



CAPSTONE PROJECTS: UNLEASHING IMAGINATION AND ENGAGING MINDS

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Many new faculty may face challenges related to effective teaching techniques. Student perception of good teaching may often be different from the instructors' opinions. Finding the technique that merges the two perspectives can be challenging and vital. Project-based learning has been documented to be a guaranteed procedure for increasing students' interest in the taught topic, while developing skills that also often reward the instructor with good student evaluations. We present the lessons learned in several capstone courses taught by three instructors at three higher education institutions. Different procedures are used. Although the instructors use different techniques undergraduates are thrilled by the projects and their freedom to innovate and perform research. They usually perform outstanding work, presented at local and international conferences. Their attitude is also reflected in their evaluations of teachers. We are hopeful that our experience will provide useful ideas, particularly to new faculty.

1. INTRODUCTION

Undergraduate students go through a steep learning curve during their studies. They are likely to reach high theoretical knowledge and may expect everything to be clearly spelled out for investigation. A recent IBM study¹ based on face-to-face conversations with more than 1,500 chief executive officers worldwide concludes that creativity is the most important factor for future success. However, although students accumulate more knowledge in different classes, creativity is not built into most technical courses². A capstone course comes in much contrast to regular classes as it is supposed to be a peak experience of the undergraduate journey, aiming at developing skills for working in multidisciplinary teams, unleashing technical creativity and improving communication skills³. The capstone experience integrates theory and practice, providing genuine research experience⁴ through a hands-on learning process⁵, and open-ended interdisciplinary questions. The experimental work to be conducted in capstone projects comes to demonstrate a different side of the neatly arranged theoretical concepts and represents an essential part in their preparation for real jobs^{6,7}. The choice of one- or two-semester capstone can make a difference in what students experience and what can be achieved. Most engineering schools opt for a two-semester capstone⁸. In addition, the experience obtained is in tune with ABET accreditation requirements^{9,10}. Moreover, close interaction with students offers the instructor an invaluable chance to mentor them and initiate them into research and design in an informal and actually more effective manner than in traditional courses. It was reported that promoting creativity in engineering classes leads to student retention and better student-professor interactions¹¹. Therefore students are also likely to understand the instructor's guidance from a more personalized perspective and this in turn helps instructor and student perspectives on good teaching¹² converge. This would implicitly reward the instructor with better student evaluations.

Three different implementations of capstone classes by individual instructors working in different fields are presented.

2. PHYSICS CAPSTONE EXPERIENCE

XX University... was recently granted approval for a new undergraduate program in electrical and computer engineering (ECE). The program will be hosted in the new \$118 M Science and Engineering building scheduled to be fully functional in the Fall of 2013. This was a unique opportunity to design both classrooms and laboratories according to our vision of good practice and needs. One of the ECE faculty temporarily based in the Physics department developed an applied electrostatics laboratory from scratch to be used in the ECE program and taught the Physics capstone course twice using the lab facilities. The Applied Electrostatics Laboratory was thought to allow for great flexibility of projects related particularly to nanotechnology by means of electrospaying, electrospinning, and gas discharges. The main available equipment consists of a couple of high voltage power supplies (one high voltage amplifier), single syringe and double syringe pumps, a high speed camera system, a Keithley picoammeter, a modified Veeco system for studying electrospay, electrospinning, or gas discharges at reduced atmospheric pressure, a 3-D printer, a 10⁰ fan laser sheet at 80 mW, and a EOS 7D Canon camera. In addition, a new research grade SEM is available within the same building. Along with the mechanical shop situated on the same floor, the lab facilities allow for a great selection of research projects that can be undertaken.

Course design

In the Department of Physics each faculty teaches the capstone course periodically. The course was designed to allow for maximum flexibility in topic range within the available resources and student work schedule.

The central idea of the course was to involve students in genuine research, preferably in a direction they like, within resource constraints. Intentionally, students were guided through the main steps of conducting research starting with the choice of a research topic; students were told that they would choose their projects but should be realistic in terms of resources needed. Introductory lectures were offered on topics related to nanotechnology, electrospaying, electrospinning, ferrofluids, and corona discharge. In addition, a binder with a few dozen articles related to the discussed topics was offered to each student. The purpose was to familiarize students with possible topics and resource availability and to help them choose a research path. On the first run of the course individual topics were targeted. This approach proved to be challenging, as there were four projects to coordinate and share resources. Upon the second run of the course, student projects were grouped so that two students focused on the same topic. Although the topics were different, the intention was to facilitate student cooperation and peer-learning among all students, irrespective of project. All students were familiar with and

contributed partially to all projects. They helped their peers and followed their projects' development. In addition, they had joint presentations in preparation for conferences and the final talk, open to all interested. Moreover, students sometimes had to share resources and coordinate with their colleagues. This brought more attention to and respect for the work of their peers. At the end of the course, students were expected to have become proficient in their research topic of choice, to have conducted systematic work in the lab to design their apparatus or experimental setup, to have collected and analyzed experimental data, and to have reached pertinent conclusions.

