A Consulting Engineering Model for the EE Capstone Experience

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I. abstract

The ABET-accredited EE degree program at the University of Washington Bothell was started in 2009 with 24 students. Currently, the total enrollment in the program, including BSEE and MSEE students, is approximately 250 students. The program has achieved significant support from the surrounding industrial base in our metropolitan area, largely due to the success of its EE Capstone Experience.

The Capstone program was created with the following educational objectives:

- Master the soft-skills necessary for success in industry
- Experience a complete product design lifecycle
- Engage in community-based educational activities

With these goals in mind the Capstone Experience was designed so a team of three or four students would form small "consulting engineering" companies and then, over the course of two quarters (six months), work on projects submitted by companies in the area.

The student teams are mentored by an engineer or manager at the company and "managed" at our university by part-time faculty from the local industrial talent pool. The Capstone faculty brings the necessary real-world experience and soft skills, such as creating and tracking schedules that students need to execute their projects within the allotted time.

In Capstone I the student team creates their development contract. It is then signed by the students, the industrial mentor and their faculty advisor. The course begins with an intense research and design phase during which the students learn the technology they'll need to actually design their project. Capstone 1 concludes with a detailed project specification that is submitted to the industry sponsor for approval.

Capstone II consists of the actual construction and validation of the project, followed by a formal presentation for the company, a colloquium and poster session at the university, and finally, a detailed evaluation of each student by the industry mentor that is part of the overall evaluation rubric used to determine student grades.

II. history

One year prior to the admission of students in the Fall of 2009 and the approval of the degree by Washington's Higher Education Coordinating Board (HEC Board)[1] and the Board of Regents of the University, a faculty committee was formed to lay the foundation for the EE degree and develop the goals, educational objectives, and desired student outcomes for the program.

Of key concern to this committee, chaired by the author, was obtaining ABET accreditation as soon as possible[1]. Therefore, much of our planning was focused on creating a robust BSEE degree from the outset. Particular attention was given to the Capstone Experience. According to ABET, students in an accredited EE program must have a Capstone Experience:

> *Students must be prepared for engineering practice through a curriculum culminating in a major design experience based on the knowledge and skills acquired in earlier course work and incorporating appropriate engineering standards and multiple realistic constraints.* [2]

We also considered the eleven student outcomes specified in General Criterion 3 of the General Criteria for Baccalaureate Level Programs[3]. These outcomes are listed below:

(a) an ability to apply knowledge of mathematics, science, and engineering

(b) an ability to design and conduct experiments, as well as to analyze and interpret data

(c) an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability

(d) an ability to function on multidisciplinary teams

(e) an ability to identify, formulate, and solve engineering problems

(f) an understanding of professional and ethical responsibility

(g) an ability to communicate effectively

(h) the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context

(i) a recognition of the need for, and an ability to engage in life-long learning

(j) a knowledge of contemporary issues

(k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

When we mapped our courses to the student outcomes, we found that the Capstone Experience mapped into outcomes c, d, e, f, g, i, j, and k. This was a sobering realization and showed us that the Capstone program had to be a significant contributor to the EE program.

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[1] The HEC Board was particularly adamant that timely ABET approval was a necessary condition for their approval of the program.

Fortunately, or unfortunately, depending upon one's point of view, the Capstone requirement is very broad and leaves much of the design of the Capstone Experience to the faculty. As we studied other EE programs, both nationally and in our immediate area, it became clear that few, if any, Capstone Experiences ***actually modeled the experience of a product development lifecycle at a typical technology company*** likely to employ graduates of their programs. [2]

For many programs that we investigated, the Capstone Experience can be as basic as a student doing an independent research project and writing a paper. While a research papers certainly has merit, a guiding principle in our Capstone designing our Capstone Experience was our desire that the students actually build something tangible. We also placed a very high value on the soft-skills such as:

- Project definition
- Contractual commitments
- Formal design specifications
- Test plan
- Validation
- Documentation
- Scheduling and meeting deliverables

Therefore, a key component of our Capstone Experience is mastering of the skills not typically taught in undergraduate engineering courses. Equally important is the completion of their project by building a working prototype that meets the customer's[3] requirements specifications. We felt that our student should be able go to a job interview and provides an in-depth discussion of both the technical aspects and managerial aspects of their project, thus demonstrating the key skills valued in an engineer and usually lacking in recent Electrical Engineering graduates.

