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Selection Criteria for Cornerstone and Capstone Design Projects*

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While many engineering programs have long offered capstone design courses, more are beginning to offer a cornerstone introductory project-based course as well. At Harvey Mudd College, this has been the accepted practice for almost 40 years. This paper presents the considerations used in selecting projects for both the introductory course and the capstone Clinic Program, and notes the key differences and similarities in selecting projects. Both programs use actual clients from outside the college, and both expect the students to learn aspects of professional practice beyond intellectual techniques and skills. In both cases, the key to selecting successful projects is to focus on the ability of the students to perform the project, and the relationship of the project to 'real-world' engineering.

INTRODUCTION

HARVEY MUDD has a long tradition of introducing project-based learning (particularly engineering design) at the beginning of the engineering curriculum, then using this experience as a springboard into engineering science courses, systems engineering courses, and culminating in three full semesters of project-based learning in its Engineering Clinic [1]. The use of both freshman and upper division project-based learning has been characterized as a cornerstone/capstone approach, in which conceptual design and associated methods and experiences form the foundation for subsequent engineering education, and Clinic allows the students to unify their experience and integrate it within a significant project [2]. This introduction occurs in a semester-long freshman course, *E4: Introduction to Engineering Design*, in which students complete several projects which teach formal conceptual design methods and simple elements of project management, and also experience team dynamics [3]. The students work in teams of 4–5 students, attempting to solve design problems for actual clients. The clients are not charged any fees for their participation, and the results are often quite interesting and useful, so there are usually a number of projects from which to choose. The Clinic projects, on the other hand, are performed for clients who pay a significant fee, are much more advanced in their engineering content, and occur over a full academic year. As in E4, however, there are often more project opportunities than can be accepted, and the Clinic Director must select appropriate projects. The criteria for selecting E4 and Clinic projects is the subject of this article.

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BACKGROUND INFORMATION ABOUT E4

Harvey Mudd has offered it first course in engineering, *E4: Introduction to Engineering Design*, since 1963. Because it is a freshman-oriented course, students are presumed to be interested in engineering, but to have no formal education in design or analysis, and no scientific knowledge beyond that offered in other first-year courses. By the end of the course, students should demonstrate proficiency in a number of design-related tasks, including:

- clarification of engineering problem statements;
- identification of relevant stakeholders;
- development of specifications, including objectives, constraints, and functions;
- generation and evaluation of alternatives, including various forms of proof-of-concept testing;
- management of design activities by use of standard project management tools (work breakdown structure, gantt charts, calendars, and precedence analysis);
- documentation of results in the form of presentations and written reports.

The students initially work through several small-scale design projects in teams of two or four. These typically include a two-week simple design project, a two-week reverse engineering (dissection) project, a three-week research and design project, and culminate in the major project. In each case, the teams must document the results of the design activities listed above. In addition to design and project management knowledge, the students should experience the 'forming, storming, norming, and performing' phases of group formation [4]. To this end, the students are randomly assigned to a team at the beginning of the term,

and are subsequently reassigned to a new team when the major project is assigned.

Enrollment in E4 ranges from approximately 20 students in the Fall semester to as many as 90 students in the Spring. Since we want students to see how other teams have attacked and solved the same problem, it is desirable that at least 2 teams be assigned to each project. Typically, this translates into 1–2 projects in the Fall, and 5–6 projects in the Spring.

In past semesters, a wide range of design projects have been conducted, covering such topics as: a gate for an elementary school, a cartilage cutting device for a medical research laboratory, chicken coops and greenhouse-type environments for a women's cooperative in Guatemala, a portable lighting system for a marching band, and a giant calculator for use by a 'mathemagician'.

To put the course into a more general context, one can consider the framework for such courses described by Sheppard and Jenison [5, 6]. They propose a two-dimensional framework in which one axis characterizes the style of pedagogy (individual vs. teamwork), and the other the degree of domain-specific knowledge in the course (content vs. process). E4 is an example of a course which is very much in the extreme team-process quadrant; that is, most of the learning occurs in the context of team activities and events, and the knowledge is more about the processes applicable to any type of engineering design rather than domain specific.

SELECTION PROCESSES FOR E4 PROJECTS

Generally, when choosing among projects, the teaching team for the following semester will first meet with prospective clients, discuss their needs, and explain the nature of the course and projects. The teaching team then applies the following criteria to the complete set of available projects and selects a bundle of projects. The accepted projects are offered to the students, who indicate preferences. In cases where only a very few students are interested in a project, the project is dropped. (This is quite rare, consisting of no more than one project per academic year.)