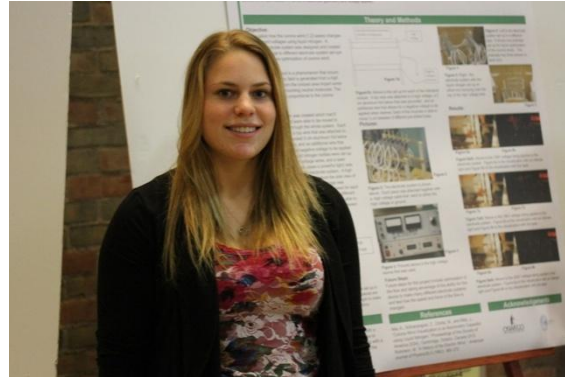


Fig. 1 Students in the initial phase of literature review (a) and poster presentation (b) – capstone run two.

In the regular classes students are taught known things and theories but this class intended to be quite the opposite and succeeded. Students were guided in an informal manner to find undiscovered or not yet researched topics or new ideas and also to find ways to approach, investigate, or design new apparatus. Although students had some initial doubts about their potential success, the procedure actually thrilled students to work on something not yet discovered or designed.

Individual projects were chosen and approved after the second week of classes:

Table 1. Research topics

Capstone -1'st run	Capstone -2'nd run
<ul style="list-style-type: none"> ● Electrosprays of Water-Based Ferrofluids ● Magnetically Controlled Electrosprays ● Amorphous NaCl particulates synthesized by means of electrospray ● Synthesis of microfibers with magnetic properties 	<ul style="list-style-type: none"> ● Corona wind visualization and optimization ● SEM characterization of magnetically sensitive PVA nano-fibers synthesized by electrospinning

After choosing the topic, students researched out articles on their own and made a plan of action guided by the instructor. It was interesting to see how new ideas emerged right from the start. Directions of research were discussed with the instructor and were not altered by the instructor unless the choice was clearly wrong. Sometimes students wanted to pursue their work in directions not entirely wrong but not optimal. In such cases, the instructor refrained from stifling the initiative and allowed students to come to the correct conclusion as a consequence of their experience rather than by using the instructor's knowledge.



Fig. 2 Experimental apparatus designed and built by students for investigation of corona wind (a) Experimental setup for observing a new electro-spray regime of ferrofluids (a)



Fig. 3 Students and instructor (a) student at a poster presentation (b) - capstone first run

There were various **challenges** during the lifetime of the projects. For instance, we were lacking an intense source of magnetic field. A spare one was eventually identified, borrowed, and adapted to our purpose; the electromagnetic noise was found to be larger than the signal in the lab. In order to pursue the measurements the setup was moved to an anechoic chamber that was made available to us; the ordered equipment was not received in due time: this led to changes in plans and new approaches to the research; Limited lab space was a strong constraint, which made the group share resources wisely by planning the required activities absolutely needed in that lab

in phase opposition with their peers, which turned out reasonably well most of the time. The laser sheet malfunctioned and it was sent for repairs that lasted the entire semester. New research plans were developed in order to compensate for the unavailability of the instrument. The SEM time slots were saved in advance and at the end of the semester the SEM malfunctioned. A sensitive scale was ordered and returned because it was not working properly (drifting). Multiple apparatuses were built in order to have one fit for studying the corona wind.

These challenges pushed students into finding new solutions for solving technical difficulties, compensating for lack of resources, sharing resources, reducing experimental errors; it made students learn and be excited about results in a very different way than in regular class settings.