Since the ABET requirement mentions nothing about the deliverables that should result from the Capstone Experience, the author, having been a working design engineer and engineering manager, steered the faculty committee on a path to create a program in which students (working in teams of three or four) had to design, build, debug, validate, and deliver something tangible, representing a completed electronic design, fabrication, debug, and validation lifecycle.

III. program launch

The Capstone Experience was originally designed as a 5 credit-hour, one-quarter-long project course. Projects were solicited from internal faculty and from local industry, tapping into the contacts of members of the EE Advisory Board. A faculty member (the author) was the faculty advisor and, in lieu of charging companies to participate in the Capstone program as some schools do, each company was asked only to provide material support, such as the cost of fabricating a printed circuit board, and provide an engineering mentor for the team. The mentor

[2] The author is quite knowledgeable about the technology lifecycle, having come late to teaching after spending the majority of his professional career as an engineer and engineering manager at three technology companies; Hewlett-Packard, Advanced Micro Devices and Applied Microsystems.

[3] In our model, the customer is the industrial sponsor of the project.

functioned as the primary technical contact, typically holding meetings with the team, weekly, or whenever questions arose.

Otherwise, the team functions autonomously. In fact, our model for the Capstone team, as previously noted, is a consulting engineering company. The faculty advisor serves the role of the team's manager. Twice-weekly meetings are held with the faculty advisor. At these meetings the students learned how to create documentation and the finer points of creating and tracking project schedules.

One aspect of the original program was that it was open-ended in time. The students completed the Capstone Experience when they completed the project. There was no set time limit, such as the end of a quarter. This turned out to be problematic for two reasons:

> 1. Over the course of several years, only one team was able to finish their project in one quarter (about 11 weeks). By the time they fully grasped the scope of their project, the quarter was nearly half over. Even the most responsible teams, working very diligently, could not complete projects given the inevitable engineering issues.
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> 2. Students only register and pay tuition for the first quarter. They can continue through additional quarters with no added tuition expenses. For some part-time students who were in no hurry to graduate, the Capstone Experience dragged on for up to five quarters.

As part of our ongoing ABET assessment process and after several teams completed the program, we made some significant changes and these changes represent the Capstone Experience as currently implemented. Three key changes were implemented:

> 1. The Capstone course was extended to two quarters. Capstone I is a two-credit course in which the students research the project and create a formal specification that must be approved by their industry mentor. Capstone II is a three-credit course in which the students actually build, debug and validate their design. Capstone II ends with a report, a formal colloquium, and a poster session during which each team presents their project. Many of the teams also give their presentation at their sponsor's facility.[4]
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> 2. When the number of Capstone teams became greater than the author could reasonably manage, engineers and engineering managers from the local pool of technology companies were invited to become affiliate faculty in order to advise, lead, and evaluate the students on their teams. These dedicated adjunct faculty members have contributed significantly to the success of the program.[5]
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> 3. The open-endedness of the Capstone Experience was eliminated. Students who did not complete their project in two quarters were required to register for an additional quarter.

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[4] One local company is such an enthusiastic sponsor of our program that they invite the entire engineering staff to the students' Capstone presentation at their facility.

[5] The local section of the IEEE sent out a call for interested volunteers in its monthly newsletter and we received over 50 CVs from local professionals with MS and PhD degrees who were interested in mentoring and guiding our students.

If they still failed to complete the project in three quarters, they received a grade based on what they had accomplished versus what they set out to accomplish and the project was ended.

IV. overview of the Capstone Experience

As of December, 2016, 65 teams have completed their Capstone Experience and there are another 16 teams currently registered in either Capstone I or Capstone II. Five affiliate faculty members mentor the program, each one supervising up to four teams. Since our enrollment is steadily growing, we will likely need to hire additional affiliate faculty in the near future.

