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From Capstone to Cornerstone: A New Paradigm for Design Education*

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This paper proposes a new role for the traditional capstone design course that culminates many undergraduate engineering curricula. We envision the outcome of the capstone experience serving as the cornerstone for an integrated sequence of design projects throughout the curriculum. In this paper we describe the benefits of this approach to students, faculty, the university, and industrial clients. While this paper describes how this transformation could be accomplished in the Mechanical Engineering Department at the University of Washington, we believe that it has similar potential in other departments and universities.

INTRODUCTION

ACCREDITED undergraduate engineering curricula in the United States must culminate . . . 'in a major design experience based on the knowledge and skills acquired in earlier course work and incorporating engineering standards and realistic constraints . . .' [1]. This major design experience typically takes the form of a capstone design course whose duration varies from one academic quarter to an entire academic year, depending on the campus [2]. Many capstone design courses involve professional engineers as sources for project ideas, sponsors of projects, clients that interact with students, and evaluators of student performance [2–6].

While this industry involvement adds an important sense of realism to design education, there are two major shortcomings to this approach to capstone design. First, since the capstone experience occurs in the last quarter(s)/semester(s) of the curriculum, students who have not reached that point have no advance appreciation for the nature of capstone design. Pre-capstone design education, even though it may include short project-type activities, does not give students an adequate sense of the scope and dimensions of professional design practice.

Second, while most students perform impressively under these circumstances, and truly value the opportunity to engage in a realistic design activity and to interact with engineers from industry, the experience does not usually lead to a successful closure to the design experience. A key reason for this lack of closure is that many students graduate as soon as the capstone design project is completed, so there is no opportunity for them to participate in follow-up design refinements, implementation efforts, or commercialization. Thus, while design process models universally stress both the iterative nature of design and the importance of the complete design life-cycle, most capstone experiences are terminated before the students can experience either of these phenomena.

Efforts to deal with these shortcomings include expanding pre-capstone design experiences [7–11] and restructuring curricula to provide the students with a more integrated set of design experiences [12–14]. However, these efforts can encounter many pedagogical and institutional difficulties. The approach to design education described herein advances incomplete industrial-sponsored capstone projects through the remainder of their design life-cycle and simultaneously provides students with an integrated sequence of pre-capstone design experiences. In addition, the concept can be implemented without requiring major curriculum changes or significant new faculty resources.

PROPOSED APPROACH

This paper advocates using the results of capstone design projects as the cornerstone for project activities in other design-related courses, thereby transforming those courses into an integrated sequence of design experiences for students. To accomplish this, the proposed approach uncouples a student's design education chronology from the chronological progression of a capstone design project through its life-cycle.

Under the framework described in the paper, the post-capstone evolution of a typical design would move through the following stages:

> Market and commercialization analysis → Design documentation → Production of prototype(s) → Product testing → Design refinements

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The design refinements stage will then launch further iterations beginning with design documentation until the design matures. At maturity, the design will either be implemented by the industrial sponsor or manufactured by a licensee. Some designs may not need to move through every step in this sequence. This could occur if that step was already accomplished as part of the capstone activity. Or the project may be intended as a one-of-a-kind turnkey installation for an industrial client with no commercialization goal.

Candidate courses

Each of these post-capstone stages would be undertaken as a student project activity in a non-capstone design-related course. The specific courses that can form such a sequence will depend on the department and university, but we argue that there are many such opportunities. Seven courses (in addition to the capstone course) that are candidates for inclusion in this sequence at the University of Washington are described in this section. Their role in the post-capstone design evolution stages are depicted in Fig. 1. The dashed lines in Fig. 1 represent feedback loops.

1. **Capstone design.** This existing course for seniors provides the foundation or cornerstone for the new approach to design education. Many of our current capstone design projects have industrial sponsors who define the project and establish the design criteria and success parameters. In most situations, the students develop innovative and functional designs. However, these designs are rarely commercialized or fully implemented by the sponsor because the students graduate immediately after completing the course and there is no systematic mechanism for follow-on work.
2. **Engineering entrepreneurship.** This is an existing course for seniors in industrial engineering. Students (in collaboration with the University of Washington's Office of Technology Transfer) will take the most promising designs from Course 1, conduct market analyses and develop commercialization plans. The results will help identify the refinements needed to enhance commercial potential and fully meet the sponsor's business design parameters or criteria.
3. **Engineering graphics.** In this existing course for freshmen, students learn principles of engineering graphics and use CAD software to produce two- and three-dimensional drawings of engineered products and systems. If designs generated in Course 1 are not fully documented, additional drawings will be produced by students in this course. As designs are subsequently refined, updated drawings will be generated by the students in this course.

