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Twenty-year Evolution and Lessons Learned from GMU ECE Capstone Projects

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Abstract

It has been twenty years since capstone projects became team projects and evolved from a simple format to the current challenging endeavor for our students. This paper describes the changes that have been made to senior design and presents the key goals and objectives of the program. The current format combines engineering, entrepreneurship, practical business practice, and top-down system design. It challenges students to approach difficult engineering problems and provides a platform for truly interdisciplinary projects and industry-sponsored projects. There have been many lessons learned over the last two decades, and some are presented here along with some recommendations that are based on our experience.

Keywords

Capstone project, senior design.

1. Introduction

The last two decades have demonstrated the value of team-based senior design projects in undergraduate engineering education. The requirements and format of a team capstone project in our two engineering programs have evolved significantly over that time. We share our experience and provide guidance and lessons learned that could be adopted by other universities.

2. Early Days and Transformations

Prior to 2002, the capstone project in our department was done by individual students or teams of only two students. Over the next two years, ABET and industry requirements became more specific and required the formation of larger teams. As a result, the size of the senior design teams increased to 3-4 students, and the focus became one of solving larger-scale problems. Specifically, the projects changed from small technical to stakeholder-defined larger-scale problems that involved building a system followed by testing and evaluation. Capstone design, a two-course sequence, was reorganized into class meetings and separate team meetings that involved faculty supervision of projects. Class meetings were handled by the course coordinator who acted as a coach and mentor. The first set of class materials emphasized:

- Top-down system design typical for systems engineering practice
- The small business practice of submitting a proposal and running a project
- Government and venture capital framework for reviews and reporting
- Student teams taking full responsibility for their project rather than the faculty
- Establishment of formal senior design presentations in a conference-style format

Every couple of years, the format of the course sequence was re-evaluated and revised, but only minor changes were made, and these changes were based on feedback from faculty supervising teams, students, and the course coordinator. Incremental changes included:

- Entrepreneurial spirit when selecting and running projects
- Development of case studies illustrating the top-down design process
- Offering extracurricular seminars on practical aspects of engineering
- Increasing competition for the ECE Award given to the best team
- Promoting student-suggested topics
- Building/expanding senior design fabrication lab
- Providing faculty with a course release after supervising eight capstone projects

The last review and modification of our capstone project occurred in the spring of 2022. Based on the feedback provided by faculty, the following recommendations were implemented:

- Speed up the teaming and project selection process
- Place more emphasis on the early definition of the acceptance test in the proposal
- Add a "dry run presentation" before the final presentation that is open to the public
- Require more involvement in intermediate presentations from the faculty
- Expand offerings of seminars on practical aspects of engineering
- Develop training materials for faculty, which is particularly important for new faculty

3. Current Format of the Capstone Project

3.1 Approach

Beginning in 2002, class meetings were converted into business meetings to give students the sense that their ECE capstone project was not a typical class. Figure 1 shows the guidance given to students at the first meeting to emphasizes the principles of the capstone project.

➢ **This is a business arrangement where teams proceed through all steps of a typical engineering design and prototyping as practiced in the industry**

➢ **A large engineering effort where teams must solve a larger scale problem**
  - **This is NOT yet another homework**
  - **This is NOT a typical college course**
  - **A team runs a real project with specific deliverables and under crisp restrictions such as time, schedule, and funds**

Figure 1. Capstone project guiding principles

This approach is mirrored by the system engineering discipline with the following characteristics:

- There are real stakeholders and requirements.
- The process is guided by the top-down system design approach
- The goal is to solve a problem, design, build, and test a system
- Projects are multidisciplinary.

- The business practice of running an engineering project is embedded at every step.

The top-down design process, and case studies, are taught very early during the first semester. Elements of this design process are shown in Figure 2. In addition, the following topics are also covered: 1) Engineering designs, 2) Innovation in engineering design, 3) Teaming and team organization, 4) Engineering notebook, 5) Proposal and report preparation, 6) Giving a proper presentation, and 7) Handling effective team meetings.