By far, the biggest challenge is the constant need to "feed the beast." It is generally the author's responsibility to find companies willing to sponsor teams. Since the program began, the author has made approximately 75 visits to local companies and given presentations to companies both local and remote from our geographical area. At the time of this writing, 41 companies, both local and distant, have sponsored Capstone projects.

An ideal situation is to partner with a company willing to sponsor multiple projects. Fortunately, we have a core of industrial partners that have been very supportive and continue to sponsor new teams.

Some students find projects working through their employers or through family connections. Approximately one-third of our projects are initiated by students themselves. Finally, several of the EE faculty sponsor teams to support their own research efforts, or just to support the teams. [6]

IVa. an ideal Capstone project

The first hurdle is finding a company willing to sponsor a team. Defining a worthwhile project is equally as challenging. The ideal project is:

- Significant but not time-critical. The project is of value to the company, but not high-priority. Most companies have "back burner" projects that aren't so important that they would staff them with internal resources. A typical project in this category might be a test fixture that improves an existing manufacturing process.

  Projects of this type can generally be completed by one or two experienced engineers working 40+ hours per week, far less time than it takes a Capstone team of four students. The companies understand this and set their expectations accordingly.

- Scoped as executable rather than exploratory. In the past this was an issue. We've learned that when a company gives us a vague project description, one of the team's first tasks is to redefine the scope of the project so it can be completed by

[6] Faculty sponsorship, though welcome, is not as desirable as industrial sponsorship. Most of the faculty members do not have industrial experience and they are as unfamiliar with the soft skills as are the students.

four students in six months of part-time effort. Too often, exploratory projects lack focus and direction, and neither the mentor nor the students know how to proceed.

- Extendable over multiple teams. Sequential teams can step in and take over from each other. Each team's sub-project is scoped to cover a reasonable aspect of the overall project. A good example of a project in this category is a cable tester that was developed for use by a local Fortune 100 company. This will be discussed later in this paper.

IVb. student teams

During the development of the program we considered how best to create teams. Ultimately, we allowed the students to self-select teammates. Only when students were unable to create a team or find a team did we step in and assign them to teams with less than four members. However, this was rarely necessary; somehow, the teams seemed to come together organically.

Any time a team of students are involved in a school project, there is the possibility the team will become dysfunctional. All new teams are urged to review and discuss guidelines provided by a professor in our School of Business and a former Human Resources manager at a technology company. These guidelines help teams set expectations for their participation and how they want the team to function as a unit.

While the penalty for poor performance in a company is termination, a student team will receive, at worst, a poor grade. Unless all team members are equally motivated and share a similar set of expectations, it's possible for internal conflicts between team members and with their faculty advisor or industrial mentor to arise.

Generally, if there is a problem within the team with one or more members, the faculty advisor steps in and will attempt to resolve the issue. Sometimes a problem cannot be resolved and, at the team's request, the problem student is asked to leave the team. The affected student may be required to retake the class with a new team, complete a portion of the project directly under the supervision of his faculty advisor, or be given a project to complete on his own.

IVc. launching a project

We have created a streamlined process that makes it easy for companies to partner with us. To launch a project, the only requirement is a one-paragraph description of the proposed project and contact information for the liaison to the program. The liaison may or may not be the team's mentor, particularly if that person is a management or HR person.

Since there is no formal requirement for financial support to the Capstone program, a project launch typically does not require high-level corporate approval. Our most expensive project to date cost the sponsoring company $1000 US because the project team required a high-voltage power supply for an automated cable tester.

Once the project is reviewed for academic merit and appropriateness, it is posted to the course website. Figure 1 is a page from the Capstone course website listing available projects.

