Capstone Courses: Why They Work and Why They Don't

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Abstract – For an engineering capstone course to be successful, several parties need to be involved: student teams, faculty, and practitioners. In this paper, the authors will discuss the benefits and disadvantages for those involved in a capstone course. The reported observations are based on the combined experiences of the authors, who have acted as capstone course instructor and mentor, engineering student employer, engineering practitioner, design course instructor, and judge of final capstone design presentations. Inherent differences between the university environment and professional practice are noted. The authors argue that, instead of departments being required to have capstone courses, they should focus on meeting the broader goal of integrating professional practice into engineering curriculum and should be able to decide how to accomplish this goal, with or without capstone courses.

Keywords: capstone course, civil engineering, senior design

INTRODUCTION

Description of a Typical Capstone Course

A typical civil engineering capstone course primarily serves to fulfill a department's program outcomes, which are usually based on recommendations of ABET, formerly known as the Accreditation Board for Engineering and Technology. ABET specifies general criteria for accrediting engineering programs. Criterion 3 contains 11 Program Outcomes that students must attain, such as an understanding of professional and ethical responsibility, an ability to communicate and to function on multidisciplinary teams, and an ability to design a system. Criterion 5 specifies curriculum requirements, namely the timeframe for basic math and science courses; the timeframe for engineering science and design courses; and a culminating "major design experience based on the knowledge and skills acquired in earlier coursework and incorporating appropriate engineering standards and multiple realistic constraints." Program-specific criteria for civil engineering programs require "design experiences integrated throughout the professional component of the curriculum, and an understanding of professional practice issues." To meet these general and program-specific criteria, it is understood that a "culminating major design experience" by way of a capstone course is required and heavily reviewed by ABET evaluators when a department's accreditation is being reviewed.

The capstone course is typically completed during a student's senior year. According to a national study [McKenzie, 4], 50% of projects last for two semesters and 31% for one semester. For 71% of survey respondents,

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grades are individually assigned based on integrated individual performance; 9% said the final grades are the same for all team members; and 19% use a combination of the two approaches.

In a typical course, the students complete a comprehensive design of a civil engineering project, where they plan the project from conception to design. The students transition from well-defined, short, narrowly-focused assignments to an open-ended, detailed, multi-faceted project that requires integration of knowledge and skills gained in multiple undergraduate courses and lifelong learning skills. The students work in teams, and each team typically is assigned to work on a unique project. In a 2005 survey [Todd, 5], 62% of survey respondents indicated that only one team is assigned to the same project; others reported that multiple teams are assigned to the same project.

Students are usually guided by industry and/or faculty mentors. According to Todd et al. [5], for 35% of the survey respondents, 1 to 20% of the faculty in a department are involved in capstone, and 30% of respondents reported that 20% to 40% are involved. Twenty-seven percent of departments employ one professor to instruct the entire capstone course. Faculty instructors' responsibilities include forming student teams, soliciting projects from industry, and supervising multiple student projects. [Dutson, 1]

A capstone project typically involves more than a single faculty member's expertise. Furthermore, for the projects to take on real-world "flair," it is extremely important that practitioners who are involved in design on a day-to-day basis be involved in the course. These engineers volunteer their time to guide and advise students. Many who have taught the course agree that, as reported by Dutson [1], peer reviews and input from an industry panel help with grading.

Almost all projects require written documentation. [Todd, 5] Ninety-four percent of instructors assess students during oral presentations, usually occurring multiple times during the course. [McKenzie, 4]

Recommended Best Practices in Literature

Lillevik [3] describes the advantages and challenges of and offers advice on best practices for teaching capstone courses, specifically with regard to team teaching. He acknowledges that "no one capstone design course will fit every institution's setting and environment." He notes several faculty challenges: different styles of interaction which affect students' learning experience; some advisors commit less time than others because it is not part of their teaching load; an advisor's technical expertise may not match that needed by the team; and faculty members have inconsistent expectations for different teams. Having industry practitioners involved can be challenging because they are not sure how hard to push the students or can disagree with the faculty advisor. Lillevik notes that the practitioner's motivation is an intrinsic reward. The instructor of the course is challenged with recruiting industry participation, applying consistent and equitable grading "across a widely varying set of students and teams," students acting unprofessionally in their interactions with industry, and "unfamiliar" grading rubric that differs from all other courses.

