AC 2010-364: DEVELOPING AN OPEN ENDED JUNIOR LEVEL LABORATORY EXPERIENCE TO PREPARE STUDENTS FOR CAPSTONE DESIGN

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Developing an Open Ended Junior Level Laboratory Experience to Prepare Students for Capstone Design

Abstract

A junior level Nanosystems Engineering open-ended laboratory course was developed to provide students with a common experience to enable them to be more effective in their capstone design course. Traditionally, the lecture and laboratory courses build specific technical skills that the students apply in the capstone experience. However, there is little transition between the highly defined problems provided in lecture and laboratory courses versus the open-ended project students are asked to solve in their capstone design course. The capstone design projects for the Nanosystems Engineering program is provided by faculty across a variety of disciplines. Therefore, it became evident that rather than expecting each faculty mentor to provide certain basic skills, a more effective approach would be to have all Nanosystems Engineering students to work on a smaller open-ended project in the last quarter of the Junior year to teach all the elements that they would need to apply more deeply in their capstone project the following year. The educational goal of this course is primarily to enhance the engineering design process (ABET 3c), however other educational goals include the development of: critical thinking skills/problem solving (ABET 3b); written/oral communication of results (ABET 3g); economics, safety and environmental considerations (ABET 3h); literature search approaches (ABET 3j); teamwork (ABET 3d); and analytical techniques (ABET 3k).

This course presented in this paper is very different than the majority of nanotechnology laboratory courses that expose or demonstrate a wide variety of nanotechnology techniques. The junior level laboratory course focuses on a single process: requiring students to improve the process to manufacture CdSe nanoparticles. Students have performance objectives (control particle size and produce a narrow distribution) that they must balance with economics, safety, environmental, and manufacturability concerns. Students are taught literature searching techniques of both the patent and scientific literature. The students are shown the common structure of literature documents to enable them to extract the information necessary to plan their own experiments. Students work in teams of three or less in the course and provide weekly peer assessments of both time and impact of their progress. The students begin by justifying a process in the literature to focus on by comparing reported particle size performance with economics and safety/environmental concerns. The students conduct baseline experiments similar to the literature and then plan areas of process improvement by focusing on parameters that should provide the greatest economic impact (i.e. recycling or changing solvent, reducing reaction time, increasing batch concentration, etc.).

Very positive feedback has been received in the end of course assessment. Students felt the course strongly impacted their ability to perform design and they appreciated the flexibility (and responsibility) of pursing their own ideas of process improvements. The effectiveness of the course in preparing students for senior design is being assessed by comparing cohort students enrolled in the multidisciplinary capstone course from traditional disciplines (primarily mechanical, electrical, and biomedical engineering degree who did not take the junior nanosystems laboratory course).

I. Introduction

Nanotechnology education is evolving from the inclusion of a broad freshman/sophomore level overview courses to greater depth leading to certificates, concentrations, and minors. _ has developed a complete B. S. level Nanosystems Engineering Degree. Details of the structure of this program have been delineated in the literature[1,2]. The approach utilizes a common freshman engineering sequence, a nanosystems specific sophomore introductory course, and a junior level nanosystems seminar course. Pre-existing graduate microsystems engineering courses are utilized to teach metrology, processing, and other areas. Appropriate courses from traditional engineering disciplines are used to determine optional tracks that the students can pursue. The capstone experience for the nanosystems engineering majors is managed through a college multidisciplinary design course. This course is provided as an option to traditional engineering students to replace the discipline specific capstone design experience.

The multidisciplinary design course consists of a single instructor providing lecture content to the students, and evaluating the student performance on milestones throughout the academic year. The student teams work on projects with a faculty mentor. The majority of faculty mentors are research active, and the projects typically support their ongoing research areas. However, most of the faculty mentors do not have experience teaching capstone design in their disciplines.

