While similar questions have been grouped in Figure 3, they were interspersed throughout the survey to attempt to improve the reliability of student responses.

Several observations from these survey questions may be made. Firstly, from Questions 1-3, it is clear that students felt they were being asked to play a more active role in their education, but also, they appreciated the approach. However, Question 4 suggested that a significant percentage of students felt previous courses left them unprepared for the design laboratory. In response, after the first semester we began giving a preview lecture to students in the fall semester’s Introduction to Chemical Engineering course, and we added material to the lab discussions to address weaknesses; improvement in student’s perceived readiness can be seen in subsequent semesters. From Questions 5-7, it appears the variety of labs and discussion topics caused students to feel they had been given a broad introduction to the variety inherent in Chemical Engineering. Because team working can be a significant source of student frustration and over half of a student’s grade in this course relied on team assignments, we included Questions 8-10. It seems students, in general, had positive team experiences. While we did anecdotally witness some dysfunctional team dynamics, because we switched up teams and assured no student was ever with the same peer twice, this dysfunction was short-lived and it seems students appreciated this approach. Finally, by maximizing interactions throughout the student body, we intended to increase social interactions, which have been shown to boost retention12,17, particularly for students in underrepresented groups18; Question 10 suggests we were successful in the aim of creating connections between students.

Questions 11-14 were intended to assess the effect of the course on retention. Historically, we have found that around 50% of students from our freshman year make it to graduation in our department. Because a significant percentage of our students may leave for two-year religious missions in the midst of their education, we have been unable to directly measure the retention rate after the implementation of this course. However, about 90% of students leaving the new design lab “Agree” or “Strongly Agree” with the statement “I will graduate with a degree in
Figure 3: Student Responses to Survey Questions. Black, blue, green, and yellow bars indicate percentage of students responding “Strongly Disagree,” “Disagree,” “Agree,” and “Strongly Agree,” respectively. Neutral responses are not shown. Red circles indicate the average response from -100 to 100 scale for “Strongly Disagree” to “Strongly Agree.” Each statement includes data for three semesters. The 2013 Spring (top bars), 2014 Spring (middle bars), and 2014 Summer (bottom bars) semesters represent 61, 70, and 12 students survey responses, respectively (82% mean response rate).
chemical engineering,” and we are experiencing the highest junior and senior classes in our history. Such results suggest we have consequently improved our ability to retain students, which would be expected from the literature on active learning environments and students’ positive regard for the course\(^5,10–12\).

Student free-form written comments were overwhelmingly positive, with only a single negative response about the teaching methods in almost 150. Common themes included appreciation for simulation homework, the open-ended “real-world” nature of the assignments, and the classroom atmosphere.

Comparison to Control – This new course is taught in the second semester of the freshmen year. In the first semester, these same freshmen took a traditional lecture-based introductory course, providing a means of comparison. Both courses cover similar introductions to core theory and concepts: fluid mechanics, mass transfer, process engineering, programming, and so on. While we did not use custom surveys on students in the traditional course, all students fill out standard course evaluations for university courses. Figure 4 shows a comparison of relevant questions from these standard post-course evaluations. Positive student assessments were substantially more common in the evaluations of the new introductory course, and they have continually improved as we have honed our new pedagogy.

Skill Development & Student Confidence – One primary aim of this course was to develop

![Figure 4: Comparisons of Two Freshmen Introduction to Chemical Engineering Courses.](image)

Each bar graph shows student responses to questions on a six-point Likert scale. One year and approximately 65 students are represented in each graph. a) Data from a traditional lecture-based course. b) Data from a new introduction to ChE course, for the same cohort. Inset graph in b shows average course evaluation for the three semesters this new course has been taught and shows continual improvement; a score of 6 is the maximum possible.
student’s workplace skills, such as laboratory aptitude, machining, prototyping, teamwork, and communication skills, all of which are difficult to quantify. As the semester progressed the quality of written assignments notably increased, and, of course, students’ lab capabilities greatly increased to the point where they were capable of proposing and executing their own project in a space which intimidated most of them at the semester’s beginning.

In previous semesters we did not track student training, however, in the current 2015 semester, we have begun to record successful development of new laboratory skills in individual students. In general, student who need a specific laboratory skill to accomplish their design goals must be trained by an instructor on that skill and, after a 24 hour waiting period, they must then demonstrate proper procedure and retained understanding of associated safety issues. Once they pass, the student is given an icon on their lab name badge, indicating their ability to perform a particular lab skill, without direct supervision. The training percentages for this current class of 106 students are shown in Table 1. Many new skills have been demonstrably developed by our students in this freshman laboratory, from simple lab glassware care to the more complicated ability to operate the lab’s laser cutter.