Project Title	Sponsoring Company	Contact Information	Instructor	Complete the design a non-intrusive system for ships that will measure the flow of fuel to the engines and send this data to instrumentation in the ship's bridge. Phase I did the initial design and proof-of-concept. Phase II will complete the development and packaging of the product.
A modular, programmable ultrasound pulse generator	Company A	Company contact name and contact information	WK	This project is to create a pulse generator/amplifier for therapeutic ultrasound transducers. A new modular design is needed to power ultrasound therapy transducer arrays. The design will contain a backplane board that generates and distributes low-voltage signals, and separate boards to amplify the signals that can be easily installed/uninstalled to create a system with a variable number of channels. An existing pulse generator design is given as an example, with the following properties: 400 Vpp for pulses from one to 100 cycles in length, for carrier frequencies between 0.1-2.0 MHz. Design work will involve FPGA board programming in Verilog or VHDL, selection of surface mount and through-hole circuit board components, PCB layout and assembly, and output signal testing using an oscilloscope and high-voltage probes.
Internal Flow Transducer Test Fixture	Company B	Company contact name and contact information	RK	The ventilator uses an internal flow transducer module to measure inspiratory flow to the patient. The transducer module consists of an orifice flow transducer, a differential pressure transducer, associated signal conditioning circuitry, an onboard EEPROM to store a characteristic curve, and an I^2C bus to communicate with the main controller. An automated test fixture is need that will connect to the module, run through a series of flows and leakage tests, and determine if the module is within acceptable limits.
Ultrasound Amplifier	Company A	Company contact name and contact information	RK	RF Amplifier to drive ultrasonic transducer for transcranial research, Phase II
Ultrasound Palpation System for Non-Invasive Determination of Intracranial Pressure: Phase II	Company C	Company contact name and contact information	ES	Follow-on to be original work of the first team by integrating the entire system so it works (this is a small task), signal processing for a new application (pushing water while monitoring its displacement (what it already does) as well as 'listening in' on cavitation. the latter will require construction of a new ultrasound probe (not your problem) but also require acquiring and filtering and analyzing the cavitation signal in a way synchronized with the displacement of the water. i'll want a digital filter in line with the cavitation detection with the ability to tune the filter to optimize it.
Integrated heated ski suit phase II	Company D	Company contact name and contact information	RK	Build upon the work done by the previous Capstone team. Add heating elements to the pants and jacket, improve packaging, mechanical connections and user experience, as well as characterize performance
3D Printer Project	UW ME program	Company contact name and contact information	WK	We in Mechanical Engineering are putting together a 3D printer that can print chocolate. this device requires replacement of the existing 'brain' [RAMPS Arduino board] so that it can control in real time not only the position of the chocolate syringe but also the temperature at and near the point of extrusion and humidity within the entire printer chamber. This will require Arduino-like hardware manipulation and coding, identification and installation (with help from the ME team) of appropriate sensors, and integration and analysis of real-time temperature and humidity data versus chocolate quality.

Figure 1: Web page showing available Capstone projects. The company names, the contact information and the affiliate faculty assigned to the project have been omitted from the table.

The project list is quite dynamic and Capstone teams form every quarter, including summer. Interestingly, there does not seem to be any preferred quarter to begin the project.

Of particular note is that teams may be multidisciplinary. Our school now has three engineering degree programs, Electrical Engineering, Computer Engineering and Mechanical Engineering. Both Computer Engineering and Mechanical Engineering are currently undergoing review for ABET accreditation and have adopted our model for their Capstone Experiences. We now have teams that bring mechanical, software and circuit design expertise to their projects. These additional skills have been requested by our industry sponsors since the program's inception.

Once a team makes a tentative project choice, they are encouraged to meet with their industrial mentor and discuss the project at length. At that point the mentor or students may decide they are not the right team for the project or that the project is not a good fit for the interests of the team. This initial meeting saves a lot of aggravation further down the road.

If the team and the company mentor decide that the project should move forward, the next step is to meet with their faculty advisor and the Capstone Experience supervisor (the author) to set expectations for the months to come. At this meeting, the team has the opportunity ask any additional questions they may have. For example, they are encouraged to review and work through the Team Expectations Worksheet[7]. If they haven't already chosen a project, they are encouraged to choose one from the course website or find one on their own. Many excellent projects were initiated by students using their own networks.

