Best Practices for Managing Large Capstone Classes

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Abstract

The senior major design experience, (Capstone) mandated by ABET, is define is defined as the completion of a design that incorporates skill and knowledge acquired throughout the engineering curriculum and manages constraints and standards that might be encountered in practice. The overarching goal is to provide a real-world environment for the students to complete a design and to also experience brutal realities of completing a project on time and within a budget. In this paper we present best practices, learned through our experiences during this period. We present techniques for managing parts and circuit boards, keeping teams on track to finish within a single semester, and managing reports. We also present approaches for grading, and for weighing individual team member contributions. A highlight of our approach is a Capstone Fair, in which faculty and students from across the school are invited into the laboratory to see demonstrations of the final projects.

Keywords

Major Design Experience, Capstone, experiential learning

Background

At the University of Virginia, the Capstone implementation is left up to the individual departments. Most departments have a two-semester program, but several offer a single-semester class, completed in the Fall semester of the 4th year. There are normally two methods for handling Capstone projects. In one method the class divides into teams and every team does the same project, all managed by a single faculty member. In the other method, teams do separate projects, with each faculty member in the department managing one or two teams. While each approach has merits, neither scales to a third scenario in which each team chooses their own project, and a single faculty member manages the whole class. Electrical and Computer Engineering follows the latter approach.

We piloted a Capstone program in the fall of 2003. At that time our faculty voted to develop a one-semester course, to be administered in the Fall semester only. Design and fabrication were to be a part of the course, with the students working in teams of no less than three or more than five students. Each team was to produce a tangible working project, and not simply a paper-only design. The initial pilot was by “invitation” of a select group of students based on their interests in working on independent projects. The pilot was primarily used to assess our student’s abilities to work in such an environment and to develop a sense of what could actually be done in a semester. This evolved into an “official” class for Fall of 2004. Student teams were allowed to come up with their own ideas for a project that they found interesting. Students were not required to invent new technology, but to do innovative designs – instructor approval was required.

This class instituted several activities which have been expanded upon in successive offerings. We instituted a mid-term design review process in which each team discussed their progress and answered questions from the faculty member involved in the class. This began as an informal process for the first two years of the class offering. Also, a final project demonstration was required and a short project writeup. The early offerings of the class were still in a state of evolution, with requirements and activities being updated for successive offerings.

The class took a major step towards its current format in 2006. In this offering, we formalized the mid-term design review and each team had formal presentation requirements which were done for the entire class as well as invited faculty and graduate students. Each team submitted a reviewer's packet containing essential diagrams and datasheets. A major element of the design review was presentation of a test plan, and justifications for each major design decision. In addition, each team scheduled a weekly advisor meeting in which progress reports were given and goals for the next week were established. The final project presentation was further formalized and each team presented for the whole class. At this time the class consisted of eight to ten teams.

In the period from 2013 to 2016 the class underwent dramatic changes that necessitated a number of key logistical techniques to facilitate both enhanced student project capabilities as well as a major increase in class size.

Current Class Format

In 2013, the department of Electrical and Computer Engineering began a thorough restructuring of our undergraduate core curriculum. Our original, and very traditional courses in *Circuits*, *Electronics*, and *Signals and Systems* were phased out in favor of a breadth-first approach taught entirely in a studio format. We significantly increased the hands-on component of these courses, exploiting the techniques of problem and project-based learning as a mechanism for increasing concept retention [1]. Additionally, each of the new studio courses required a printed circuit design project as an aid in preparing the students for more advanced Capstone projects.

In 2015 the Capstone sections for Electrical Engineering and Computer Engineering were merged; prior to this there was a separate process for Computer Engineers. This more than doubled the class size and created major space and logistical problems. In 2016 we were able to acquire a large section of space in the department as a "Capstone" lab, and is dedicated solely to the class for the Fall semester; it is used for robotics and other classes in the Spring. This space has enabled us to expand our activities for the class. For example, we now have a poster presentation early in the semester, open to the public, in which each team meets with interested students, faculty, and alumnae to explain their projects and solicit suggestions for further direction. We also now have a Capstone Fair at the end of the semester, again for the public, in which the teams show working demonstrations of their projects. Over the past 12 years we have experienced a steady growth in our Capstone class as a result of merging the Computer Engineering with the Electrical Engineering one, and this has led to multiple logistical problems to be solved for managing the class; our current class has 21 project groups!