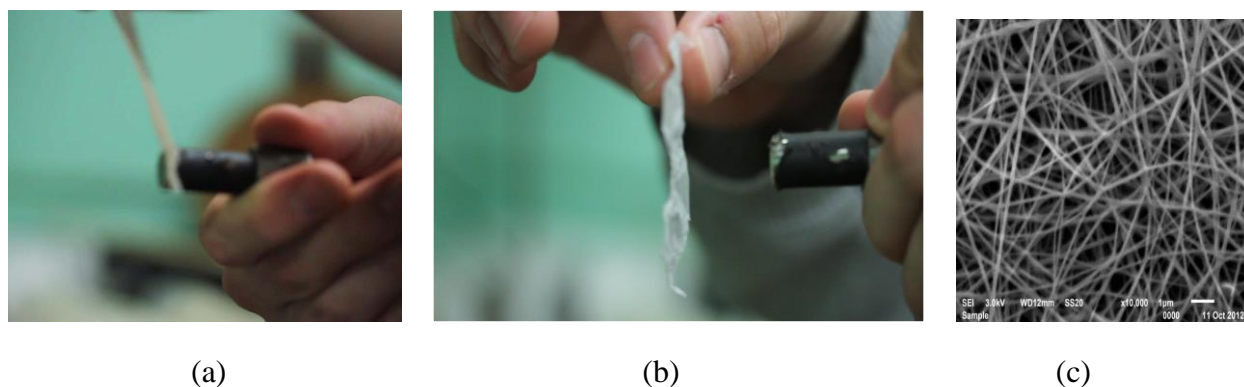


Fig. 4 Magnetic (a) and nonmagnetic nanofiber (b). SEM image of nonmagnetic PVA fibers (c)

Students were encouraged to present their research at local and regional undergraduate conferences, and they did. Both student groups had oral and poster presentations, as well as international conferences (6 presentations¹²⁻¹⁸ for the first group and 9 presentations¹⁹⁻²⁷ for the second group). Preparing the presentations and the presentations themselves were a different way of learning. Students did this job very well and received good feedback and interactions at the meetings. As the first group was presenting at an international conference, they were also awarded prizes.

Assessment

The measure for student achievements in the course was obtained directly by observing the contributions of each student to projects and presentations and indirectly by obtaining feedback from presentations given at local and regional undergraduate conferences, as well as at international conferences and even from the papers published with students. In addition, all students commented on their perception of the course:

Table 2. Student comments

Capstone -1'st run	Capstone -2'nd run
<ul style="list-style-type: none"> • <i>The professor is very open to student ideas and invests a lot of time in helping us pursue them. It's been educational and a lot of fun in the lab.</i> • <i>This is a great class. We get the opportunity to perform hands on research, which I feel is a definite benefit.</i> • <i>Excellent course. The instructor is one of the most helpful Professors here. He is a pleasure to work with in and out of the classroom.</i> • <i>Thank you for all that you have done for me.</i> 	<ul style="list-style-type: none"> • <i>I really enjoyed this class. I liked the flexibility and the relaxed nature of it. It did not feel like a class, yet I learned more than I do in a normal class setting.</i> • <i>I liked being able to do hands on experiments; having a certain freedom to research in our own way; interesting topics.</i> • <i>I really enjoyed this class and wish I could continue with it. It should be two semesters because right when it started to get really interesting it ended. I really, really liked it.</i> • <i>So much freedom :)</i>

A final presentation of the projects to an open audience was part of the requirements for this capstone class; thus students received additional feedback.

The students enrolled in the second run of the capstone course have just finished it. However, after the oral presentations they gave the instructor very important feedback: they unanimously expressed the desire to continue the project they realized at the end of the semester that “*has just started*”. They are obviously emotionally touched and intellectually intrigued by the research they have pursued:

- *I've got some great ideas on the applications of electrospinning. Also how to research and gain new ideas that haven't been done yet.*
- *I want to look more in-depth at the topics we researched.*
- *I would like that we produce a real filter from our nanofibers.*
- *I would like to see how magnetic forces influence (magnetic) fibers (we created); see if we can make a filter or a waterproof material.*
- *I wish it could be two semesters so we could have more time!*

3. SOFTWARE ENGINEERING CAPSTONE EXPERIENCE

ECE faculty hired prior to the official state approval and opening term of the program had to be assigned to existing departments closely related to their areas of expertise. One such area is software engineering, a recently started degree program under the long standing computer

science department. Three students have reached the capstone course level in SE, offered during fall 2012. In SE, the capstone experience is designed as a two-term course sequence that allows students, during the first course, to determine and research a suitable project topic, write a complete proposal along with a development plan, produce a UML (Universal Modeling Language) model²⁸, and a project test and quality assurance plan compiled in the form of a report. During the second course of the capstone sequence, students complete the project and develop the software product into a fully functional package that is presented and demonstrated to the software engineering faculty.