Lillevik's best-practice recommendations are to have industry involved because of the technical expertise they offer and to help ensure minimum standards; to have several required deliverables throughout the course; and for the faculty advisor to review documents before the students interact with industry, to prevent them from leaving bad impressions of the department. [Lillevik, 3]

As a result of a survey given to faculty members, practicing engineers, and students, the most important elements of a capstone course are "that the design experience be based on realistic conditions; that the students schedule the design activities; and that the products of the design include drawn plans, a written report, and an oral presentation." The least important factors are team size, requiring students to log activities, and peer performance evaluations. [Wilmot, 6]

Kuder and Gnanapragasam [2] advocate incorporating experimental, research-based designs into capstone courses.

Premise of Paper

The purpose of this paper is to provide dialogue on why capstone courses work and why they don't. There has been much research and literature regarding recommended practices for capstone courses – for example, with regard to method of instruction, evaluation techniques, deliverable requirements, recommended team size, etc. Strong support for capstone courses is evident in the literature, and it is well known (and feared) that ABET evaluators look carefully at how a department runs its capstone course. However, there are many aspects of these courses that do not approach professional practice, no matter how well taught or organized. There are inherent differences beyond the control of an instructor or department.

In this paper, the authors will discuss the benefits and disadvantages of capstone courses for the people involved: students, faculty, and practitioners. They will point out the differences between a capstone course and professional practice. In addition, a capstone course is unlike any other typical engineering course and can lead to inequality in terms of students' experiences and a department's chance of success. All departments may not be able to effectively provide a capstone course. Herein, the difficulties of running a capstone course are openly acknowledged.

The reported observations are based on the combined experiences of the authors; one of the authors has acted as capstone course instructor, and all three have acted as a mentor, engineering student employer, engineering practitioner, design course instructor, and judge of final capstone design presentations. Benefits and disadvantages of a capstone course to students will be discussed first; then to faculty; and, finally, to practitioners. The authors will make conclusions and recommendations.

STUDENT TEAMS

Benefits to Students

The students benefit from a capstone course in many ways. They learn to function on teams (or at least the difficulties of doing so), to understand professional and ethical responsibility, to recognize a need for lifelong learning, and to use (available) modern engineering tools. They learn to meet deadlines (usually), to adapt to the open-ended nature of design, and to prepare a (near) professional-quality submittal. They learn that design takes iteration, critical thinking, and decision making. By the end of the course, they likely communicate more effectively, both in oral and written form. Their speaking skills can greatly improve, especially when they have to present their design to a panel of practicing engineers and faculty, and when they are coached on oral presentation skills throughout the civil engineering curriculum.

Disadvantages to Students

On the other hand, the students can be, in many ways, disadvantaged while taking a capstone course, in terms of the core values being unavoidably mis-timed and disconnected from real practice. The students' main disadvantage is that they haven't finished their coursework at the time they begin the capstone course. Students take the majority of the required design courses during this same final semester(s); it is conceivable for students to go into the course having had completed zero or perhaps one design course. In this case, they are expected to learn theory while completing a comprehensive design project within the same semester. An authentic "capstone" course, in which students apply skills already learned in previous design courses, should be taken by students after all coursework has been completed. This, of course, would extend a student's studies by an extra semester, an idea which would be opposed by most people, faculty and students alike. The students would be better off spending that semester interning in an actual design firm anyway.

Although the course mimics a real design project that would be completed in a real office, there are several differences between the academic experience and a professional one. It takes a design office several months or years to complete a project, with experienced engineers, CAD technicians, and project managers working on it full time. A semester or two typically does not allow enough time for students to complete details to a professional level, no matter how high the instructor's expectations.

In addition, Quality Assurance/Quality Control in an engineering firm takes a substantial amount of time; for a capstone course, there is typically not enough time in the semester to do proper checks. Nevertheless, the students could learn the skills they need while they are on the job, in much less time. Notably, the amount of time spent on a typical capstone design project should be at most 150 hours (assuming 10 hours per week) -- the equivalent of less than a month on the job.