Figure 1 Capstone Lab

Teams self-organize during the first few days of class, and typically consist of both Electrical and Computer Engineers, providing extra depth, and leading to more diverse projects compared to earlier offerings of the course. Teams develop an initial abbreviated project proposal according to their interests and we then approve (or disapprove) it and offer suggestions on how to improve the project, or alternatively to limit the scope. All work is completed in one semester, consistent with a typical accelerated industrial design cycle. The projects are defined as complete when an "alpha stage" prototype is produced. All projects must result in a physical product; simulations or software-only projects are not eligible. Final designs must be rendered on a printed circuit board with professional level interconnects to external devices. Projects that employ line voltage must comply with NEMA standards.

Class Activities and Semester Milestones

An important consideration a Capstone class of this size is to keep teams on track and managing expectations as well as individual team member contributions. This involves 3 hours per week of class time with activities designed to keep teams focused. In the first week interested industrial partners are invited in to explain what their company produces, and to solicit teams for potential projects. Note that all of our projects are considered open-source, and students are not asked to sign any form of contract when working with outside companies; most of the teams are funded by our Department. In the second and third weeks of class teams do five-minute presentations to the class in which they explain the background and justification for their projects. We use this as a means of gathering suggestions from the class, and furthermore forces teams to coalesce their thoughts and plans into a concise format. At this point most teams have completed some early prototyping and testing to assure the assumptions that they are basing their designs on are valid.

Formal proposals are due near the beginning of the fourth week of class. At this point more advanced prototyping of key elements is underway, and the students have developed enough technical proficiency with their project to have a degree of confidence in their approach and