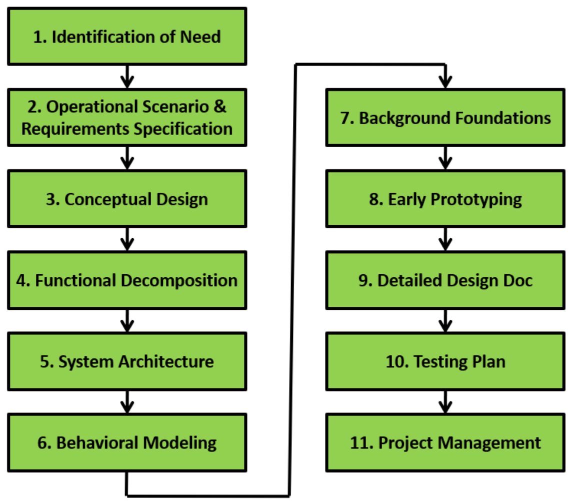

Figure 2. Elements of the design process executed during the first semester

Students form teams on their own and select a project from a faculty-suggested list. Team meetings are also run by students. They are fully responsible for their project, where faculty involvement is limited to an advisory role.

3.2 Homework

Almost all topics of the design process are verified through homework before teams present their designs in proposals, presentations, and design documents. Intentionally, homework is not graded. Instead, an extensive open-class discussion of homework provides early feedback to the teams. In such a way, a team can compare the quality of its own design against other teams' projects and designs. The introduction of ungraded but openly discussed homework allows teams to spot problems and avoid unnecessary failures during proposal presentations and interim reviews.

It has been observed that open discussion of homework leads to an overall quality improvement. Senior design is the first course where students face a top-down design process on a much larger scale. Homework, along with Case Studies, help them to proceed through the top-down design steps.

3.3 Case Studies

In the feedback received from students in the past, one was a request for case studies that illustrate the design steps. Recognizing the importance of this request, a search was done to find a simple, comprehensive, and informative case study. Unfortunately, a case study that would be useful for electrical and computer engineering students could not be found. Therefore, the course coordinator developed a sample case study called "Bike Computer." Following this, a more detailed case study was developed in 2015 called "Pendulum Clock Timer." The case study consists of 65 slides that illustrate each step of the top-down design process in Figure 2. The project is to design an electronic device that is to be attached to a 2-sec swinging pendulum as a mechanical grandfather clock. The goal of this simple device is to measure the period and quality of the pendulum oscillator. The study is detailed enough so that students can follow the steps in developing their own designs.

3.4 First-semester schedule and activities

The schedule for the first semester of senior design is shown in Figure 3. The semester is divided into two main activities: (1) Proposal preparation and (2) Detailed design, testing selected parts and software components, and early prototyping. Proposal preparation and oral defense are key milestones for all teams in order to verify a team's approach to solving a problem and demonstrate knowledge of an applied domain. Teams that do not pass this milestone on the first attempt are given one week to improve their written proposal and to give another presentation. The content of the proposal includes Background and Identification of Need, Approach and Alternative Approaches, Background Knowledge, Requirements Specification, Conceptual Design, Functional Decomposition, System Architecture, Preliminary Experimental Plan, and Preliminary Project Plan.

ACTIVITY	*TIME*	*MILESTONE*
• Project selection • Research	**Week 1**	→ **Class meeting #1**
	Week 2	→ **Class meeting #2**
		→ **Project selection deadline**
• Proposal preparation	**Week 3**	→ **Class meeting #3**
	Week 4	→ **Class meeting #4**
	Week 5	→ **Class meeting #5**
	Week 6	→ **Proposal and Oral Presentation**
• Detailed design • Testing parts • Early prototyping	Week 7	
	---- Spring Break ----	
	Week 8	→ **Class meeting #6**
	Week 9	
	Week 10	
	Week 11	→ **Design Review and Presentation**
	Week 12	→ **Class meeting #7**
	Week 13	
	---- Thanksgiving Break ----	
	Week 14	→ **Design Document Submission**

Figure 3. First-semester schedule

In the second half of the first semester, early prototyping is emphasized as a key activity. Early prototyping may include simulations, experimentation with selected components, and implementation of project functionalities that may impact project success. The goal of early prototyping is to engage in activities that verify the design and discover design modifications that may be necessary. Since it is encouraged that teams undertake risky projects, this phase provides early feedback. We have found that is necessary to be strict in requiring teams to run a meaningful early-prototyping effort.

For successful completion of the first semester of senior design, teams must have the following four issues resolved and documented in their Design Document.