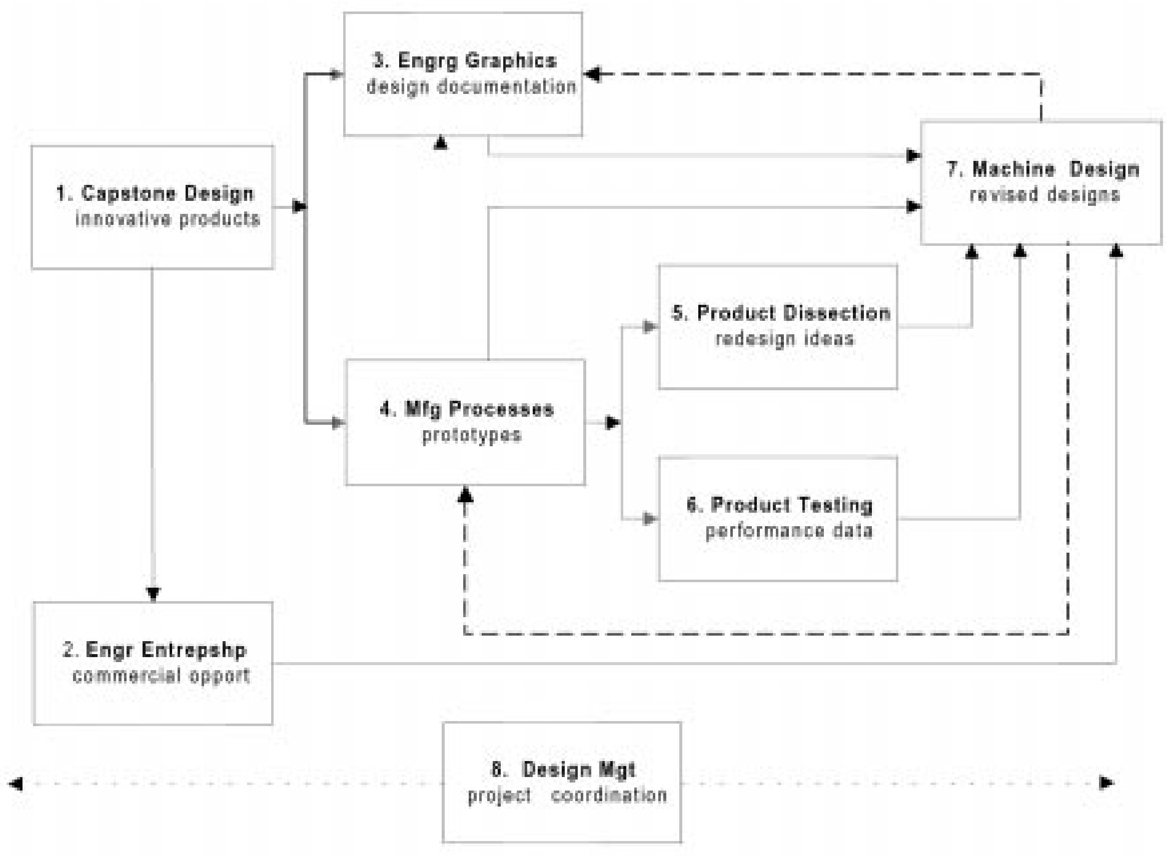

Fig. 1. Post-capstone evolution of design projects.

4. **Manufacturing processes.** This is an existing junior-level course covering manufacturing principles and practical skills in machining, casting, welding, etc. The only change required will be that the product selected for the term-long project will be the product previously selected from among the product ideas generated in Course 1. The output of this course will be sufficient prototypes for display, testing, disassembly, for reference in other courses in the sequence, and for presentation to potential licensees.
5. **Product dissection.** This is an existing sophomore-level course in which students take apart products to identify the underlying design principles and to explore ideas for design improvements. The only change required in this course will be that the product dissected will be the prototypes produced in Course 4. The output provides a basis for redesign activities in Course 7.
6. **Product testing.** This will be a new senior/graduate course. Students will design and implement a testing protocol on the product design that emanated from Course 1 to determine if the design meets the sponsor's criteria. The tests will be conducted on one or more of the prototypes produced in Course 4. The test results will serve as the basis for design refinement activities in Course 7. Development of this course will address issues such as availability of test facilities and instruction in relevant topics such as design of experiments.
7. **Machine design.** In this existing course for juniors, students learn design principles for fasteners, gears, bearings, shafts, seals, etc. The only change required is that the design projects will be associated with the design developed in Course 1. Input will be the design improvement ideas, documentation, prototypes, and test results from Courses 2–6. Outputs are revised designs that either fully meet the sponsor's criteria or spur the next design cycle beginning with refined prototypes in Course 4 and updated documentation in Course 3. The design cycles will continue until the design has matured. Then, focus switches to another design developed in Course 1.
8. **Design management course.** This graduate-level course will provide the project planning, oversight, and coordination needed to ensure that the activities described above are completed. Essentially the students enrolled in this course will be the liaisons with students and faculty in Courses 2–6, providing some of the supporting role traditionally provided by teaching assistants. In addition, the course will cover project planning techniques, concurrent engineering, product realization principles, requirements of ISO 9001, etc.