Gassert *et. al.* describes the differences between research and a capstone design experience that is necessary to satisfy ABET requirements in an engineering discipline[3]. These authors recognize that a research project could consist of a number of design challenges, but one must be intentional to provide an experience where students manipulate parameters to meet a desired need or target rather than allowing a completely unstructured research environment. Lee *et. al.* describes a different scenario where the senior design projects are intentionally chosen to expose students to the multidisciplinary research area of Bio MEMS (Micro Electro Mechanical Systems)[4]. This intentional exposure can be beneficial in recruiting and preparing senior engineering students for graduate study. The objective is similar to that of a Research Experiences in Undergraduates that has been long supported by the National Science Foundation[5]. The nanosystems engineering program is similar to many biomedical engineering programs, where a greater number of opportunities are likely afforded with graduate training. Therefore, in both of these programs it is advantageous to provide a senior design experience that also exposes students to research (if only in a supporting role of designing certain devices or processes as part of a larger research program).

Cordon *et. al.* clarifies that much of what is described as research for a capstone design project is really gathering and assimilation of prior art which is better defined simply as project learning[6]. This is distinguished from research where the primary purpose is to develop new knowledge. Regardless, it is important to teach undergraduates library skills to effectively utilize all the resources available to them[7].

Recent papers in the American Society for Engineering Education demonstrate the need of a formalized course to facilitate transitioning students from content oriented core courses to an open ended capstone design experience [8-11]. Ebenstein *et. al.* describes a course to teach soft skills applicable to all students but little training on tackling open-ended problems. Rogge and Livesay presents a course to prepare biomedical engineering students using mini-design projects, however no details of the projects are given in the paper. Csavina and Seeney discuss a product design course for biomedical engineering students to prepare of open ended constraints by designing a Home Lift Position and Rehabilitation chair. Co *et. al.* write about a pre-capstone course for electrical engineers where teams work on various subsystems of an overall electrical device. A number of team and soft skills were also reinforced in the course to provide better management and integration of efforts. The course described in this paper is differs from prior articles in that the students work on a process rather than a product or component. There are team skills but also a competition among the small teams to reinforce the competitive nature of industry.

A field dominated by basic research such as nanotechnology especially requires a transition course to effectively achieve the outcomes desired in an engineering capstone design course. Providing the students with a uniform initial experience on a smaller project models desired outcomes such as safety, environmental, and economic considerations along with the quantitative analysis of these and other criteria to guide their path forward. Including potential capstone faculty mentors in the assessment of the junior level course institutionalizes these behaviors into the college.

Course Content

A 1 SCH Junior level laboratory was developed for nanosystems engineering students to provide the uniform experience described above and elevate the product achieved in the capstone design course. The course has been taught two years (the first year was a pilot). Nine students took the class the first year and eleven students took the class the second year (one student dropped half-way into the quarter). In both years, students were given the objective of producing CdSe nanoparticles in a manner that provides a narrow size distribution at the lowest possible cost. The students were asked to envision that they were participating in a startup company that would be selling these nanoparticles commercially and that they would need to compete on both cost and performance (size distribution and control). The course is taught in a ten week quarter, meeting once a week for approximately 3 hrs of contact time. There is no constraint on the chemistry or process chosen, other than it is amenable to the labware available to the students (this precludes some very high temperature or microfluidic processes). Students work in groups of three or less on their process.

The first lecture consists of literature searching and safety training. The first assignment given to the students is to identify, collect, and provide a summary of all the available literature on the synthesis CdSe nanoparticles. SciFinder is demonstrated to the students along with the common structure of journal articles (background, methods/materials, results/discussion, conclusions). Students are reminded that the background literature of an article can be an effective means of identifying other relevant articles. Patent literature is also covered. The claims, prior art, and examples are discussed in a similar fashion to show students how to read what is specifically covered and clues for finding additional sources of information.

Safety training is also given in this first lecture to highlight the importance of this topic. Expectations of behavior and Personal Protective Equipment (PPE) in the laboratory are discussed in context of the instructors experience in the chemical industry (where a blatant disregard for safety such as a second violation of improper PPE was grounds for termination of employment). Safety information provided by the Material Safety Data Sheet (MSDS) of each chemical is discussed, but the lack of oversight of this information is discussed. Students are highly encouraged to seek multiple sources of information, and Bretherick's Handbook of Reactive Chemical Hazards and Sax's Handbook of Dangerous Properties of Industrial Materials. The emphasis is not merely on safety information collection, but analysis and proposed steps to mitigate these hazards in their process. A video by Crowl on the hazard analysis of a lab scale phosgene process demonstrates to the students what is desired of the students. The video is available through the American Institute of Chemical Engineers (AIChE) Safety and Chemical Engineering Education (SACHE) Program and the process is discussed in Crowl and Louvar's textbook Chemical Process Safety: Fundamentals with Applications.