The final item discussed at this meeting is the issue of ownership of intellectual property (IP). As a rule, any IP that may be invented by the students is the property of the sponsoring company, just as it would if an actual consulting engineering company was providing the work product. This is also spelled out in the Capstone contract that the students, their faculty advisor, and their mentor all sign.

If a student or students object to signing the IP waiver, they are given the option to find another project or work with an EE faculty member on an internal project. Though less desirable than working with a company, we recognize that students may have patentable ideas for a project, want to develop the idea, and protect the IP they create in the process.

Since the program began, we have had two projects where this was an issue. In the first project, the company had no desire to pursue a patent and they turned the rights over to their Capstone team. The second project was just the opposite; the company is pursuing a patent and the students waived any claim to the patent, but their names will be on the patent if and when it is granted.

Students and their faculty advisor may also be asked to sign Non-Disclosure Agreements. This is a standard procedure with many technology companies. In fact, it is highly unlikely that our program would have gotten very far along without the assurance that the company's proprietary material would be respected.

IVd. Capstone I

Capstone I is a two-credit project launch. During this phase, the students choose one of the team members to be their team lead engineer. This is not a supervisory role. The lead student is the liaison with the faculty advisor and the mentor. The lead manages the schedule as well as all documentation. The lead is also expected to be a technical contributor on the team.

The students understand that the extra workload assumed by the lead is offset by greater reward at the back-end of the project. Typically, the student lead can demonstrate his mastery of the soft skills to a prospective employer, a potential advantage with all other things being equal.[8]

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[7] Available on request from the author

[8] In one instance, a student lead was interviewing at a local high-tech company and the interview was proceeding rather routinely until the student began to discuss the scheduling tools he had developed for his project. The project finished remarkably close to the predicted completion date due to the student's excellent project management skills. As he left the interview to return to his car, he was called back in and offered an engineering position at the company.

The initial phase is one of research. Deliverables in this phase are as follows:

- The Capstone contract. The contract is only signed when the students learn enough from their research to confidently commit to the device and feature set they intend to develop. This may be 4-6 weeks into the project. Once the contract is signed off by all the stakeholders, the team focuses on developing the other deliverables.
- A formal specification that will be approved by the customer. The specification has two parts: an internal specification and an external specification. The internal specification describes how the device operates and is intended to be the design document for the team. The external specification is what the customer sees. It describes the feature set, the environmental constraints, and how the product will be validated.
- A test plan. Each team is required, with the help of their mentor and faculty advisor, to develop a formal testing plan and process. To this end they are given a bound "lab notebook" for recording their observations as they execute the plan. While this may seem like overkill, we have found the notebook to be an invaluable tool for training students in developing a logical sequence of steps to turn-on, debug and, finally validate their design.

  In the past, too many students wasted too many valuable hours attempting to "shotgun" problems by making wholesale changes hoping to fix a defect in their design. Usually, the result was a ruined PC board and a collection of broken components.

Capstone I concludes when the formal specification is approved by the sponsoring company. If the students have not satisfactorily delivered the required material, they move on to Capstone II, but their Capstone I grade is withheld until all the Capstone I deliverables are completed.

IVe. Capstone II

Capstone II is the three-credit conclusion to the Capstone Experience. In Capstone II, the students actually build their project and verify that it meets the design specifications. Capstone II is the most intense part of the program because they must now put their other coursework into practice. For many students, designing something more involved than the problems asked at the end of a textbook chapter is a new and daunting experience. However, we anticipated this and provide informal design guidance if the student is willing to make the effort to ask for assistance.

Just like working engineers, students are encouraged to use, adapt, and collaborate to solve their design problems. Our only requirement is that they cite their sources.

The deliverables for Capstone II are as follows:

- A working prototype that is acceptable to the customer
- A complete report of their project including all schematic designs, board layouts, software, and supportive documentation
- A poster to be presented at a poster session before the formal colloquium
- A thirty-minute-long presentation at the colloquium

- An individual ethics paper on a topic of interest to the student[9]

If the Capstone II team does not finish during the second quarter, they are required to register for another quarter in order to complete their project and receive their grade. About one-third of the teams need the third quarter to complete the project. Although there are many reasons for projects taking longer than six months to complete, by far, the main reason is that the Capstone Experience is a long-term effort and students are accustomed to focusing attention on near-term demands on their time.