1) Detailed design of the system, including schematics down to the component/resistor/capacitor value, as well as algorithm and software design.
2) Model of system operations, which includes functional model and system architecture.
3) Prototyping effort is demonstrated through simulations (when needed) and prototyping with selected components.
4) Implementation plan, Gantt chart, list of tasks, and team member responsibilities.

Students are advised to follow simple principles identified as "Keys to Success":

- Apply a top-down system design approach
- Start simple – complicate later
- Run an extensive early prototyping effort
- Show discipline in organization and planning
- Review and use course materials frequently

3.5 Second semester schedule and activities

The schedule for the second semester is shown in Figure 4.

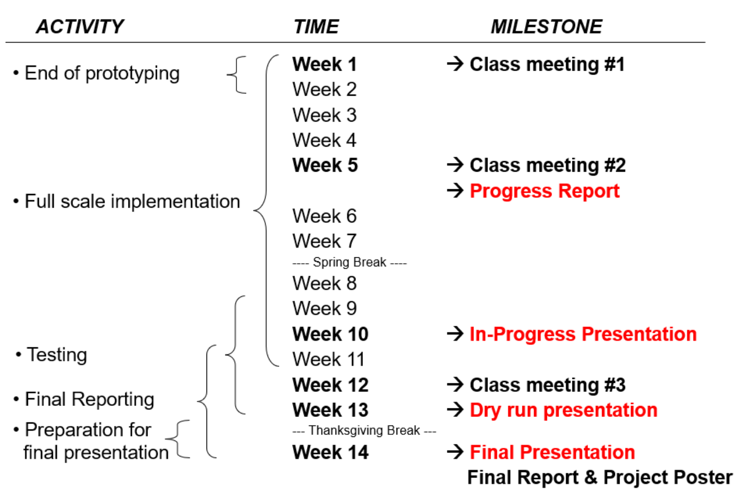

Figure 4. Second-semester schedule

The schedule includes three main activities: (1) Full-scale implementation, (2) Testing, and (3) Reporting and preparation for the final presentation. The number of meetings between the course coordinator and teams is scaled down and replaced by advising as needed. Such advising may involve helping/guiding in debugging of equipment, assisting in the fabrication of Printed Circuit Boards (PCBs), and solving a variety of non-technical issues, such as team dynamics and problems with individual team members. There are two interim reporting requirements followed by a final presentation.

No matter how much the importance of testing is emphasized, teams often struggle with delays and face limited time for testing, and this is one of the persistent problems with senior design.

The final presentation is an event open to the public and runs in a conference format. Each team has a 20-minute time slot, divided into 15 minutes for presentation followed by 5 minutes for questions and answers. It is required that teams practice their presentations and give a dry-run presentation to at least two faculty. Both the in-progress presentation and the dry-run final presentation serve as feedback to the teams. It has been observed that teams will overestimate the audience's understanding of the project's need and scope. This can lead to questions that are not on target, which leads to students having problems with understanding and answering these questions. Finally, teams must deliver a Final Report and a Poster of their project.

For successful completion of the second semester, teams must: 1) Build a working system, 2) Obtain test results and evaluate them, 3) Give a final presentation, 4) Submit a Final Report and a project poster, and 5) Leave the lab in order. During the second semester, students are advised to follow simple principles identified as “Keys to Success”:

- Proceed from modules to a system
- Promote incremental implementation and immediate testing
- Follow the implementation plan/schedule
- Show discipline and good working habits
- Focus on quantitative results

4. Non-Technical Problems to Overcome

In the first semester, design teams are presented with a list of twenty-three non-technical problems faced by previous teams, and these problems are discussed with the students. This is a wake-up call to those who expect to be able to go through the capstone project with the minimum amount of effort, and it emphasizes the fact that students must take the course seriously. Feedback has been received from teams that say that such exposure to past problems helps them to run their team better and has resulted in better team organization. It is interesting to note that the number and severity of the problems that were typical ten years ago have been reduced significantly. Some of these are documented below along with comments and possible solutions.