Students also assessed their personal pre- and post-course confidence in a variety of related skills (e.g. laboratory skills, circuitry, data analysis, communication, etc.). Students ranked each of their skills on a 6-point scale from zero experience to strong confidence in their abilities. In every category, the average student felt their skills had increased compared to their younger selves over the semester, with an average of a 33% increase. In short, they left the course with greater confidence in their capabilities.

**Pre- and post-tests** – Though the course focusses on the development of difficult-to-measure skill sets, such as team working and creativity, students did measurably improve on every question given to them in a pre- and post-test, on average by 24%. These tests focused on basic conceptual questions regarding core chemical engineering topics, which were also covered in the fall introduction to chemical engineering course (a sample test is given in the supplementary material). It appears students who did not pick up on these concepts in a traditional lecture-based course, were able to gain better understanding through hands-on design projects.

**Underrepresented groups** – Lastly, we observed no statistical difference in any of our data with regards to traditionally underrepresented groups of students. Such lack of difference is somewhat encouraging, considering that traditional curriculum has been shown to possibly dissuade underrepresented students\(^5,10-12\). As one possible exception, we found that women performed

| Table 1: Laboratory & Prototyping Skills & the Percentage of Freshmen Certified at Them. |
|---------------------------------|------------------|
| SACHE’s Basics of Laboratory Safety Program | 94% |
| Use of Laboratory Glassware & Labeling | 82% |
| Proper Micropipette Technique | 73% |
| Hand Drills, Drill Press, & Grinder | 57% |
| Miscellaneous Hand Tools | 30% |
| Soldering | 57% |
| Laser Cutter & 2-D CAD | 24% |
| 3-D Printer & 3-D CAD | 2% |
better than men in this course (one-sided P = 0.096), by an average of 6 percentage points.

Conclusions & Lessons Learned

The process of establishing this design laboratory for chemical engineering freshmen has been much like the open-ended design process we now ask our freshmen to exercise in their design projects. There was no single correct solution to our need for more-engaging pedagogy in our freshman year, but there were approaches that led to more or less effective results. A traditional lecture-based introduction to chemical engineering, using static homework, did not seem to appeal to our students. With our new course, student self-assessments of their learning experience are now significantly increased. They are also demonstrably improved in their conceptual understanding of chemical engineering topics, which they were to have already absorbed in a traditional course.

Some of the benefits of such a course may be rather intangible and difficult to measure. Student personal confidence in their skills, for example, has been notably increased in both their demeanor in a laboratory setting and on pre- and post- course surveys. Furthermore, their social connections to the department have grown. By the end of the course, each student has participated on a team with almost a third of their cohort and has spent a great deal of time interacting with several faculty members and older students, developing important and useful social and professional connections. Anecdotally, we have seen our freshmen enter research internships which are being vacated by seniors with whom they worked on their collaborative projects. Our results, both quantitative and qualitative, have been, in short, wholly positive.

However, there have been several challenging hurdles that needed to be overcome, in order to establish this freshman design laboratory as a permanent foundation of our curriculum.

Managing Logistics – Reorganizing teams for each project has had many benefits at the cost of complexity. Team grades for a particular team will apply to a different group of students depending upon the project number. With such a team assembly strategy, there is a pointed need for clear and detailed communication between TAs and students in this laboratory. We have relied heavily on our university’s course management system (Canvas by Instructure) to arrange teams, collect assignments, and properly distribute credit. The collaborative project with seniors has been another logistic hurdle. In surveys, freshmen satisfaction with this project was found to be directly proportional to the time they spent working with their seniors. Teams that could not properly schedule enough time to work together found the experience far less satisfying. As a result we have begun instructing student on the use of web-based calendars and scheduling web applets.

Managing Growth – Possibly due to our extensive outreach program, we have nearly doubled our freshman population since the inception of this course, but we have been able to maintain its original content. To do so, we have kept the lab benchtop area needed per project to a limit of 1 m², and cost per project below $10/team. We have also removed much of the grading burden
from TAs by using browser simulations which automatically assesses students, thus opening up a single TA’s time to be spent facilitating several sections of the laboratory. Lastly we have moved to a model with a single discussion section per week, which is followed by several lab sections, instead of placing a discussion before each lab. Currently we are managing 106 freshmen in spring semester; if growth continues, we plan to add another section in spring, and then begin offering the course in the fall or summer.