For example, a student might reasonably decide that since she has a paper to complete and a problem set due, her Capstone deliverables can slide a week. Consistently yielding to near-term demands at the expense of Capstone progress inevitably leads to slipping schedules.

The faculty advisors address this with the students but they are not "bosses." All an advisor can do is provide guidance and then evaluate the students' performance. They can't fire a student who doesn't meet commitments. We do what we can to prepare them, but every student matures at his own rate.

IVf. evaluating student teams

The final task we require of the industrial mentor and the faculty advisor is to complete an extensive evaluation of each student's performance on the project. The original evaluation form was adapted by the author from the engineering evaluation forms used at Hewlett-Packard[10], where the author was an R&D engineer and project manager.

Each student is evaluated in seven categories:

- Technical Competence
- Productivity
- Quality
- Organization
- Deliverables
- Communication
- Overall performance

Within each category, the evaluation includes a short narrative and a letter grade. Here is an example of such a narrative extracted from the evaluation of a former student:

[9] This was added to the requirements in order to strengthen the ABET outcomes (f), "an understanding of professional and ethical responsibility"and (i), "A recognition of the need for, and an ability to engage in life-long learning."

[10] Formerly Aglient, now Keysight Technologies, Inc.

Technical Competence: B
This team's experience and knowledge base was limited when they started on this project. However, they displayed a willingness to research the unknowns in a variety of ways. Resources included: engineers from various groups, marketing personnel, vendors and the IS group. In addition, the team proved to have the ability to grasp the not so subtle complexities of a variety of our products and the two Real Time Operating Systems (RTOS) that they were exposed to.

The evaluators are also asked to evaluate each student as part of our ABET process for tracking educational outcomes. The Capstone Experience is a crucial aspect of the EE program because eight of the ABET Student Outcomes map directly to the Capstone Experience.

For each outcome and each student on the team, the evaluators grade the students according to the following rubric:

Categories	Points	General Description
Excellent	3	Student applies knowledge with virtually no concept or procedural error
Effective	2	Student applies knowledge with no significant conceptual errors and minor procedural errors
Minimal	1	Student applies knowledge with occasional conceptual errors and minor procedural errors
Unsatisfactory	0	Student makes significant conceptual and/or procedural errors when applying knowledge.

The evaluator completes a table for each outcome containing the students' names and their scores. If necessary, a brief narrative is included to justify either exceptionally good scores or very poor scores.

V. results

Of the 65 teams that have completed the Capstone Experience, most teams did reasonably well. Some teams performed exceptionally well and they are highlighted in the next section. Thankfully, only a small number of teams (less than five) could not successfully complete their project. Two of the teams suffered from the inevitable personality clashes and imploded. The other teams had other reasons for failing to complete their projects; these will be discussed in the next sections. The rest of the teams fell somewhere in between.

IVa. examples of successful and unsuccessful projects

Most projects successfully complete with the teams more or less delivering their final project to their sponsor as promised. There have been some notable successes and some regrettable failures. Here are a few examples of very successful projects:

- Voltage Source Converter

One of the first Capstone teams designed a replacement control board for a high-voltage, high-current power supply used in the testing of renewable energy sources, such as wind generators and solar arrays. The board is circled in red in the photograph on the right.

The team members had just completed their Control Systems course and put theory to work by design a control board with better performance (by a factor of ten) than the model the company was selling at the time. The student team utilized a high-performance 32-bit Power PC microprocessor running an algorithm that they learned about in class. The board is now in production.

- Cable tester

This project was a three-team evolutionary project. The first team did preliminary work but suffered from personality issues and, although they eventually passed the course, the team disintegrated and each member completed the Capstone doing individual projects.

The second team was more successful and completed the cable tester for the Fortune 100 company mentioned earlier. Previously, the company performed manual tests on its custom cables. The process was error prone and costly. The team built an automated tester that ran a complete series of open-circuit, short-circuit, and wiring error tests. Finally, the third team added high voltage current leakage tests, improved the packaging, and the user interface.

