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Vertical Integration of the Capstone Experience to Facilitate Undergraduate Research

A two-semester capstone in mechanical engineering was transformed through the vertical integration of topical themes and multi-year teams into an integrated series of courses in engineering design. The integrated sequence is composed of five courses, one each in the spring of the freshman, sophomore, and junior years, followed by the two-semester capstone in the fall and spring of majors' senior year. In addition, a freshman engineering course offered in the fall semester has evolved into an informal sixth course in the integrated sequence.

Project-based learning (defined here as learning related to both research and engineering design), a common software package, and professional skills are emphasized throughout the sequence of courses. Teams are vertically integrated with seniors leading teams composed of undergraduates at all levels working on common projects. Courses within the integrated course sequence provide scaffolding for the development of skills that all mechanical-engineering students need to be productive members of the vertically integrated teams. The course sequence facilitates the effective conduct of projects in undergraduate research or engineering design by allowing students to develop technical and professional skills through multiple opportunities to learn. Students have six sequential opportunities to develop their writing skills though the preparation of proposals and reports, six opportunities to develop their oral-presentation skills through the defense of their work, six opportunities to perfect their professional skills (such as effective teaming, project management, and leadership) through their experiences both good and bad, and six opportunities to develop expertise in their technical field through the application of project-based learning.

Because students can work on the same project over multiple years, a real strength of the integrated sequence is that students can work on more complex research and design projects and can be more productive than is possible for students in a typical two-semester capstone, because experience with the project is retained in the team even after the seniors graduate.

The integrated course sequence is unusual in that all courses within it are degree requirements, two of the courses satisfy the senior capstone requirement, and the sequence is required for all students in the program. Examples of this type of vertically integrated teams approach to research are limited. Coyle, Allebach, and Krueger (2006) describe the use of such teams in the Vertically-Integrated Projects (VIP) Program originally at Purdue and currently at Georgia Tech. In that model, teams composed of sophomores through seniors, masters students, and PhD students work on a faculty member's research program. The VIP program differs from the current University of Evansville program in three ways: freshmen are not included in the teams, students may apply the courses within the program for credit toward unrestricted electives instead of the capstone experience, and the program is optional and not a degree requirement.

Undergraduate research has also been conducted in two-semester senior capstone courses at other institutions (e.g., Schneider 2002; Ford, Bracken, and Wilson 2009). While these courses are required of all students within the programs, they differ from ours since they do not include undergraduates other than seniors on the research teams. Our integrated model appears unique in its ability to offer to all students a project-based or research-based learning experience using vertically integrated teams as part of a degree requirement.

Vertical Integration of the Capstone

In the first semester of their freshman year, mechanical-engineering students take the three-credit cornerstone course, Introduction to Engineering (ENGR 101), which meets for one hour three days a week. Student teams learn the engineering-design process through designing, building, and testing a pneumatically powered ball launcher. Lectures provide the theoretical material allowing students to mathematically model a team's unique design for the ball launcher, introduce the students to professional skills—for example, managing their project, forming effective teams, and understanding professional ethics—and introduce students to NX, a solid-modeling software program developed by ANSYS, Inc.

The actual first course in the integrated course sequence, Integrated Design I, is a two-credit class offered in the spring semester of the freshman year. Lectures focus on the design process and workshops teach students manual machine-shop fabrications skills that will be useful for senior-led projects. Students continue to develop their solid-modeling skills using the NX software for graphical communications. The sophomore course, Integrated Design II, is a two-credit class that teaches students about computer-aided manufacturing and expands their understanding of the ANSYS suite of software for rapid prototyping and numerically controlled milling and lathing. In the three-credit, junior-year course, Integrated Design III, lectures cover the design of experiments and instrumentation and measurement techniques. They also introduce the students to LabVIEW, software developed by National Instruments Corporation for automatic data acquisition. The course's labs reinforce the lecture material through progressively more complex measurement projects, and students may then apply their data-acquisition skills to senior-led projects.

The last two courses of the integrated engineering-design sequence make up the actual senior capstone, Professional Practice I and II. The centerpiece of the capstone is a two-semester project that focuses on research for students interested in pursuing graduate school or an engineering-design project for students who intend to seek employment directly after graduation. Professional Practice I is a three-credit class in which lectures focus on professional skills, such as project and time management, effective teaming, professional ethics, and leadership skills, to help seniors lead non-seniors in successful projects. Workshops reinforce the lectures. Professional Practice II is a three-credit class that allows students to implement their recently acquired professional skills.