Managing Safety – Our freshmen come to us with a wide range of skill sets, from the recent high school graduate who has never picked up a tool to nontraditional students with years of experience in a machining job. As the class size grew, we found it became increasingly difficult to keep track of which students have proper training to use particular tools. To address this problem, we have instituted a name badge policy in this course. Each student must wear a name badge on which we have various icons representing the training they have received, such as passing the SaChE basic laboratory training, use of soldering irons, and use of our laser cutter. Once a student is trained and observed using proper technique, we sign them off on their badge, enabling instructors to quickly assess which students are capable of using which equipment and further enforce a culture of safety throughout our curriculum.

In summary, we feel the addition of these new methods to our freshman year has significantly improved our students’ abilities, understanding, socialization, and satisfaction. Due to such, we plan to progressively move similar collaborative hands-on projects and simulations into our mid-curriculum courses, to augment teaching methods which have traditionally relied primarily on lectures. While such methods may not fully replace the use, or even the need for forms of more traditional content delivery, we believe they have shown significant potential towards furthering our educational mission.

References


### Supplementary Material: Course Survey

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<thead>
<tr>
<th></th>
<th>Strongly Disagree</th>
<th>Disagree</th>
<th>Neutral</th>
<th>Agree</th>
<th>Strongly Agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>I played a more active role in my education in this course than in typical courses.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>I prefer the teaching methods used in this course over a more traditional laboratory style.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>This course has improved my understanding of what chemical engineers do.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>This course has helped me understand the modern societal issues addressable by chemical engineering.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>This course has made me more aware of the various areas of chemical engineering in which I may specialize.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
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<tr>
<td>This course has increased my interest in chemical engineering.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Courses I took before this course adequately prepared me for this course.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>The time commitment for this course was reasonable.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>The credit hours for this course should be increased from 2 to 3.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>My teams were able to get help from the instructor or TAs in lab when needed.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>On the whole, I had a good experience working with my team members in this course.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>I prefer switching teams for each project, as we did in this course, over remaining in the same lab teams throughout an entire semester.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>This course helped create social connections with my peers.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Unlike most labs, this lab used open-ended design problems where there is no one right method or answer. I preferred the open-ended approach used in this course.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>This course replaced a physics and organic chemistry lab in our chemical engineering curriculum. I believe I would prefer this course. (Do not answer if you have not taken a laboratory from the chemistry or physics department)</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>As a result of this course my ______ skills have improved over the semester:</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>problem solving</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>team working</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>written communication</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>oral communication</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>
I enjoyed the following class projects:
1. Basic Sensor Circuit
2. Spectrophotometer
3. Drug Delivery Alginate Beads
4. Photobioreactor
5. Biodiesel
6. Collaborative Project with 4905
7. Final Project

I learned important engineering concepts & skills from the following class projects:
1. Basic Sensor Circuit
2. Spectrophotometer
3. Drug Delivery Alginate Beads
4. Photobioreactor
5. Biodiesel
6. Collaborative Project with 4905
7. Final Project

If I had to remove a single module from this course, I would remove (circle one):
1. Basic Sensor Circuit
2. Spectrophotometer
3. Drug Delivery Alginate Beads
4. Photobioreactor
5. Biodiesel
6. Collaborative Project with 4905
7. Final Project

If I could keep only one module in this course, and had to replace the others, I would keep (circle one):
1. Basic Sensor Circuit
2. Spectrophotometer
3. Drug Delivery Alginate Beads
4. Photobioreactor
5. Biodiesel
6. Collaborative Project with 4905
7. Final Project

How many hours did you spend working with the students from CH EN 4509 (the graduating seniors) in your collaborative project? _____

What aspects of this course worked well and should not be changed?
_____________________________________________________________________________________
_____________________________________________________________________________________
_____________________________________________________________________________________
_____________________________________________________________________________________
_____________________________________________________________________________________
_____________________________________________________________________________________
How could this course and any of its individual modules be improved?

_____________________________________________________________________________________
_____________________________________________________________________________________
_____________________________________________________________________________________
_____________________________________________________________________________________
_____________________________________________________________________________________
_____________________________________________________________________________________

Please tell us anything else that you would like to tell us regarding this course or the chemical engineering department or program.