- Water Purification Cell Monitoring System.

A local builder of industrial-scale water purification systems needed a way to monitor the health of its reverse osmosis cells in the field and know when to replace or repair them. The team designed a self-contained device for field service personnel to connect to the cells and monitor their health. The project is currently being used by the company.[11]

[11] This project is of particular note because one of the students on the team is now an EE for the company and he is a mentor for another team being sponsored by the company.

Unfortunately, some team's projects did not live up to our expectations because the teams failed to succeed due to internal conflicts among the students. Anyone wishing to replicate our Capstone Experience model should be prepared to deal with student issues.

The following projects were not successful.

- Non-invasive fuel flow meter for shipboard use

  The team's project was to design an ultrasonic transducer-based system to measure the rate of fuel consumption on commercial shipping vessels using the Doppler shift in the velocity of ultrasonic pulses traveling with the fuel stream and against the fuel stream. They found an integrated circuit that seemed to be ideal for the task, but even with significant coaching from local experts, they could never get the IC to function properly.

  They had several problems, but the most serious was their inability to actually test the part. The device was single-sourced from an Asian company and no applications notes were available. They tried to test it using a simple prototyping plug board, but at the ultrasonic frequencies of the device, the simple test fixture did not provide the necessary ground planes and power planes.

  When the team finally designed an impedance-controlled PC board for the project, they miscalculated the pin spacing for the special socket required by the part. At this point, the lead student on the team lead left for an out-of-state engineering position and the team, without the leader, stalled.

  From this experience we learned to avoid exploratory projects and focus on projects that were achievable.

- Quadcopter

  Given our proximity to major distribution centers and the publicity surrounding the idea of autonomous-drone package delivery service to customers, it was inevitable that a team would attempt to build an autonomously-controlled quadcopter that could take-off and land on a designated target, identified by a large sheet with a red cross painted on it. The team never mastered the basic software required to simply keep the quadcopter stable in flight. After spending three quarters on the project, they were able to make it rise only 30 cm before it became unstable.

  Our lesson was twofold:

  1. Our students needed a class in C or C++ with a focus on embedded programming techniques. As part of our course review, we identified this weakness and worked with our Computer Science program to develop a programming sequence for engineering students uses C++ rather than Java as the course programming language.
  2. This team was comprised of four academically weak students. Since the students self-select their teams and this project was chosen by the students themselves, there was little that we could do but hope for the best.

- Remote Electrical Engineering Lab

The author's research interest is focused on developing a system to enable EE students located off-site to work on the lab experiments associated with their core courses. The first team to work on this project had a very strong student as team lead and three weaker students. The strong student was an exchange student from South America and had a hard deadline for his return home.

His initial design for the motherboard was well-done but probably more complex than it needed to be. After he left, the remaining students were not able to design and debug their experimental daughter boards without his leadership. A second student did more than her fair share to create the software and some peripheral functionality, but was not completely successful.

Our lesson: Exchange students should be treated as exceptions and their Capstone projects should be carefully chosen if they are to be teamed with regular students.

IVb. alumni feedback

As part of our program's continuous improvement effort , the EE faculty held two focus group meetings with our alumni in June 2015. Thirty-five alumni from the area attended the event. The recent EE graduates were divided into two groups and were each interviewed by two faculty members.

One of the faculty members served as the moderator, asking open-ended questions designed to create discussion among the participants. The other faculty member served as an observer, taking notes and asking follow-up questions when appropriate. Both sessions were recorded as well. The focus group process that we followed was modeled after McQuarrie [4].

We asked the following questions about the value of the Capstone Experience,

Could you please discuss how the Capstone program impacted your professional development?