During the first two weeks, students are directed to seek and research a suitable project topic by querying faculty members, employers, or any other source available to them. The caliber of the project and its suitability as a capstone experience are subject to faculty approval. In the current case, the three students made two important decisions: they decided to work as a team and, among the few topic choices that were offered to them, they selected a project in robotics.

The ECE department owns two Cyton V2 7-dof robotic arms²⁹ in need of a simple intuitive user interface that allows easy programming of manipulation tasks. Figure 5 shows a picture of one robotic arm.

Multidisciplinary project experience in SE

In regards to the capstone experience, multidisciplinary team projects are particularly encouraged as they correspond more closely to an industrial experience while allowing better assessment value for accreditation purposes. However, in a small school with only two starting engineering programs, in SE, only 4 years old, and ECE, to start in Fall 2013, it is not possible to have several engineering disciplines participate. However, in this particular case a *multidisciplinary component* is provided by having the three students following different minors (one student is a double major in mathematics and software engineering and another has completed an embedded systems track that covers hardware digital design and microprocessor applications courses).

The Cyton robot is controlled by a computer connected through a USB port. Its software includes utilities that allow joint actuation as well as joint sensors for feedback control. It can also be controlled through user-developed software in Visual C++ Express 2010³⁰, conveniently available from Microsoft free of charge.

Software Engineering Capstone Project Objective

The objective of this project is to design and develop a Graphics User Interface software package that allows users to control and program two Cyton robots in cooperative tasks. The software will be developed in two phases. First, a GUI capable of controlling a single robot will be designed as a virtual teach pendant, a commonly used interface in automated manufacturing to program robotic trajectories locally or remotely. The teach pendant GUI provides the following functionality.



Figure 5. Robai 7-DOF Cyton Robot Arm

The stakeholders for this projects are primarily instructors, students, and anyone interested in using this software product for education or other goals. The virtual GUI for cooperative control of two Cyton Robotic Arms is to be made available as freeware on successful completion.

I. Joint Control and Programming:

- *Joint control mode:*
 1. The user is able to vary each joint independently until the robot is in a desirable configuration.
 2. The user can save a desirable configuration with a name or number reference.
 3. After a complete trajectory (several configurations along a trajectory) has been saved, the user can then switch to Programming mode.

- *Programming mode:*
 1. The user is able to write a simple motion program. For example:
 1. Go to Configuration 2, fast
 2. Open gripper
 3. Go to Configuration 3, slow
 4. Close gripper
 5. Go to Configuration 1, slow
 6. Go to configuration 4, fast
 7. Go to step 3
 8. Etc...
 2. Once the program is complete the user can save it as a file for later use or modification.

3. The user can then
 1. Trace through the program one instruction at a time causing the robot to execute the motion described by that instruction
 2. Run the whole program once and stop
 3. Run the program and repeat it continuously.

II. Cartesian Control and Programming

In this function, the user moves the robot by changing the gripper position x , y , and z and the gripper orientation angles α , β , γ (describing roll-pitch-yaw rotations)³² instead of moving each joint separately. Everything else is the same. This part is addressed only after the Joint Control Programming part has been completed.

III. Programming Cooperative tasks

The functionality of the virtual teach pendant developed in steps I and II is expanded to the control and programming of two robotics arms cooperating on a single task. This part is particularly challenging as the development software provided by the robot manufacturer does not offer any utilities for interfacing a computer to two robots.

It is possible that the expansion of part III may be too complex for three students without sufficient training in robot kinematics and control to accomplish without reliance on all low level control tasks being performed by integrated software development environment supplied by the manufacturer. However, as a capstone experience, the students will have achieved their learning objectives of producing a valuable software product.

While students were given the freedom to choose their own software tools for project management, they elected to use SCRUM which was introduced in a class lecture early.

Capstone Learning Outcomes

Since the capstone project is designed to pull together knowledge from the whole software curriculum, it should cover several if not all the program learning outcomes. The first part of the course outcomes are stated as:

- Demonstrate understanding of the software development process
- Use of current tools and methods to plan, analyze, design, test, measure, and manage software projects.
- Articulate the advantages and disadvantages of current software life cycle models
- Create a working plan for continuation of the project in the next capstone course.

However, the assessment process for the course consists of several evaluation criteria as per Table 3 below which provides the relative weight given to various course components.