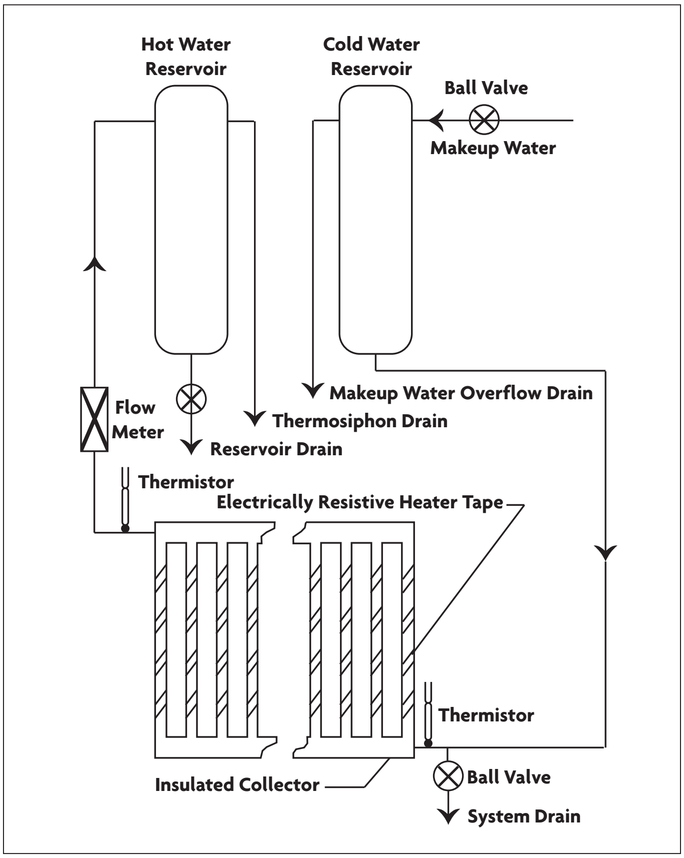
All the courses in the engineering-design sequence teach engineering through project-based learning. In addition to the lectures and labs, students work on one large project and sometimes smaller projects each semester. Communication is a focus that is integrated into all courses through the students' writing of proposals, design reports, and final reports, as well as students' defenses of their work through oral presentations. The use of common software packages is consistent throughout many of the courses and provides a skill set for non-seniors. Finally, professional skills are taught in the cornerstone and capstone courses and practiced in the remaining courses.

Seniors are required to form vertically integrated teams, although there is no specific requirement that every undergraduate level be represented. Seniors informally begin to identify projects and form teams near the end of their junior year. Seniors may add non-seniors during the beginning of the fall or spring semesters. Seniors are encouraged to add sophomores and juniors to their teams in the fall since this promotes buy-in during the formative stages of the project and yields more-motivated team members. Since the non-seniors are not enrolled in the integrated design course in the fall, their efforts are documented in weekly progress reports and hours applied to their spring course. Seniors must wait until spring to formally add freshmen to their team since first-year students are already performing a project for their fall semester's Freshman cornerstone course. However, freshmen may participate voluntarily in team meetings in the fall, which encourages their buy-in for the project.

Freshman and sophomore team members are expected to put 60 hours into the senior-led projects, while juniors and seniors are expected to put in 45 and 250 hours, respectively. In any given year, not all of the non-seniors participate in senior-led projects. Due to attrition within the engineering program, there are significantly more underclassmen available for teams than there are seniors to manage them. Early in the program, an attempt was made to place all non-seniors on senior-led teams, but this was generally counterproductive. Throughout the life of the program, non-seniors not placed on senior-led teams have worked on projects of equivalent length and effort, either with teams composed of students within their own course or of students drawn from two courses, notably sophomore-led teams composed of freshmen and sophomores.

The types of senior-led projects in the integrated course sequence are the same as were performed in the capstone

Figure 1. Schematic of a Thermosiphon



courses in the past. Since the majority of seniors plan to go to work directly after graduation, most of the projects focus on engineering design, such as industrially sponsored projects, service-learning projects, or regional or national competition projects. However, students who are interested in pursuing graduate school often work on research-based projects, which made up one-third of all of the projects during the 2013-14 academic year. Students working on these projects perform academically oriented research activities that are somewhat different from the typical engineering-design projects. The students are expected to perform a comprehensive literature review, identify an appropriate research topic and scope of research in conjunction with their faculty advisor, and develop a test matrix to achieve their research goals. They are encouraged to publicly disseminate their work at a conference.