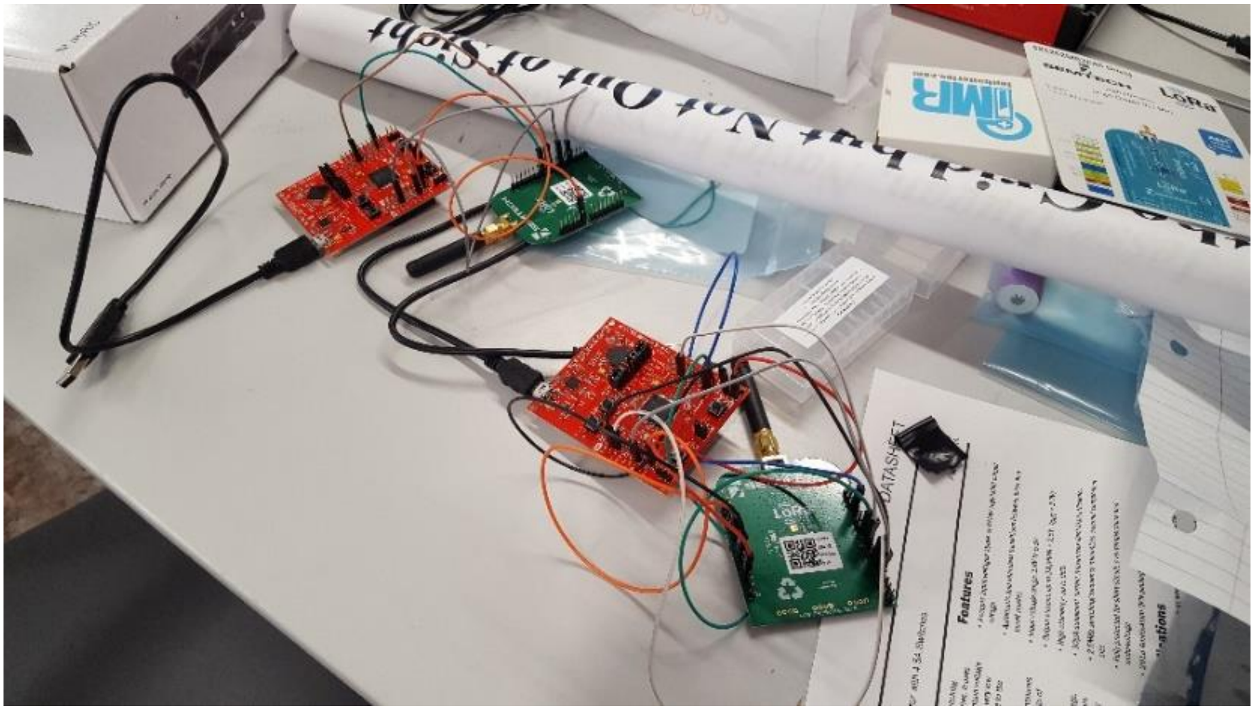

Figure 2 Early Stage Prototyping

expected outcomes. Formal proposals are submitted using a required template which includes subject headings as well as formatting. We have learned from experience that the template requirement facilitates comparison of proposals and ensures that all of the necessary elements are covered. The proposal template includes item headings such as *Background*, *Description*, *Deliverables, Timeline*, *Expectations*, *Team Member Primary* and *Secondary Responsibilities*, and in accordance with ABET expectations there are required sections detailing *Constraints* and *Standards*. In addition, we have found that having required document formatting for headings and text improves readability when assessing large numbers of proposals. References are required, IEEE formatting, and we have an expectation of ten to fifteen references minimum. Students are afforded a “rough draft” submission for feedback, with the final document due within one to two weeks.

At the time of the rough draft submissions a weekly schedule is set up for team meetings with either the instructor, or with a graduate teaching assistant who is selected from students who have been through our Capstone program and are now enrolled in our Master’s or PhD programs. Team meetings are scheduled for 30-minute slots and all members are expected to attend. A spreadsheet is maintained for each team which includes entries for each team member. Entries include a statement of work performed by each member in the past week, and a comparison is made with expectations of work to be performed from the previous week. Each team member is scored on a zero to ten basis and this is updated weekly. This mechanism allows us to track a team’s progress, provides incentives, and scores the work of each team member individually.

We also endeavor to provide students opportunities to interact with the public and raise school-wide awareness of the work they are doing in the Capstone. Early in the semester we have a required Friday afternoon poster session which coincides with a reunion weekend for the school.

Figure 3 Capstone Poster Presentation

Faculty and students from across the Engineering School as well as department alumnae are sent invitations and we have found the interest level to be quite high. We have found that this also instills a sense of pride in the students, and most groups receive very useful feedback from practicing engineers.

At midterm, we have formal design reviews. Each team submits schematics, data sheets, and other required manufacturing documents, and delivers a 15-minute presentation to the class. The design review includes explanations and justifications of all key design decisions, and a thorough description of each portion of the project. All team members participate and questions from the instructor and teaching assistants may be directed to any team member; students are told in advance to be prepared for tough questions. Time permitting, the class may also pose questions.

From midterm to the end of the semester class time is divided between student presentations, and technical topics review. One class period each week is devoted to brief 3-minute updates from each team in which the overall progress of the previous week is explained and problems encountered are discussed. Also included are goals for the current week. We have found that this tends to increase student awareness of their actual progress, and requiring a presentation tends to keep them focused. It also gives them practice and develops confidence in presentation skills. The second class meeting of the week is devoted to topics useful to large segments of the class. Among the topics discussed are programming techniques, tips, and coding standards for embedded CPU's. We also discuss board layout techniques and methods for saving space and enhancing performance as well as voltage regulation and circuit protection techniques.

Additionally, we devote time to professional develop topics and industry speakers as available. We also devote time to discussing the patent system and intellectual property issues; a patentability analysis is required as part of the final project report.

As part of our ongoing assessment process, we administer concept inventory tests near the end of the semester, i.e *Electronics* and *Signals and Systems* [2]. We feel that this is an extremely valuable exercise both for our program as well as for the students. Note that the material in the tests is from our core content, and that students have not had formal classes in the subject material for a year – the tests give a measure of what the students are truly retaining. No reviews are performed, and the students are encouraged not to study for them. While students may see their score, their grade on the exercise for the class is participation-based. If they take the test, they are given full credit for that part of their grade.

The class requires a final report as well as a working demonstration. The final report uses a required template and the topic headings are aligned with ABET criteria. Among the required sections are *Design Constraints, External Standards, Tools Employed, IP Issues, Ethical Social* and *Economic Concerns, Test Plan,* and *Future Work Suggestions*. The final report has strict number and formatting requirements, and all references are in IEEE format. From experience we have found that the formatting and section requirements are of enormous benefit in assessing reports, especially when so many need to be read and graded in the short time period between the end of class and the grade submission deadlines. Our template outline is in Appendix 1.