Table 3. Evaluation of course components

Component	Percentage Points
Requirements Specification	15
UML Design Document	15
Test Plan	15
Build Plan	15
Cost Estimate	15
Project Journal / Presentations	15
Attendance	10

Assessment Process

Progress is assessed weekly through class meetings that require presentations, and discussions of

- the current state of the project,
- difficulties encountered and brain storming for solutions,
- instructor lectures on relevant topics such a software development tools and robotics concepts
- directed research avenues for efficient progress,
- evaluation of each team member’s contribution and instructor review of individual log books
- assignment of tasks for the coming week.

The students complete the first part of the course by submitting a report that includes a problem statement, the proposed solution and a complete development plan and schedule as well as all the relevant components listed in table 3 along with their logbooks.

4. Biomedical Capstone

McMaster University in Hamilton, Ontario, Canada offers a Biomedical specialization as a competitive-entry, limited-enrolment option within the department of Electrical and Computer Engineering. Originally offered as a one-term design course, it was expanded in 2008 to two-terms to become a senior full-year project. This course serves as the synthesis and application of undergraduate theory and practice for the selection and investigation of a biomedical engineering problem. Analytical and/or experimental work is carried out by individual students or project groups. Proposal, progress reports, final engineering report, a public presentation are components of the final grade. Students are provided access to the ECE Biomed instrumentation lab for prototyping, testing, and functional demonstration of their projects.

Final reports are publicly available through XY University's Digital Commons:

<http://digitalcommons.XY.ca/ee4bi6/>

Course Design

The course is structured to facilitate the engineering research and development design process. Students are required to independently meet certain milestones under the supervision of a faculty or industry mentor. The following is an overview of the BME course design as organized by XYZ

Construct a Framework: This is the first independent design project that the students have undertaken, thus helping them define a framework with their own goals is necessary. To start the process, and to get an early survey of interests, the following three questions are asked of the individual students:

1. Define Biomedical Engineering (BME)
2. Most significant contribution that BME has made to mankind
3. Define the area of BME that you wish to work in after graduation

Define a BME problem *scoped within the field of ECE*. By giving consideration to their framework, the student can explore existing solutions to the problem and/or approach faculty members and become involved in current research projects.

Submit a proposal that clearly outlines the problem, initial proposed solution, functional criteria, and a Gantt chart outlining tasks/milestone *vs.* time. Teams must be less than 4 members and clearly delineate each member's contribution. As each member is required to submit an independent final report, it is necessary that the team define the scope and interface of subprojects very clearly. Proposals are reviewed by the Capstone faculty supervisor and the course-coordinator for comments, refinement, and iteration.

Technical Lectures: A few examples of recent publications are presented and methodology discussed. This leads into a technical discussion on electrophysiological instrumentation and data acquisition.

Support Lectures: In addition to the technical lectures, the students are also given lectures and instruction on Intellectual Property, Research Ethics, Conducting Literature Searches, Software Tools (Matlab, LabView, MapleSim, etc.) and the required use of Log Books. Students are also made aware of external competitions and potential publication avenues for their completed works.

Technical Meetings with Advisor: Once the proposal is accepted, the student(s) and advisor agree on periodic meeting intervals. Suggested intervals are to start biweekly and adjust as

needed. During each meeting the student(s) will give an update of progress, comment on their adherence to the initial Gantt chart, and request advisor input. Groups that appear to be struggling may require weekly meetings with defined goals for each meeting.

Progress Update: At approximately halfway through the course, a progress update is a required milestone. A Brief Technical Report is submitted to the student advisor and Brief Technical Presentation is made to the class. The Report is graded and returned with comments. The Presentation allows the student to receive constructive feedback, technical input, and presentation practice. The Presentation is peer and coordinator evaluated with comments returned to the student. Although the presentation is considered informal, it is clear benchmark for students to self-evaluate on personal progress and for most it is highly motivating.

Functional Testing: The next major milestone is the functional testing of the project. Based upon the student(s) own functional criteria, supervisor assessment, and course coordinator assessment the functionality of the project is evaluated.