Another disconnect between a capstone course and real practice is that most firms have their own already-established methods for designing systems and components. Many designs done by engineers are similar to previous jobs, modified for the new project's requirements and constraints. A student will be able to learn how to use these methods and tools on the job, after graduating. While taking a capstone course, the students sometimes spend a lot of time struggling to develop these tools. If a student ends up practicing in a field that is similar to their design project, then developing these tools can be a benefit to the student. Unfortunately, though, some students work in a field upon graduation that is not related to their capstone project – which, in itself, is another disadvantage to students.

A final disconnect is that the student's commitment to a capstone project is short term, compared to a real project or employment. Undoubtedly, it is much easier for less-motivated students to rely on their better-performing teammates to "take up the slack" in a capstone course than in a real job. A student's motivation in a capstone course may often be to receive a good final grade; a real project, however, directly involves lives, money, and the engineer's career.

FACULTY

Benefits to Faculty

Faculty who are involved in the course by either teaching or mentoring get to see the students grow in their maturity and communication skills. Also, some capstone design projects prompt both students and faculty to solve problems outside the textbook domain. The course provides good opportunities for developing relationships between faculty and practicing engineers.

Disadvantages to Faculty

A capstone course offers many disadvantages to faculty. Frankly, most faculty aren't equipped to teach the course. Many don't have design experience. In most departments, there are a small handful of faculty members who would be able to manage such a course and provide practical guidance to students. This is not a criticism of faculty; it is an acknowledgement that research instead of practical skills often takes center stage in academia. Being multidisciplinary in nature, the course requires the instructor to be flexible and able to teach outside his/her area of expertise. This course has demands unlike any other course.

Correctly and thoroughly overseeing design projects takes an inordinate amount of effort and time. Faculty who teach such courses do not get "extra credit" towards promotion and tenure.

For any other course, faculty can feasibly prepare a lecture or example problems to give to all students in the class, even if the class has large student enrollment. In a capstone course, however, students are all working through their individual thought processes on unique, full-scale design projects. The instructor becomes akin to a project manager in a design firm, except that he is overseeing an office full of entry-level engineers (in fact, pre-entry-level), all of whom are working on different tasks -- requiring a high degree of mentoring on the part of the project manager. A capstone course is very difficult to "teach"; it is a management challenge.

A capstone course cannot realistically be taught without multiple faculty and practitioner involvement, especially when so many civil and environmental engineering projects are multidisciplinary and require expertise in many areas. These projects require working knowledge of current codes, specifications, and regulations, which are used almost daily by practitioners. If 50-60 students take the course in a given semester, there will be 12-15 teams to oversee – and twice that many over a year-long period. The instructor is often left to his own devices to search the community for volunteers; this is a difficult position to be in. For large departments in small communities, dozens of volunteers are needed but may be difficult to find.

PRACTITIONERS

Benefits to Practitioners

Practitioners can be involved in a capstone course by donating and/or overseeing a design project, mentoring students, or guest lecturing. Although the practitioners likely give more than they get, the course can benefit them. Many of them enjoy mentoring. For alumni, the course gives them the opportunity to be active with their alma mater. Some firms that mentor students in the course use this as a "trial" and then hire whom they see fit after graduation.

Disadvantages to Practitioners

Practitioners usually have limited time that they are available to help. Mentoring students cannot be billed to a client, so their time is voluntary. In addition, they are not always familiar with the knowledge level of the students. Also, there can be conflicts between firms, such as when a mentor/firm donates a project, but the students who want to work on the project work for a competing firm. Most engineers will tolerate this, except when the project itself is sensitive. Also, when practitioners mentor students who don't meet their expectations, they can feel frustrated or unimpressed by the department as a whole – which is a disadvantage to the department.

FURTHER OBSERVATIONS

How the University Environment Differs from Practice

The university cannot provide support that is equivalent to what can be provided in a design office. Even help from practitioners who donate a few hours during a semester does not compare to the day-to-day support that an entry-level engineer receives in the office.

The atmosphere and resources that are available at the job are appropriate for the tasks that need to be done. A design firm will purchase the best tools that are needed to complete a design project; these tools are often specialized or created in-house. Typically, firms develop efficient methods to, for example, make calculations or create a set of drawings. Reuse of specifications from project to project is an excellent example, also; it would be an inefficient use of students' time for them to create a set of specifications from scratch.