From the products of the first two years, it is clear the students have difficulty the first week identifying the commonality of the various literature obtained to provide an adequate summary. The students are at first lost in the details and length of the articles rather than trying to view the bigger picture of what is common or different between the various articles. This is a necessary skill to categorize various approaches and determine classes of approaches first before determining the details of the first sets of experiments. One faculty member is able to collect these assignments, read quickly through them and provide an initial assessment to the students on what needs to be improved for the next week. For the second week, students are asked to provide a safety, environmental, economic, and manufacturability analysis of the various processes to compare and justify (quantitatively where possible) which process they will choose to focus their development studies.

The second week lecture begins with the topic of economics. The nanosystems emphasis provides a very different environment than traditional process economics taught in chemical or other engineering disciplines. The volumes of most commercial nanosystems processes would be considered pilot scale or even applicable to a kilogram/liter scale laboratory equipment. As such, estimation of cost of processing equipment and necessary instrumentation can be estimated directly through vendor catalogs. Labor costs can also be estimated directly through by determining batch times and determining the numbers and function of each employee (students are asked to consider this as a startup where they will need secretarial support, a book-keeper, etc.). Similar to larger scale chemical processes, the predominate cost is usually raw materials. Students are asked to estimate the cost per gram and cost per pound of product of nanoparticles based on a theoretical yield of limiting reagent. The small volumes enable pricing through small suppliers such as Sigma-Aldrich to be valid versus large scale pricing tracked by ICIS or other services. Students are made aware of the differences in bulk pricing to recognize when opportunities might exist for significant savings (such as with solvents or other high use chemicals). Capital and annual costs are discussed in the context of present and future values of lump sums and annuities.

The students are taken to the laboratory and given an orientation on the facilities and glassware that they can expect to be available. The students are also given training and demonstration on the two analytical instruments available in the laboratory for this course – a Microtrac Dynamic Light Scattering (DLS) particle size analyzer, and one of six Ocean Optics Red-Tide UV/Vis Spectrometer. Students are taught the principles of these instruments. In addition to learning the operating principles of these instruments, students learn about optical properties of quantum dots and how quantum mechanics can be used to relate the nanoparticle particle size to the spectral emission wavelength of a quantum dot using a "particle-in-a-sphere" model[12].

The third week, the students arrive and are asked to setup their experiments. Students are asked to draw their setup, and write-up each step that they will perform (with volumes/masses at each step). The instructors watch as the students perform a walkthrough of their experiments using water for each step (see Figure 1 for laboratory). Mineral oil is used as a surrogate for a solvent if the process requires temperatures above the boiling point of water. Students are asked to operate the process through the point of developing effective sampling procedures. Once the students have demonstrated that they have a safe process that has been practiced through the use of surrogates, the students are allowed begin their first baseline batch.

Figure 1 – Nanosystems Engineering Laboratory

From this third week to the ninth week, the students continue developing their process. Figure 2 and 3 below depict the students working in the laboratory and products of their work. Students are asked to turn in a weekly report delineating their progress and proposed experiment plans (again, with quantitative justifications where possible). At approximately the fifth week of class, there is an in-class exam covering safety, economics, and instrumentation principles. This exam is approximately one hour, allowing students to perform at least one batch of an experiment if they are properly prepared. Individual accountability on the teams is emphasized through peer assessments and reporting required each week. Students are asked to provide a time and impact report based on a scale of unsatisfactory, below average, average, above average, and excellent performance. The students are told that this will not be used to grade assignments (average does not mean a "C" grade) but potentially as a tool to differentiate their grade among team members (i.e. average scores of all team members providing A level reports would allow all students to share equally in the grade). Each team member is required to provide a list of their daily accomplishments on the project. Each team member is required to sign the time and impact report to denote that they agree with the assessments provided by the other group members. If there is an issue in agreeing on the content of the assessments, then the team is to contact the instructor on guidance on how to resolve any issues.