_____________________________________________________________________________________
_____________________________________________________________________________________
_____________________________________________________________________________________
_____________________________________________________________________________________
_____________________________________________________________________________________
_____________________________________________________________________________________

On average I spent ____ hours per week outside of the class period working on this course.

Survey Questions about You:
The following questions are meant to help us better understand who our students are, the issues affecting them, and where they may need more help.

What was your classification within our department at the beginning of this semester (circle one)?

<table>
<thead>
<tr>
<th>Pre-engineering Status</th>
<th>Intermediate Status</th>
<th>Major Status</th>
</tr>
</thead>
</table>

What is your gender?  
M  F

To what racial/ethnic group(s) do you belong?

___ African American  
___ Asian (please specify)  
___ Japanese  
___ Filipino  
___ Chinese  
___ Korean  
___ Vietnamese  
___ other (please specify) ______________________

___ Hispanic Caucasian  
___ Native American  
___ non-Hispanic Caucasian  
___ other (please specify) _______________________
<table>
<thead>
<tr>
<th>Statement</th>
<th>Strongly Disagree</th>
<th>Disagree</th>
<th>Neutral</th>
<th>Agree</th>
<th>Strongly Agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>I have a comprehensive understanding of what chemical engineers do.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>I understand the steps needed to graduate from the chemical engineering program.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Choosing to major in chemical engineering was the right choice for me.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>I will graduate with a degree in chemical engineering.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>I will graduate with a degree in a science, mathematics or engineering field.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>I will continue on to graduate school.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>I have had or will have an internship or co-op in a field related to chemical engineering while I am an undergraduate student.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>I prefer learning through hands-on activities over traditional lectures.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>I enjoy working in teams.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>I often socialize with peers from my department in classes and college facilities.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>I often socialize with peers from my department outside of the university.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>I am an active part of the community in my college.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>I am able to approach a chemical engineering professor for advice or help.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>My department cares about me and my professional development.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>I am confident in my:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mathematics skills</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Science skills</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
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<tr>
<td>Engineering skills</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Computer skills</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Team working skills</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Writing skills</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Oral communication skills</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>So far and on the whole, the most difficult parts of my college experience have been:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Managing time to meet course demands</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Managing family demands</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Getting enough sleep</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Understanding difficult theoretical concepts</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Poor teaching methods</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Poor interactions with professors</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Poor interactions with peers</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Other:</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>
CH EN Courses I have taken or am now taking (circle):

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH EN 1703</td>
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<tr>
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<tr>
<td>CH EN 3353</td>
<td>Fluid Mechanics</td>
</tr>
<tr>
<td>CH EN 3453</td>
<td>Heat Transfer</td>
</tr>
<tr>
<td>CH EN 3853</td>
<td>Chem Eng Thermo</td>
</tr>
<tr>
<td>CH EN 3603</td>
<td>Mass Trans. &amp; Sep.</td>
</tr>
<tr>
<td>CH EN 3553</td>
<td>Chem Rxn Eng</td>
</tr>
<tr>
<td>CH EN 5103</td>
<td>Biochem. Eng.</td>
</tr>
</tbody>
</table>

CH EN Courses I will take next year (circle):

<table>
<thead>
<tr>
<th>Course Code</th>
<th>Course Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH EN 1703</td>
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</tr>
<tr>
<td>CH EN 2450</td>
<td>Numerical Methods</td>
</tr>
<tr>
<td>CH EN 2300</td>
<td>Thermodynamics I</td>
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<td>CH EN 3853</td>
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<td>CH EN 3603</td>
<td>Mass Trans. &amp; Sep.</td>
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<tr>
<td>CH EN 3553</td>
<td>Chem Rxn Eng</td>
</tr>
<tr>
<td>CH EN 5103</td>
<td>Biochem. Eng.</td>
</tr>
</tbody>
</table>

I am particularly interested in pursuing a career in the following field(s) or industries:

_____________________________________________________________________________________

If I could not be a chemical engineer for my occupation, I would be a: _______________________

Please tell us anything else that you would like to tell us regarding yourself, your education, or the chemical engineering program.