Team dynamics at school are different than those in a work environment. At work, employees have more incentive to be good team players, especially if they want long-term employment with the firm. Students, however, are at the end of their academic careers. On the other hand, they can use the capstone experience and/or portfolio to help obtain an entry-level job.

Inequality Among Schools

For typical engineering courses, the faculty at any given university or college stand about the same chance of teaching their students design principles. They have the same resources to use (e.g., textbooks), and the theories and codes are the same no matter what the geographic location of the school. The "notes" given by the professor and the problems worked in and outside the classroom are essentially the same, even if the methods of delivery are vastly different. To prepare students to practice engineering, a profession that thrives on some measure of uniformity, consistency, and reliability, requires that the basic content of undergraduate courses be kept similar and intact. Capstone courses, however, do not always provide equal opportunity for an enriching student experience. For example, large cities typically have more engineering firms nearby than smaller cities; therefore, greater chance to provide interesting design projects and mentoring is available. (Inarguably, universities are distinguished from each other because of their differences and individual faculty members' strengths; the uniqueness of graduate programs and research specialties are, and should be, celebrated).

Inequality Among Students

The goal of a capstone course is to have students perform a complete engineering design, while making decisions and engaging in life-long learning. For this to happen, the project should be unique, in that it has not been completed by former students. In a large class, e.g. with 30 or more students, several mentors are needed so that all students receive support on practical issues. Because of mentors' different experience levels, personalities, and available time, there is a large amount of variability in the quality of the mentors' help; some students can be guided every step through the design, while others can be given vague information. The course's fairness – which an instructor strives to assure – is out of his control when mentors are involved, particularly when different mentors help different students in a given class. Additionally, some students have the benefit of interning for a design firm, where they can get assistance or use a real project for their capstone course project; other students do not have this benefit. Finally, hardworking students who are teamed with weaker students can be hurt in the long run because of the extra effort they give in order to compensate.

Questions That Need to be Asked

- What are the learning goals of the course? Should the instructor "teach" comprehensive design, or is the purpose to "evaluate" whether or not the students can complete a project?

- What do the students need to learn in the course that they cannot learn elsewhere (on the job)?
- Can the students learn these things in a different venue as well as or better than in a capstone course?
- A capstone course by nature is the primary tool for assessing if a student can combine principles learned in multiple other courses. If the instructor deems the student to be not so good at this, what is the consequence? Should the student be required to repeat courses? Furthermore, if his teammates have compensated for his lack of abilities, the instructor may never know.
- Are young engineers today less prepared than young engineers were two or three decades ago?

Experienced engineers can be critical of graduating seniors, questioning whether or not they have had proper preparation for the workplace. In defense of the students, they are faced with more challenges than engineers who graduated two or three decades ago. They must learn the same theory; to use modern tools than can be daunting for even the most experienced engineer – especially those who practiced during the pre-computer age; and to meet expectations of more efficient, faster design in a global, competitive economy. The point is that a capstone course cannot substitute for on-the-job training, where an engineer builds long-term working relationships with co-workers, on real projects that have lives and resources at stake.

The irony is that many practicing engineers who believe that capstone courses should be required have never taken such a course, nor have they had to teach one. One can argue that those same engineers do their jobs quite well; their success is not in spite of not having a capstone course -- it is because they have practiced the art of design. Some experts say that it takes on the order of ten years or 10,000 hours for a person to become an expert in any field. A capstone course, even if highly effective, gets a young engineer no closer than 1% towards that goal (based on the equivalent one month of experience that the course provides).

The purpose of this paper is not to argue that capstone courses cannot provide a meaningful experience for students. The intention of such a course is to help make the students better practitioners. However, years of practice cannot be replaced by one college course. There are other ways of meeting the educational goals, and departments should be able to decide how to best use their available resources to meet these goals.

CONCLUSIONS AND RECOMMENDATIONS

Engineering programs should be encouraged to focus on *preparing* students' *minds* and *attitudes* for the practice of engineering. Students should understand professional identity, understand the role of an engineer, appreciate engineers at all levels and non-engineers who have roles in an engineering project. To teach this, departments could offer a course on the front end of design courses, rather than on the back end. If coaching on oral presentation skills, proper engineering documentation, etc. is given *before* students take design courses, then they will be able to repeatedly practice these skills in those design courses.