Figure 2 a, b – Junior Nanosystems Students Optimizing CdSe Nanoparticle Process

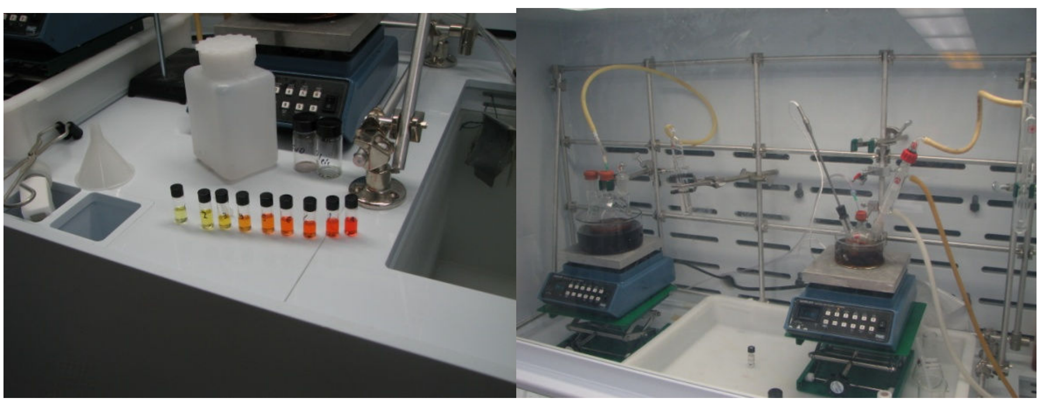

Figure 3 a (left) depicts range of CdSe particles obtained from Junior Nanosystems Engineering students. 2 b (right) are setups of Junior Nanosystems Engineering students for two processes to generate CdSe nanoparticles

An example of employing a quantitative assessment to guide the direction of their process improvements is in the area of solvents. An economic analysis of the majority of processes written in the scientific literature suggests that the solvent costs dominate the CdSe nanoparticle cost. An obvious step that one would take in a commercial process is to reuse the solvent if possible. However, the ability to reuse the solvent without further processing must be validated. The potential savings can be easily quantified if this can be demonstrated. In addition, increasing the concentration of the reactants in a batch allows a greater throughput. A higher temperature can potentially reduce reaction time, however some processes with longer reaction times allow greater product consistency.

One challenge to the students is that critical portions of the process that are often not described in the article because of the assumption that an experienced synthesis chemist would be aware of such requirements. For example, many of the reactants in the CdSe processes are sensitive to ambient oxygen at the relatively high reaction temperatures. Therefore, providing an inert environment through the use of nitrogen from a bottle sweeping through the reactor headspace and leaving through an oil bubbler is a necessary component that is not always explicitly described.

A final written project report is required along with an oral presentation given the last week of class. Current and future potential faculty mentors for senior design projects are encouraged to attend these oral presentations to provide outside assessment and feedback. This involvement of the faculty mentors also provides a benchmark of skills that the students should be able to build upon as they begin their capstone projects the following year.

Assessment

End of course assessments from the Spring 2009 offering were performed to determine student opinion on the achievement of course outcomes on a five point scale (Strongly disagree, disagree, Neutral, Agree, Strongly Agree). Results, which are summarized in Table 1, indicated that students generally felt the course outcomes were achieved as evidenced by all of the objectives and outcomes receiving.