1) <u>Lack of understanding of top-down design principles</u>.
   Students are exposed to the top-down design approach of a large system for the first time in the capstone project. Many of them have problems understanding the process, and it may take several weeks for them to change the way that they think. Students are referred to follow a case study and apply these techniques to their own projects.
2) <u>Difficulties with motivation</u>. It is difficult for students to return from a break and start working immediately on a project. Therefore, each team along with the Project Manager (PM) are encouraged to begin organizing the project two weeks before the semester starts. During the first six weeks of the first semester, the faculty supervisors hold meetings with their teams on a weekly basis, and check the contribution of each team member. Students with weak motivation are given warnings. Twice per semester, each team member fills out an evaluation that states their responsibilities and the level of effort of other team members.

3) Delayed work with microcontrollers or complex chips.
   Designing a new system with a microcontroller can be difficult. Such designs require that students digest what they have learned about embedded systems, and this typically takes time. Therefore, it is strongly recommended that students take microcontroller and embedded system classes early and before signing up for senior design.
4) Insufficient PCB skills or late jump-start in PCB design and fabrication.
   Learning practical PCB design requires that students go through several projects and gain design skills. For our students, the capstone project is the first large project where they learn these skills. The basics are taught in a separate course or through a seminar.
5) No Plan B on hand when things go wrong.
   During their final presentation, a team will often advise new teams to have a "Plan B" and even a "Plan C" to deal with technical problems that may arise. This recommendation illustrates that teams often face serious obstacles and need to go back and redesign their system, or use a different hardware component.
6) Problems with presentation skills.
   This is typical for engineering students. However, it was observed that by having interim presentations, team members gain presentation skills and confidence over time. In the past, and to our surprise, students suggested increasing the number of presentations in place of technical report(s) and this increase was implemented.

5. ECE Award for Outstanding Senior Design Project

Since 2004 when changes to the senior design format were made, it was observed that student teams were undertaking more advanced projects even though these projects required more effort. These advanced projects result in very successful outcomes. To reward these projects and the design team members, in 2008 an 'ECE Award for Outstanding Senior Design' was introduced. A committee composed of three faculty members listens to the final presentations, receives nominations from individual faculty supervising projects, and makes recommendations for the Award. The final decision of what team receives the award is left to the Department Chair.

Immediately after the outstanding senior design award was introduced, student teams began to compete against each other to win the Award. The Award became an object of desire among teams. The Award is given only when a project truly deserves it, and one semester it was determined that no award should be given. Each member of the winning team receives a personalized plaque that they can post in their office, and a poster of the winning team is placed in the hall of the ECE Department for the next 10 years to honor their project and allow other students to learn about these projects. The award is also publicized on the ECE Web Pages and in its Newsletter. The decision to award teams with this special recognition was one of our best decisions as it stimulates students and provides lifelong recognition for their effort.

6. Student-Suggested Projects

In the early years of senior design, faculty and industry-suggested topics were generally the only ones included in the list of topics to be selected by students. Occasionally, a student would suggest a topic, and if it was determined that it had merit, then it would be included on the list. However, as the senior design program grew, students more frequently would come up with project ideas and pitch them to their colleagues and course coordinator for inclusion on the list. Each idea had to go through a “qualification process” where a student proposing the topic would be given time to present the problem. Students and the course coordinator would have an opportunity to ask questions, and interest in the topic was determined by checking to see if a team could be assembled. Proposed projects that were very challenging were reshaped by identifying a core project along with options. This was a frequent occurrence since most students' ideas were challenging, and students were often overly ambitious. In these cases, the core project was shaped to comply with the given time and budget constraints. Options were defined as extensions if a team had more time and the core project proceeded faster than expected.

A turning point in having a larger number of high-quality student-suggested projects was the introduction of the ECE Award, as described previously. This award provides special motivation for students and is also gets them interested in participating in the Inventor Club. Another remarkable thing happened – a large number of student-suggested projects were winning the competition for the ECE Award! Since 2008, twenty seven percent (eight out of thirty) student-suggested projects have received the ECE Award. This is a much higher percentage than for projects that were not student-suggested. These projects typically had a very steep learning curve and were truly challenging. In our view, the project of Fall 2012 titled “Digital Optical Spectrum Analyzer” is still considered to be the most difficult project to date. The project was an instrument for the analysis of a laser spectrum with relatively high resolution. The instrument and the team are shown in Figure 5. It is not clear what the reason is for the success of these projects, but it could be linked to the significant excitement that these team members appeared to have compared with other projects.