Student progression through the post-capstone sequence

Chronological progression of our students through such a sequence is shown in Table 1:

Table 1. Student progression through the proposed design sequence

Engineering graphics → Product dissection → Manufacturing processes → Machine design → Product testing → Capstone design → Technology-based entrepreneurship → Management of engineering design

This sequence is typical; not every student will participate in every step, and some students may modify the order in which they participate in the steps. Four of the existing courses are currently required; two of the existing courses and the proposed new course will be electives. Further, since more than one project may be moving through its post-capstone evolution at the same time, an individual student may not necessarily experience every step with the same project.

BENEFITS OF NEW APPROACH

Using the results of the traditional capstone design project course as the foundation for project activities in seven other courses yields many benefits to students, faculty, the university, and industrial clients. We examine the benefits to each of these constituencies in this section.

Benefits to students

- Entering engineering students will associate with a design that will continue to be the focal point of their subsequent design education. This will add an important touch of realism to their pre-capstone design education, give them a sense of ownership in the design, and instill pride in contributing to solving a real industrial problem or designing a commercially successful product.
- As students progress through these courses, they will engage in a series of focused and interrelated design experiences involving the various stages of the life-cycle of a specific design. They thus will learn the various phases that projects and products go through before becoming fully mature. These experiences will serve as a unifying theme to tie together courses that normally are perceived by students as unrelated. This will provide students a much enhanced sense of continuity to their education.
- By integrating these courses into a cohesive and continuous set of design experiences over a four-year period, the increased understanding of the big picture goes beyond the increased understanding provided in each course.
- The post-capstone sequence builds bonds among students across class lines, providing

many opportunities to establish student-to-student mentoring relationships.

Benefits to faculty

- The coordination needed among faculty to make the new integrated curriculum successful will build a greater sense of community and esprit de corps among the faculty.
- The availability of the post-capstone activities for projects in non-capstone courses will reduce the faculty effort needed to identify and develop design projects for those courses.
- The students in the graduate-level design management course will serve as resources to the instructors teaching the undergraduate courses involved in the post-capstone design evolution sequence. These students can relieve the faculty of some of the load associated with supervising the design project activities in those courses.

Benefits to the department and university

- Prominent displays of successful designs and their evolution (in departmental hallways and at Open House and Engineers Week exhibits) will capture the interest of students from other departments, K-12 students and teachers, and the general public. This will increase understanding of mechanical engineering and motivate youngsters to consider careers in engineering.
- Increasing the number of fully implemented or commercialized designs will increase the opportunities for the department and the university to publicly and concretely demonstrate the value of the education the students are receiving and the contribution that the student efforts make to industry and the community.
- The university (and by formula, individual students and faculty) enhance their prospects of receiving royalties from their successful design efforts.
- Recently graduated students will be motivated to remain in touch with the follow-up efforts on their capstone activities, thereby potentially participating in and strengthening alumni relations.
- The graduate course in design management will attract design-oriented students to pursue graduate studies in our department because of the opportunity to manage the refinement of their own capstone project or other students' capstone projects.

Benefits to industrial clients

- There should be a significant increase in the number of capstone design projects that are either fully implemented by their industrial client or become commercially successful products.
- Industrial sponsors of capstone projects will gain greatly enhanced corporate exposure among students in non-capstone courses.

IMPLEMENTATION ISSUES

One of the attractive features of the concept described in this paper is that it does not require a major change in the curriculum. Specifically, the post-capstone activity can be implemented in the Mechanical Engineering Department at the University of Washington by adding only one new elective course (Product Testing). All that is required for the six other existing courses to become an integrated part of this effort is to change the topic of the project activity already carried out in those courses.

Nevertheless, implementing and administering the proposed post-capstone design evolution sequence will require careful planning and extensive coordination. Scheduling could be a challenge since some courses in this sequence may be offered every quarter, sometimes with multiple sections; others may only be offered during certain quarters. Some of the needed post-capstone tasks may be too large to be completed in one course offering. And some capstone projects may require more than one iteration through the post-capstone cycle depicted in Fig. 1.

Since the post-capstone efforts will typically extend over multiple academic quarters as designs progress through the sequence, a continuous management framework needs to be established and maintained. This will be accomplished via the graduate-level course in design management. The students enrolled in that course will provide crucial personnel resources needed to plan and coordinate the efforts being conducted in each of the other courses. Simultaneously, the learning opportunities provided to these graduate students will be unparalleled, real-life design management experience.

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