Table 1 Course Objectives and Outcomes Assessment

Course Objectives/Outcomes Assessment Spring 2009	**Strongly Disagree**	**Disagree**	**Neutral**	**Agree**	**Strongly Agree**
Please indicate how strongly you agree/disagree with the following statements.	**1**	**2**	**3**	**4**	**5**
Outcome 1. I am able to describe and apply appropriate safety procedures and laboratory protocols for micro/nano laboratory environments.	0%	0%	0%	62.5%	37.5%
Outcome 2. I am able to design and develop a nanofabrication process accounting for realistic constraints such a safety, environmental, economics, and manufacturability.	0%	0%	0%	50%	50%
Outcome 3. I am able to use advanced characterization and testing instruments such as a particle analyzer, spectrophotometers, and electron microscopy to characterize nanomaterials and their properties.	0%	0%	12.5%	50%	37.5%
Outcome 4. I am able to write clear, concise laboratory and design analysis reports.	0%	0%	0.0%	75%	25%

Additionally, a team of faculty composed of potential senior design instructors assessed the final project presentations. This assessment was also very generally very positive on achievement of many of the course objectives and goals. One specific result that was interesting was a question on the students' use of appropriate outside resources (e.g., references, journal articles, patents, etc.). The faculty evaluation of this assessment was a 4.3/5.0. The same assessment question was also performed on our capstone senior design projects that quarter, which was evaluated by advisory board members and faculty. The result for capstone senior design students was a 3.6/5.0 so the course appears to be having a significant impact on students' abilities to research the literature on a problem. The students who completed the junior level course this past Spring 2009 are currently in the year long capstone senior multidisciplinary senior design course. It is still somewhat premature for us to assess the impact of the junior lab for these students since they are only two-thirds of the way through the senior design course sequence but course grades from the fall and winter quarters were examined to compare how students who had participated in the junior lab are performing compared to students who did not have the course. There were 10 nanosystems engineering students who had taken the NSE 303 course and 16 students from other engineering majors (primarily biomedical and mechanical engineering) that were also in the multidisciplinary senior design course. These students are separated into seven teams in the senior design course. Three of the teams consist purely of students who have taken the NSE 303 course and three teams consist of students who did not. The one additional team had a 50/50 mix of students who completed the junior lab. The senior design course sequence is led by a team of two instructors with additional faculty serving as project sponsors for the individual teams. Grades are assigned by the two instructors with input from the faculty project sponsors. Grades are essentially assigned by team results but in some cases were individually adjusted based upon peer evaluations using an online teamwork assessment tool called Team Learning Assistant, referred to as TLA. TLA is a web-based teamwork teaching and management tool that provides qualitative as well as quantitative assessment of teams that can be used as a clear basis for assigning team and individual grades[13]. Grade point averages in the senior design course for the 10 students who had taken NSE 303 were 3.5 and 3.9 for fall and winter quarters, respectively. While the rest of the students in the senior design course grade point average were 3.4 and 3.5 for the fall and winter quarters, respectively. As already mentioned TLA provides some quantitative assessments of an individual student's contributions to their team's results as well as a measure of the student's leadership contribution to the team. These quantitative results are normalized across the entire class by TLA to provide a numerical score relative 1.0 (e.g., score of 0.85 implies student's performance was 15% lower than the class average). The average TLA results for students taking the NSE 303 course were 1.064 and 1.055 for their task and leadership contributions during the fall quarter and 1.060 (task) and 1.041 (leadership) for winter quarter. The average of other students' TLA results were 0.959 (task) and 0.966 (leadership) for fall quarter and 0.962 (task) and 0.973 (leadership) for winter quarter. The TLA results imply that the students who had taken the NSE 303 course generally were 7-10% higher in their contributions towards the team results and in providing leadership for their teams. The results are still preliminary but it does appear students who completed the junior level lab were better prepared to get their senior capstone projects off to a strong start and provide a more significant contribution to their senior design teams.

Conclusions

We believe the course described above provides an excellent bridge for the students from content oriented lecture courses, to the open-ended problem solving environment expected in a capstone design. This course provides a uniform experience for all students in the program, which is especially important when the capstone design projects are managed by a diffuse group of faculty mentors who have a high research focus but not necessarily experience at managing senior design projects. The involvement of the faculty mentors in assessing final reports of the junior projects has been instrumental in allowing a greater impact that institutionalizes needs of capstone design. The course has been well received by the students. Feedback from the students has been very positive and initial quantitative assessment suggests that there is a measureable improvement (though a comparison of the two cohorts is just beginning).

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