Table 4. Framework student topics of interest and subset of derived Capstone Projects

Framework: Topics of Interest	Capstone Projects
<ul style="list-style-type: none"> • Imaging (diagnostic, MRI 3D) • Robotics (distance surgery) • Prosthetics • Brain Computer Interface • Cell engineering • Cybernetic prosthetics (Functional Electrical Stimulation) • Modelling • Health care • Cardiovascular • Instrumentation • Biomimetics • Neurology • Drug delivery 	<ul style="list-style-type: none"> • Non-Invasive Health Monitoring System • Manual Wheelchair Automator • Speech Recognition Control for Manual Wheelchair Automator • Intelligent Hand Prosthesis / Orthosis • UWB Microwave Antenna Array Design for Detection Breast Cancer Tumor • Quality of Sleep Instrumentation using EEG • Smart Cane for Sight Impaired (collision detection, heat avoidance, haptic feedback) • Wearable ECG, Blood Pressure, Pulse Oximetry • Optical Glucose instrumentation • Skin Moisture Quantification for Management of Eczema

Final Report: The final report is a complete record of the project, including motivation, literature review, designs, experiments, observations, and results. In order to preserve the work and allow others to build upon it, the author suggests having the work archived for future reference.

Public Presentation: As a final milestone, the student(s) conduct a public presentation of the project. XYZ has run the course with both conference-style talk and poster presentation. Preference is given to the talk; however, to have consistency across departmental Capstone expectations the poster presentation is now implemented. Industry and Faculty judges are asked to provide feedback via a scoring rubric.

Costs: While some projects are able to draw upon research or industry funding, most projects are funded by the students themselves. Given that there are no required course materials, the project budget is suggested as the approximate cost of an engineering textbook.

Table 4 presents both the initial topics of interest extracted from the framework exercise and a subset of the derived project titles.

In general, students under-estimate the time required to bring a concept from an idea to reality. Even with supervisor refinement of scope and support throughout, the objectives become difficult to meet when parts must be sourced and ordered, or team projects are sequentially related. In the end, few projects meet all of their objectives, which is an important lesson for the student and also the reason why the process (successful or not) must heavily considered in assessment.

For the student(s) that follow the outlined process successfully, their final report is often suitable for a conference paper or presentation. An example of such a case is [33].

Assessment

Capstone project deliverables are presented in Table 5 as an example distribution between graders for each component. This distribution is for the oral conference-style public presentation. For poster presentations the M_{oa} and M_{op} would be combined.

Table 5. Example Assessment Distribution for Capstone Projects

		Marking Base	Advisor (%)	Co-ordinator (%)	Oral Present. Judges (%)
Proposal	M_{pp}	10	50	50	
Progress Report	M_{pr}	20	70	30	
Oral Project Summary and Status (Q&A)	M_{os}	10		50	50
Final Oral Presentation Abstract	M_{oa}	5			100
Final Oral Presentation	M_{op}	15			100
Final Report and Performance	M_{fr}	40	70	30	
Course Mark	M_{mk}	100	47	28	25

Student feedback, engagement, and learning have been so positive to the Capstone Design experience that XY University has implemented cross-discipline projects and has begun work on vertical integration of design courses into the curriculum. The Capstone learning experience is so profound and motivating that XYZ has implemented a Cornerstone project in the freshman year to offer a more structured “Capstone” design experience to first year engineering students³⁴⁻³⁶.

The Canadian Engineering Accreditation Board (CEAB) has begun the implementation of an accreditation process based upon Graduate Attributes³⁷. The Capstone Design course is a highly effective instrument in assessing the student competencies and as a result will likely become an even more important component in the student education experience.

CONCLUSIONS

The discussed capstone projects have been implemented by three instructors on different topics/specialties. However, student reactions and perceptions have some similar characteristics including:

- The opportunity to apply their newly acquired training and education in engineering work,
- The freedom to select their own solutions to an engineering problem
- The opportunity to prove primarily to themselves, that they are now empowered for a career in engineering.

The traditional educational environment lacks a “‘playful’ climate where students can explore ‘new spaces or concepts’². By contrast, students greatly enjoy the freedom they are given in capstone courses. They are enthusiastic, thrilled to perform research work; they develop strong motivation to overcome challenges and to succeed with their projects, which can greatly improve their learning skills and self-confidence. Challenges are just means to trigger their imagination into finding exquisite solutions to their problems. The fact that students usually gave great evaluations for capstone courses endorses their recognition of a unique experience that allowed them to unleash their imagination and gain the needed self-confidence to succeed in the project and in life. Moreover, many of the ABET/CEAB program outcomes are easily satisfied on this occasion. We are hopeful that particularly new faculty could benefit from the projects presented. Giving students the freedom to innovate within projects initiated in capstone or other classes appear to have multiple positive aspects. One of them is the positive impact into the perceived quality of teaching.

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