_____________________________________________________________________________________

_____________________________________________________________________________________

_____________________________________________________________________________________

_____________________________________________________________________________________

_____________________________________________________________________________________
Supplementary Material: Pre- & Post Test

CH EN 1705 Chemical Engineering Design & Innovation - Pretest

1. A 9 V battery is attached across a 1 kΩ resistor. What should the current through the resistor be?
   a) 9 A b) 9 kA c) 9 mA d) 0 A e) 1/9 A f) 1/9 kA g) 1/9 mA

2. If we decrease the resistance of resistor \( R_A \) in the adjacent circuit, without changing anything else, what would happen to the voltage at Point A (between the two resistors) in the circuit?
   a) Goes up b) Stays the same c) Goes down d) Not enough information

3. Into a barrel containing 240 liters of pure water you pour 10 liters of water containing 5 mol/liter (M) of sugar. What is the final concentration of sugar in the barrel after it’s well-mixed?
   a) 0.020 M b) 0.154 M c) 0.200 M d) 0.208 M e) 0.250 M f) 0.350 M g) 0.377 M

4. Consider the elementary irreversible reaction \( A + B \rightarrow C \) in water. If we double the starting concentrations of both A and B, what will happen to the rate of the reaction?
   a) Remain the same b) Go down c) Go up 2X d) Go up 4X e) Go up 8X f) Go up 16X

5. Which of the following are second order reactions, if we assume they are elementary reactions (circle as many as you think are correct)?
   a) \( 2A \rightarrow B \) b) \( A \rightarrow 2B \) c) \( A + B \rightarrow C \) d) \( A \rightarrow B \) e) \( A + B \rightarrow C + D \) f) \( A \rightarrow B + C \) g) \( A + 2B \rightarrow C \)

6. Which of the following is a rate equation for a second order irreversible reaction, where \( C \) is concentration, \( t \) is time, and \( k \) is the rate constant. (circle as many as you think are correct)?
   a) \( \frac{dC_A}{dt} = -kC_A \) b) \( \frac{dC_A}{dt} = -2kC_A \) c) \( \frac{dC_A}{dt} = -kC_A^2C_b \) d) \( \frac{dC_A}{dt} = -kC_AC_b \) e) \( \frac{dC_A}{dt} = -kC_A^2 \)

7. We want to make an elementary irreversible reaction, \( A + B \rightarrow C \), behave like a first order reaction with respect to molecule A, to simplify finding the rate constant. How could we do this?
   a) Measure the rate of reaction without any B present. b) Add a catalyst to speed up the reaction. c) Add an inhibitor to slow the reaction. d) Continually remove molecules of C during the reaction. e) Use a starting molar concentration of B that is much larger than that of A.

8. We have a chemical reaction, \( A \rightarrow B \), that is governed by the equation:
   \[
   \frac{dC}{dt} = -kC
   \]
   where \( C \) is the concentration of A, \( k \) is the reaction’s rate constant, and \( t \) is time. We want to determine \( k \) using data we have of \( C \) versus \( t \) during the reaction. What should we plot to linearize this data, such that \( k \) would be the slope of the line that fits the linearized data?
   a) \( C \) vs \( t \) b) \( 1/C \) vs \( t \) c) \( \log(C) \) vs \( t \) d) \( C \) vs \( 1/t \) e) \( C \) vs \( \log(t) \) f) \( 1/C^2 \) vs \( t \) g) \( C^2 \) vs \( t \)
9. Consider the adjacent fluid circuit. The pump takes water out of a reservoir and pumps it through Pipe 1. Then the stream splits to recycle through Pipe 2 or exit through Pipe 3. If we keep the same flow rate through Pipe 1 and shorten Pipe 2, what should happen to the flow rate out of Pipe 3?

a) Goes up  b) Stays the same  c) Goes down  d) Not enough information

10. Which of the following commands would create a vector, v, in MATLAB containing the values [20, 30, 40, 50, 60]? (circle as many as you think are correct)

- a) \( v=10*\left(1.5+1\right) \)
- b) \( v=(1:6)*10 \)
- c) \( v=linspace(20,60,6) \)
- d) \( v=20:10:60 \)
- e) \( v=20:60 \)
- f) \( v=20,60 \)
- g) \( v=linspace(20,60,10) \)
- h) \( v=20,30,40,50,60 \)
- i) \( v=60:20 \)
- j) \( v=(1:5)*10+10 \)

11. Using the same vector, v, as in problem 10, in which of the following will the output be equal to 1? (circle as many as you think are correct)