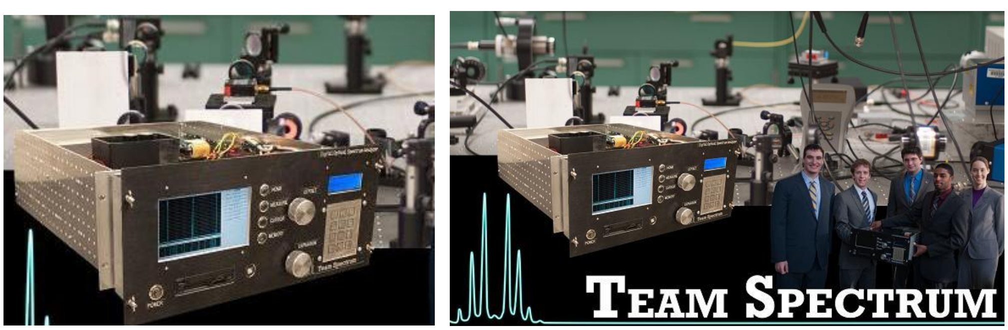

Figure 5. Team Spectrum and their laser spectrum instrument

7. Promoting Entrepreneurship

On multiple occasions, student teams came up with innovative ideas that qualified for a patent. Per university policy, students are permitted to bring their ideas to the capstone project, and if they desire, apply for a patent independent of the university (unless there is a substantial contribution from a faculty supervising the project). One of the projects of substantial innovative value was a project of Spring 2015 titled “Wave Extinguisher.” The project also received an ECE Innovation Award. The outcome of this project was a fire extinguisher that used acoustic waves to extinguish the indoor fire (see Figure 6). The application of this invention could find a place in household kitchens and, when used, would not damage appliances.

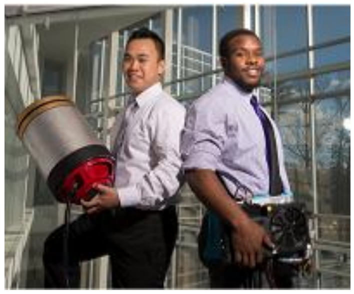


Figure 6. Fire extinguisher using acoustic waves

8. Interdisciplinary Projects Involving Students from Outside the ECE Programs

Interdisciplinary teams that include students from non-ECE programs is strongly encouraged by the College and by the University, but this is not an easy task, but it may bring rewards. The first truly interdisciplinary project was the 2018-2019 project titled "ASTERIA Project" that involved a team of fourteen students from the departments of Electrical and Computer Engineering, Mechanical Engineering, and System Engineering. The project was to design and test a payload of two experiments for a ThinSat satellite bus (Figure 7). The first experiment was to compare the performance of two power architectures in space. The second experiment was to test two different methods for battery shielding in space against large swings in temperature and specifically against freezing temperatures. After launch delays caused by COVID, our ThinSat, along with other participants in the ThinSat Program, was launched on 20th February 2021 on the Northrop Grumman NG-15 mission.


Figure 7. Team ASTERIA and their ThinSat

This first experience from such a larger-scale interdisciplinary project provided us with valuable feedback. Bringing students from four programs (three departments) into a single project was more difficult than expected. The first was managing the different requirements each program had for their capstone design requirements. The second involved scheduling, reporting, and deadlines. In the beginning, it was difficulty to bring together from different disciplines into a single team working together. During meetings, students from the same department sat together with little or no interactions between the groups. This pattern gradually changed during the second semester allowing for more open discussion and teamwork. It was satisfying to see that towards the end of the project, the team became one, albeit a bit late from a faculty perspective. This project opened a gate to more collaboration between the ECE Senior Design Program and other programs, most frequently with the Mechanical Engineering Program.

9. Conclusions

A few important take-aways from our long history of defining and refining our senior design project are, first, to emphasize projects That solve a larger-scale problem and are guided by top-down design principles. Second, allow for student-suggested projects but with sufficient scrutiny before approving them. Next, list and discuss the problems that were encountered by previous teams. Do this early, at the first meeting, so that the students understand where the difficulties lie. Another important take-away is to require teams to have a formal dry-run of their final presentation. This help improve the presentation skills of each team member, and gives them practice in formal presentations, a skill that will be very important for them as the progress through their career. Finally, give recognition to best projects by giving students an award in the form of a plaque that they can display in their office.

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