Realistically, there is a maximum amount of credit hours that can be required for an engineering degree; each credit hour (i.e., each course) is precious. The time should be spent teaching students to understand the personality and mindset of good engineers, the importance of commitment to the profession, and behaving ethically.

Instead of enforcing engineering analysis, design and professional issues in a "capstone design" course, perhaps the focus should be on the broader goal of "integrating professional practice within the curriculum." Engineering programs should be allowed to decide how to best accomplish this.

The authors feel that it is important for students to be exposed to practical design issues. Faculty who are comfortable with everyday design and are familiar with professional practice issues and regulations, codes, etc. will – and do – naturally incorporate this into their courses. In other words, they are not *more likely* to do so in a capstone course or when mentoring individual student groups. In this sense, having a capstone course is often seen as a way of filling the gap of integrating "real" design into a curriculum, and, therefore, is jumping ahead a step. Professional skills should be integrated in as many courses as possible; this way, students can get *repeated* practice.

Most of the technical and nontechnical aspects that are learned in a capstone course can certainly be learned on the job. At the college, time is better spent teaching the knowledge and skills that otherwise are not taught on the job, after graduation. Degree requirements are typically 126 to 128 credit hours – much less than the requirements of a decade or two ago. Therefore, because they are limited, it is important that these hours be treated carefully.

Required courses should cover theory and principles that cannot be easily learned on the job. Most of the capstone course content – that is deemed valuable because it is transferrable to the workplace after graduation – is non-technical in nature: teamwork and communication, for example.

One advantage of a capstone course is that a student's strengths or weaknesses in these areas are brought to the surface for all (faculty, classmates, mentors) to see. Whether or not the students actually improve in these areas is subject to debate and would require subjective study. The authors' experience is that the students' presentation skills improve, mainly because of repeated practice throughout the curriculum and because professionals – strangers with a lot of knowledge – are there to judge them. Other skills (organization, getting along well with others, inquisitive nature, etc.) are already far engrained in the student and are more likely to be improved with years of real-world experience than with a capstone course.

Having faculty who have design experience and/or licensure is important. Offering a capstone course does not help achieve this goal; other steps should be taken to encourage this. If faculty have experience or close connections with those who do, then that will benefit students in any classroom – in *any* design course – i.e., a capstone course is not the only way for faculty to transfer practical knowledge to students.

In lieu of a capstone design project, students could be charged with the task of reviewing actual professional, completed design drawings so that they can see the details involved in a project. One of the most valuable assignments that a student or entry-level engineer can complete is quantity calculations that are based on a set of design plans; by completing such a task, one can learn to read design plans and gain a better understanding of details and how components fit together in a project. Using already-completed projects as examples in guided exercises can provide valuable learning opportunities on practical issues, such as constructability and shop drawings.

With regard to making presentations, "perfect practice makes perfect." Students should be taught presentation skills before they enter their design courses so that they can practice these skills in all or several of these courses.

Departments could be given the *option* to offer a capstone course; if they were, then a well-run capstone course could be a unique feature of the curriculum. Otherwise, departments could instead offer hands-on experience or extensive labs, service learning opportunities, undergraduate research experience, internships, or innovative instruction techniques. There seems to be no one-size-fits-all solution for ways of handling capstone courses; perhaps other opportunities could be offered to students.

Departments could offer a capstone course as an *option* to students, perhaps for those who want to "try out" a specific discipline such as structural or geotechnical engineering before entering the workforce.

Students should be prepared for the idea of iteration and decision-making early on, before they take design courses. This will enrich their non-capstone design course experience.

Practitioners can be just as helpful, if not more so, by being involved in other, non-capstone, courses. They would be more likely to volunteer to help if their commitment were over a period much shorter than a full semester or year; their time would be well-spent by sharing their ideas and experiences by giving one or two lectures on a given subject in their field of expertise. Another benefit of involving practitioners in this way is that *all* students in the course would benefit, not just those who are being directly mentored by the practitioner as is the case in a capstone course.

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