A current research project to study the efficiency of thermosiphons illustrates how the vertical integration of the capstone course can be used to facilitate undergraduate research. A thermosiphon can be used to convert solar energy into useful thermal energy, which is typically used to assist in residential or commercial hot water heating. A typical thermosiphon consists of a collector composed of thermally conducting pipes attached to an absorber plate and contained in an insulated box with a glass cover, a reservoir situated above the collector, and interconnecting pipes similar to that shown in Figure 1. The thermosiphon used in the current research project and shown in Figure 1 differs from a typical thermosiphon in two ways. As shown in the photo (cover), electrical tapes are wrapped around the collector's vertical pipes to provide a controlled input of heat for testing purposes, as compared to the heat input from solar energy, and an open system with two reservoirs is used to simulate a perfectly stratified reservoir that supplies a flow of water at a constant inlet temperature.

In 2012-13, a team was formed to investigate the effect of attachments to the collector to reduce heat loss due to wind, which would improve the efficiency of the thermosiphon. The team was composed of one senior, four juniors, and four sophomores, all of whom were mechanical-engineering students. Besides leading the team, the senior designed the thermosiphon and a simple wind tunnel to control the airflow over the collector; the sophomores used their shop-fabrication skills to construct the thermosiphon and wind tunnel; and the juniors used their data-acquisition skills to help run the experiments and collect data. The senior then analyzed the data and presented the results at a regional conference (Omere 2013).

One of the juniors and one of the sophomores from this team wrote a proposal in the spring semester for further research during the summer and received a stipend and hardware budget from the university's undergraduate-research committee. Because of the research they had done the previous academic year, the sophomore and junior were able to modify the equipment and obtain meaningful results in only 10 weeks.

Although last year's senior graduated and is pursuing graduate studies, the collective knowledge of the research project is not gone. Many students from last year's team were interested in conducting additional research this year, demonstrating one real strength of the vertically integrated capstone. The 2013-14 team consists of three seniors, all returning from last year's team and two of whom are planning to pursue graduate studies; and four juniors, two of whom were on the team last year. With their experience from last year, the team completed a more in-depth study and their work was more complex than last year's team.

Table 1. Student Evaluations of Integrated Engineering-Design Courses

	Useful for Design Work in Other Courses (%)	Developed Appreciation for Other Courses in Discipline (%)	Positive Impact on Resolve to Continue Engineering (%)	Promoted Further Interest in Discipline (%)
Freshmen	55	76	90	93
Sophomores	55	85	100	100
Juniors	75	79	86	96
Seniors	74	74	81	77
Aggregate	65	77	85	90

The results show the percentage of students who responded with an "agree" or "strongly agree" to each of the four questions listed in the column headings.

Evaluation of the Integrated Engineering-Design Sequence

The revamped course sequence was evaluated in a survey using a five-point Likert-item questionnaire. Responses were obtained from 110 freshman through senior mechanical-engineering students in 2013. The students were asked to evaluate the impact that the integrated-design courses had in four areas using the following scale: 1-strongly disagree, 2-disagree, 3-neutral, 4-agree, and 5-strongly agree.

The results show that a large majority of students found that the integrated course sequence was beneficial to them. The results in Table 1 show the percentage of students who responded with an "agree" or "strongly agree" to each of the four questions listed in the column headings. As noted in the last line of the table, the aggregate results from all respondents showed that 65 percent of the students felt that the sequence was useful to design work they had performed in other courses, 77 percent said that the sequence developed further appreciation for other courses in their discipline, 85 percent said that the sequence had a positive impact on their resolve to continue in engineering, and 90 percent said it promoted further interest in their discipline.

Students were also asked to describe how the project-based course sequence aided in improving their understanding and application of the design process. It is apparent from the comments from students in each of the four undergraduate years that the course sequence is instrumental in helping them learn course material. For example:

- "It showed how the process worked, instead of telling us how." (freshman comment)
- "Has allowed me to understand the information learned in other classes better by application and testing." (sophomore comment)
- "It has been essential in learning to apply class material in a real-world scenario." (junior comment)
- "It showed me how to use the tools I learn in the typical courses. This sequence of classes, including Engr 101, has also shown me what this line of work is like in the real world." (senior comment)

Discussion

Although I have been discussing a mechanical-engineering program, no obstacles have been identified that would preclude the vertical integration of capstone courses in other disciplines. No internal or external funds were required to modify the curriculum in order to integrate the capstone courses. Of course, funds are required to support the projects, but a solution to this problem presumably already exists in any current capstone course. No new courses were developed (although existing ones were modified), and no additional credit hours were added to the major. No additional faculty or staff members were required.

The simplest approach to vertically integrating the capstone courses is to select existing courses, one each from the freshman through junior levels, that already teach skills that can be used as the scaffolding that allows non-seniors to offer needed skills to senior-led teams. Each course of the vertically integrated sequence must provide a skill that will be generally beneficial to all senior-led teams. For example, in our sequence, students learn solid-modeling software, shop-fabrication techniques, computerized numerically controlled processes, rapid prototyping, and data-acquisition techniques and software—all skills that find general applications in all projects. Students requiring skills that are more project-specific often develop those skills through a senior mentor. A research-based project must be introduced as a component of the selected courses. The only modification to the capstone courses would be to require vertically integrated research teams, if research projects were already a component of the courses.