- a) \( v(5)==60 \)
- b) \( v(20)-v(40)/2+1 \)
- c) \( \text{length}(v)==v \)
- d) \( \text{max}(v./v) \)
- e) \( v(v(1)/5)-49 \)
- f) \( \text{for } i=20:10:60 \) \[ a(i)=v(i); \]
  \[ \text{end} \]
  \[ a==v \]
- g) \( a=[1 1 1 1 1]; \) \[ \text{for } i=5:-1:1 \]
  \[ a(i)=v(i); \]
  \[ \text{end} \]
  \[ \text{min}(a==v) \]
- h) \( a=1; \) \[ i=0; \]
  \[ \text{while } a \]
  \[ a=a-i; \]
  \[ i=i+1; \]
  \[ \text{end} \]
  \[ i/2 \]
- i) \( \text{if } v(3)^{\text{a}}=30 \)
  \[ a=1; \]
  \[ \text{else} \]
  \[ a=0; \]
  \[ \text{end} \]
  \[ a \]
- j) \( a=0 \) \[ \text{try} \]
  \[ a=v(a) \]
  \[ \text{catch} \]
  \[ a=a+1; \]
  \[ \text{end} \]
  \[ a \]

12. Which of the following MATLAB commands would find the average of vector, v, from Question 11? (circle as many as you think are correct)

- a) \( n=\text{length}(v); \)
  \[ x=0; \]
  \[ \text{for } (i=0;i<n;i++) \{ \]
  \[ x+=v(i); \]
  \[ \} \]
  \[ \text{avg}=x/n; \]
- b) \( n=\text{length}(v); \)
  \[ x=0; \]
  \[ \text{for } i=1:n \]
  \[ x=x+v(i); \]
  \[ \text{end} \]
  \[ \text{avg}=x/n; \]
- c) \( x=1; \)
  \[ \text{for } i=1:5 \]
  \[ x=x+v(i); \]
  \[ \text{end} \]
  \[ \text{avg}=x/n; \]
- d) \( n=\text{length}(v); \)
  \[ \text{avg}=0; \]
  \[ \text{for } i=1:n \]
  \[ \text{avg}=\text{avg}+v(i)/n; \]
  \[ \text{end} \]
- e) \( n=\text{length}(v); \)
  \[ x=0; \]
  \[ i=0; \]
  \[ \text{while } i<n \]
  \[ x=x+v(i+1); \]
  \[ i=i+1; \]
  \[ \text{end} \]
  \[ \text{avg}=x/n; \]
- f) \( \text{avg}=\text{mean}(v); \)
- g) \( \text{avg}=\text{average}(v); \)
- h) \( \text{avg}=\text{sum}(v)/5; \)
- i) \( \text{avg}=\text{sum}(v)/60; \)
- j) \( \text{avg}=\text{mode}(v); \)

CH EN Courses I have taken or am now taking (circle):

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<tr>
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<td>3853</td>
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<td>Mass Trans. &amp; Sep.</td>
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<tr>
<td>3553</td>
<td>Chem Rxn Eng</td>
</tr>
<tr>
<td>5103</td>
<td>Biochem. Eng.</td>
</tr>
</tbody>
</table>
If you took a course which is considered equivalent to CH EN 1703 (Intro to Chem. Eng.) what was that course and at which institution did you take it?

<table>
<thead>
<tr>
<th>Course Number &amp; Name</th>
<th>Institution (if not the University of Utah)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I have a comprehensive understanding of what chemical engineers do.</td>
<td>1 2 3 4 5</td>
</tr>
<tr>
<td>Choosing to major in chemical engineering was the right choice for me.</td>
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<tr>
<td>I will graduate with a degree in chemical engineering.</td>
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<tr>
<td>I will graduate with a degree in a science, mathematics or engineering field.</td>
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<td>I will continue on to graduate school.</td>
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<td>I have had or will have an internship or co-op in a field related to chemical engineering while I am an undergraduate student.</td>
<td>1 2 3 4 5</td>
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<tr>
<td>I am comfortable approaching a chemical engineering professor for advice or help.</td>
<td>1 2 3 4 5</td>
</tr>
</tbody>
</table>

**I am confident in my _________ skills:**

<table>
<thead>
<tr>
<th>Skills</th>
<th>No Experience</th>
<th>Strongly Disagree</th>
<th>Disagree</th>
<th>Neutral</th>
<th>Agree</th>
<th>Strongly Agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soldering</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
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<tr>
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