- *Was it worth the effort?*
- *Are there things we could improve about it?*
- *Would you be willing to mentor a Capstone team? If you have mentored a Capstone team, would you please tell the group about your experience?*

Here are some of the abbreviated alumni responses,

- *Vlad: Capstone was a key factor for me. I got hired because of Capstone. I used my industry mentor as a reference. We had to learn to work together. I was better prepared for working in an engineering environment.*
- *Matthew: Same for me. Team projects taught us how to work together. I used my Capstone presentation as a job presentation.*
- *Julia: Capstone made me hirable. Also, Capstone projects need to be carefully scoped.*

An EE faculty member who acted as one of the moderators, summarized his focus group notes in this way,

> *The strength of our program lies in our Capstone project courses. Students expressed that the Capstone project helped them to get jobs. They claimed that they were more prepared in terms of practical hands-on skills than their colleagues from other institutions because of the strength of the Capstone projects.*

One task that still remains is to conduct a survey of employers in the area who have hired our graduates. The objective is to obtain feedback on the value of the Capstone program as it relates to their employees who have completed our program, and compare them to other EE graduates they've hired. As we start to prepare for our upcoming six year ABET review, we will be conducting this survey.

IVc. adoption by other EE programs

We have noted that two other universities have adopted models similar to ours for their EE Capstone program. Another university in our area recently announced a new program called the *New EE Entrepreneurial Capstone.*[5] Quoting their press announcement,

> *Building on EE's strengths in system design and entrepreneurship, the department is excited to announce the launch of a new Senior Capstone Design option that will enable students to work in teams on industry sponsored projects during winter and spring quarters 2016.*
>
> *This new program is an opportunity for our students to understand the entire engineering product development cycle and gain valuable project management experience. Student teams will be responsible for organizing, scheduling, budgeting, designing, constructing, documenting and presenting their results, as well as analyzing the business side of their projects.*

Ehime University, located in Matsuyama, Ehime, Japan has a reciprocal agreement with our campus. Faculty and students from Ehime have twice visited to speak with our faculty and students about our model for the Capstone Experience. On both occasions they were able to see the student poster sessions and hear their Capstone presentations.

In March 2016, Ehime's first student Capstone team, modeled after our program, presented their project at our Winter Quarter Colloquium.[6]

V. conclusions

Our Capstone Experience has grown in scope and evolved since its inception. We are fortunate to be located in a region where so many technology companies are located. For example, our area has become a hub of established and new biotechnology companies and they provide an excellent source of projects for our students.

We realize we are fortunate in this respect and the structure of our particular type of Capstone program might not work as well for another institution located apart from an industrial base. We've learned that keeping a program like this alive takes ongoing effort. While some companies have sponsored multiple projects, others have sponsored just one. As a consequence, the author is continually following-up on new leads and making "cold-calls" with prospective sponsoring companies. Ideally, a full-time staff member would manage the industrial relations and find projects, but we haven't yet reached that level of sophistication or budget.

A positive sign is that companies in the area have heard about the program and contacted us about the possibility of doing projects for them. Perhaps most gratifying, three teams have been mentored by former students, now engineers, at the sponsoring companies.

Other institutions interested in following our model should be prepared to make a serious time commitment to start a program and keep it healthy. As a rough calculation, divide the number of students in an entering class by four and that will be approximately the number of new projects needed when those students are in their last year of the program.

It is difficult to provide more than qualitative data regarding the effectiveness of our Capstone program. We can cite the fact that our program was ABET accredited for the longest term in its initial review. In their report, the ABET review team cited our Capstone Experience as one of the main strengths of the EE program. Citing the draft statement from the on-site ABET evaluation team,

> *The program is located in a metropolitan area having a rich, vibrant and diverse economy that allows many opportunities for industry interaction with both its students and faculty. A wide variety of large and small companies are close to the university, which allows students to work closely with industry on their Capstone projects. The program takes full advantage of the high technology nature of the industry in the metropolitan area in its selection of highly qualified and specialized adjunct instructors.*

For the first time, several area companies have contacted our program with the aim of sponsoring teams. This is very gratifying and further validates the strength of the program.

Finally, there is a large quantity of documentation associated with the Capstone program; far too much to include or even reference in this paper. Interested faculty or administrators are welcome to contact the author for examples of our contracts and formal design specifications, project reports, and our team expectations worksheet.

VI. acknowledgements

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