A vertically integrated capstone sequence is scalable with appropriate sizing of teams and course sections. Teams within the integrated engineering-design sequence typically contain between five and 20 students, and course sections usually have between 15 and 30 students. Vertically integrated teams are typically larger than senior-only teams because the non-seniors are not expected to work as many hours as the seniors. Detailed breakdowns of necessary tasks are done for every project. Each member of a team selects tasks from the list and works with the student project leader to establish how long it will take to complete the task. Team members report the time spent on each task every week in a progress report. The quality and quantity of a team member's work is compared to the estimated and actual time taken to perform the work. Team members assess every other team member's performance at the end of the semester, and the assessments are factored into the students' course grades.

Teams require faculty advisors, who are typically the instructors teaching the integrated-design sequence. This usually results in approximately two senior-led teams per faculty instructor, which is a scalable model for any size program. There are approximately 140 students in the mechanical-engineering program at the University of Evansville. Faculty members teaching the integrated courses select projects that are most closely aligned with their technical expertise and work as faculty advisors to the teams throughout the year. Students may ask other faculty for help if the issues are outside the faculty advisor's area of expertise.

The capstone course's instructor reviews the work of all senior-led teams and is responsible for working with other faculty advisors who have reviewed the work of their individual teams to establish grades for senior-led teams. The grades are then shared with the instructors from all of the vertically integrated courses and used as components of the non-seniors' course grades.

During the 14 years following the implementation of our integrated course sequence, we have identified several best practices based on the following lessons learned:

- It is beneficial for all of the courses in the integrated sequence to meet at a common time to facilitate presentations or coordinate activities,
- Course sections must be sized so that there are approximately two teams per section on average. If course instructors are used as faculty advisors, it is difficult for them to provide adequate oversight to three or more student projects,
- Teams should submit weekly progress reports to the faculty advisor that document each student member's progress compared to the established timeframe and hours expended on the project,
- Each team member should evaluate all other team members in a confidential performance assessment based on what was expected of each member. The assessments are used by the course instructor for assigning a portion of the student's grade,
- Teams should have the ability to fire a significantly underperforming team member based on appropriate documentation and after consultation by the course instructor with all team members,
- Team size should be based on the complexity of the project and not some predetermined number of students at each undergraduate level. This ensures that the teams are right-sized and that seniors can manage the non-seniors,
- Non-seniors are most productive and have a more meaningful experience when assigned a willing senior mentor from the team,
- Non-seniors are most productive when they can work on a project in the same location as senior team members, even if they are not working on the same topical area, so that they can get guidance when needed,
- Selecting the right number of seniors on a team is an art that, if mastered, allows the seniors to accomplish the required technically intensive tasks while still forcing them to rely on the non-seniors for meaningful work to complete the project, and
- Non-seniors are encouraged, although not required, to join senior-led teams in the fall semester to help them develop ownership in the project, thus becoming more motivated and productive members of the team. Some teams offer probationary team membership to non-seniors to evaluate their performance and determine if they will offer full team membership in the spring.

Conclusion

The integrated engineering-design sequence, coupled with our freshman engineering cornerstone course, offers all students communication-intensive, project-based learning in a collaborative environment in their freshman year. This experience is then extended through the sophomore and junior years until it culminates with the capstone experience in which seniors lead multi-year teams that focus on a major engineering-design project. This sequence is consistent with four of the ten recommendations from the Boyer report (Kenny 1998), which was originally written with research universities in mind. However, Hu, Kuh, and Gayles (2007) determined that students share the same frequency of inquiry-based learning across all institutional types, and Healey (2009) argued that recommendations from the Boyer report apply to all universities. Recommendations in the original Boyer report were acknowledged to be useful to all universities in a follow-up study by the same commission (Kenny *et al.* 2001).

The five-course design sequence and the freshman cornerstone course offer students six sequential opportunities for project-based learning, intensive writing and oral presentations to defend their work, and the acquisition of technical and professional skills that provide scaffolding for non-seniors to become productive members of senior-led projects. The vertically integrated teams also retain their collective knowledge from one year to the next, thus allowing for more complex topics and productive teams to facilitate undergraduate research.

A large majority of students indicated in a recent survey that the integrated course sequence was useful to the design work they had performed in other courses, helped them to further appreciate other courses in their discipline, promoted a further interest in their discipline, and had a positive impact on their resolve to continue in engineering.

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