Figure 4 Capstone Fair

The other final requirement is a working demonstration of the project, which is performed during the scheduled exam period for the class. We have instituted a "Capstone Fair" for this slot, and faculty and alumnae are invited in. Typically, many parents attend as well. Visitors circulate among the teams and ask questions during the demonstrations. The instructor and teaching assistants maintain a relative score for each demonstration and compare with stated deliverables that were given in the project proposal. Among the projects we have had for the past two years are "*Automatic Scrabble Player", "Drink Filling Robot", "Interactive Guitar Tutor", and "Water Purification System for Developing Countries".* Students also submit a short 1 to 2 minute video of their project operating. A relative grading rubric for the overall course is detailed in Appendix 2.

Managing Logistics

A class of this size and breadth of scope has required us to develop logistical procedures to keep considerations such as part ordering and board management within tractable limits. We have selected a preferred vendor for electronic components and have an arrangement that allows us to upload spreadsheets directly into the purchasing system. Students are required to submit part orders using a spreadsheet template, allowing us to merge spreadsheets for one complete order. Our vendor packages the components with the team name as part of the customer reference number, simplifying the distribution of parts when the orders arrive. We follow the same procedure for secondary suppliers although not all have spreadsheet upload capabilities.

All projects have a printed circuit requirement, and we have located a domestic supplier that produces boards at a very reasonable cost for student projects. We realize further savings by panelizing individual boards, thereby reducing the number of submissions [3]. To expedite this process, we supply the students with a file naming tool that creates consistent layer names for the manufacturing files, and makes merging boards a "point and click" process. Each team is allowed several board submissions during the semester to ameliorate the inevitable problems that are encountered during the debugging process.

Summary and Conclusions

Our Capstone experience is an intense class for most students, but in the end, they express quite a bit of satisfaction. We strongly believe that allowing students to select their projects based on interests and backgrounds is a contributing factor. A typical student comment is: *"The level of freedom that we had with the whole process really helped my learning. For similar projects in the past, the process would be very guided with frequent, strict deadlines. With the Capstone project, we had to budget our time over the course of a whole semester and make sure to fulfill the project's requirements, specified by ourselves"*. The tight timeline and class approach closely mimic the approaches used for product development in industry which adds to the realism of the experience; learning new tools and techniques on a short timeline is a standard part of an engineer's daily experience!

We have learned that a critical element to keeping a large class on track is enforcing weekly milestones through team meetings and class presentations, with essential benchmarks for the mid-term design review. Enforcing templates for submissions facilitates timely scoring of student's work, and standardizing the file formats for fabrications expedites circuit board turnaround times.

Finally, keeping students engaged with the entire engineering school and the general public increases student enthusiasm and raises the profile of our department within the school. Students view the “Capstone Fair” as a celebration of a semester’s worth of hard work.

References

[1] Dr. Harry Powell, Dr. Ronald Willians, Dr. Maite Brandt-Pearce, and Dr. Robert Weikle, “Towards a T Shaped Electrical and Computer Engineering Curriculum: a Vertical and Horizontally Integrated Laboratory/Lecture Approach,” in *Proceedings of ASEE Annual Conference 2015*, Seattle WA.

[2] K. E. Wage, J. R. Buck, C. H. G. Wright, and T. B. Welch, “The Signals and Systems Concept Inventory,” *IEEE Trans. Educ.*, vol. 48, no. 3, pp. 448–461, Aug. 2005, doi: 10.1109/TE.2005.849746.

[3] “DownStream Technologies - Solutions for Post Processing PCB Designs - Products - CAM350.” [Online]. Available: http://www.downstreamtech.com/cam350.php. [Accessed: 10-Jan-2020].

Harry Powell

Dr. Powell is a Professor of Electrical and Computer Engineering and Associate Chair for Undergraduate Programs. After receiving a Bachelor's Degree in Electrical Engineering in 1978 he was an active research and design engineer, focusing on automation, embedded systems, remote control, and electronic/mechanical co-design techniques, holding 16 patents in these areas. Returning to academia, he earned a Ph.D. in Electrical and Computer Engineering in 2011 at the University of Virginia. His current research interests include machine learning, embedded systems, electrical power systems, and engineering education. Dr. Powell is a member of ASEE, IEEE, and ACM.

Appendix 1 : Final Report Template

Statement of work:

In this section, each team member should provide 1 or 2 paragraphs describing their individual contributions to the project. This needs to be detailed and list several specific examples of work performed and how it fit within the context of the whole project.

Table of Contents

Table of Figures

(*This should list the page of each figure used in your document, including the full caption.) Word has tools to help you do this very easily)*

Abstract

This should be a 1 paragraph overview of your project. It should be concise but give the reader a clear sense of what your project is about.

Background

You should encompass the following bullet points in this section. (Note that bullet points are not used in your write up – but are here just to make sure that you cover all of the points.)

- *Why you chose this project*
- *What's been done similar in the past. Include references as necessary (IEEE Style)[1]*
- *Your spin on the project, i.e. what differentiates it from past work by others.*
- *What background from previous coursework does your project call into play.*

You should also have the following subheadings in this section:

Constraints:

Design Constraints

You should discuss design and manufacturing constraints in this section. Examples would include CPU limitations, software availability, manufacturing limitations, i.e. the limits imposed by our PCB suppliers, or parts availability in the necessary timeframe.

Economic and Cost Constraints

External Standards

In this section, you should explain any external industry standards that came into play during the course of your project. For example if you project use a wireless interface then you dealt with IEEE standards for wireless Ethernet. If you project dealt with AC line voltages in anything other than a wall transformer you dealt with NEMA standards. The part spacing and track spacings on your PCB's were derived from IPC standards. You should ***provide references*** *to these standards and explain how they were considered in your project.*

Tools Employed

In this section you should list and explain the application of all of the major tools you used this semester. This includes software for math analysis, i.e. Mathcad or Matlab, software for programming, i.e. LabVIEW or C/C++ including Code Composer, and tools for simulation and design, i.e. Multisim and Ultiboard. You should explain what role each played in your work, and which tools you had to learn, or improve your skills on, in doing your project.

Ethical, Social, and Economic Concerns

In this section you should address how your project might affect society, both from a human interaction perspective as well as an economic one. You should consider issues such as privacy, security, or how devices such as yours might influence society both for good as well as not. For example, how would a system that employs robots affect human employment opportunities? What *are the ethics of automated weapons systems? How would your device affect those who might be economically disadvantaged? (You get the idea here, I hope!)*

Environmental Impact

Sustainability

Health and Safety

Manufacturability

Ethical Issues

Intellectual Property Issues

Detailed Technical Description of Project

This should a very detailed section. It should include the points. (Not bulleted in your report!) It should explain in sufficient detail that would allow a 4th year undergrad to exactly duplicate your results at the beginning of their fall semester.

Project Time Line

This section should include the Gantt chart from your proposal as well as a final chart (showing the differences). You should explain the following and how your time lines changed throughout the course of the semester.

- *Gantt Chart – tool from collab*
- *Serial tasks*
- *Parallel tasks*
- *Who does what*
  - *Primary*
  - *Secondary*
- *Cognizant of dates discussed on the first day of class*

Test Plan

You should show the test plan from your proposal and explain how you followed this plan or how you modified it. You should explain each of your testing procedures, and how you divided your system into testable sub modules. If testing caused a partial redesign of your device, you should explain how you arrived at that conclusion and how it influenced your redesign.

Final Results

In this section you should explain the functionality of your final device in detail. You should honestly assess and explain which of the success criteria defined in your proposal you met and which you did not.

Costs

In this section, you should outline your costs, with a detailed spreadsheet in your appendix. You should also consider how costs would change if you were to manufacture in 10000 unit quantities, i.e. look at distributor pricing to get estimates of costs in large quantities, and consider if automated equipment could be used to assemble your device and how that might influence costs.

Future Work

In this section you should offer suggestions as to how the project might be improved or expanded upon if a future group of students wished to create a new project based upon yours. You should consider difficulties that were no foreseen at the beginning, and offer advice on pitfalls to watch for.

References

This section should have all references in IEEE format.

Appendix 2 : Capstone Grading Rubric

1.	Class participation	10%
2.	Concept Inventory testing	5%
3.	Formal Proposal	10%
4.	Milestones	15%
5.	Final Report/Video	20%
6.	Working Device Demo	20%
7.	Mid-Term Design Review	20%