When selecting projects for inclusion in E4, the following eight characteristics are considered:

1. *Design content*. The project should entail conceptual design with only limited elements of implementation design or detailed design. Only a small number of first year students have sufficient knowledge to undertake detailed design in a useful way.
2. *Open-ended*. The project should allow for at least three different possible solutions. If the teaching team cannot come up with a number of possible and interesting solutions in a few minutes of brainstorming, the project is considered suspect.
3. *Level of difficulty*. Solutions to the project should not be obvious or easy. If the students are not convinced that the project is difficult, they tend to defer work until late in the semester and finish haphazardly.
4. *Engineering emphasis*—The project domain should be clearly identifiable as engineering. If the project is not perceived as engineering (i.e., interior design or social problem solving), the students typically fail to consider the project relevant to their education as engineering students.
5. *Project sponsor/client*. The client should ideally be a non-profit organization. Since the students will later be working on Engineering Clinic projects, which are typically sponsored by 'for-profit' companies, it is considered valuable that the students learn that good engineering design can be done for other clients as well. (If forced to choose between a poor quality project for a non-profit and another for a private sector company, we would certainly choose the better project. Our experience suggests this is rarely a real choice.)
6. *Hands-on element*. The project should involve making a model, prototype, or other proof-of-concept. Our students seem to do much better on projects which involve a significant 'hands on' aspect. Generally, we ask the question 'how might a student team demonstrate a successful design?' If the answer suggests building something to prove the concept, the project is more likely to be selected.
7. *Relationship to subsequent curriculum*. The project should introduce the students to the need for their later courses in engineering. Ideally, the students should have learned some rudiments of engineering science or analysis from the project, but should also recognize and be able to map their ignorance against future courses in the engineering curriculum.
8. *Permission to fail*. Each semester, one or more of the projects may not result in a successful outcome from the client's perspective. This is sometimes a consequence of excessively high expectations on their part, or insufficient time to translate a prototype into a 'finished' product. The previous criteria, especially (1) through (3), require that the project be one in which the client can tolerate an unsuccessful outcome.

BACKGROUND INFORMATION ABOUT ENGINEERING CLINIC

Harvey Mudd College has been training engineers with the quintessential capstone design course for more than 30 years. The Clinic Program was instituted by Mack Gilkeson and Jack Alford in the late 1960s, and has, as of the 1999/2000 academic year, conducted more than 850 Clinic projects. Engineering Clinic projects can be

classified into two broad categories. One type of project is design-build-test. This type of Clinic project is the most popular among students. The other type of project is plan-monitor-review. In rare cases, projects involve feasibility studies on current technology. In all cases, the projects have the following characteristics:

- Real problems;
- An interested, 'invested' customer, who has paid a significant fee;
- Fixed end date, with specific deadlines for various deliverables;
- Team effort necessary for successful completion;
- Reports and presentations to both the client and a larger interested community;
- No guarantee of a unique solution.

SELECTION PROCESS FOR CLINIC PROJECTS

The following method is currently used to select Engineering Clinic projects at Harvey Mudd College (HMC). Near the end of the Spring semester, student input on project interests is solicited. Students are asked to pick their field of interest from the following general categories: Bioengineering, Chemical Engineering, Civil Engineering, Communications, Computer Engineering, Electrical Engineering, Environmental Engineering, Materials Engineering, and Mechanical Engineering. These indications of student interests are used to guide the Clinic Director in the selection of contact companies during the summer. For example, during the 1998/99 academic year, the following project mix was requested by students:

- 4 Bioengineering
- 2 Chemical Engineering
- 4 Communications
- 5 Computer Engineering
- 3 Electrical Engineering
- 1 Environmental Engineering
- 1 Materials
- 8 Mechanical Engineering

Potential Clinic sponsors are contacted during the Spring and Summer. The following guidelines are provided to the potential sponsors. Experience suggests projects that meet these guidelines, which have been developed over the past 30 years, provide the best educational value to the students.

1. Choose a problem that you, the sponsor, really want solved (neither you nor your HMC Clinic team wants to waste time with inconsequential or simulated goals).
2. Choose a project that emphasizes design and/or experimental skills.
3. Do not choose a project involving only the accumulation of published information and/or test data. (A 'task-type' project may not provide the latitude for the 'fresh approach' thinking that your HMC team can bring to your program.)
4. Give preference to projects that allow students to interact as a team and which are sufficiently broad in scope to allow your HMC team to apply their creative talent to fullest advantage.
5. Plan a project that can be completed within the academic year (you can count on about 1200 person-hours, of which one quarter is spent on project management).
6. Seek a project which will stand on its own and which is not on the critical path of a program that has a stringent deadline.
7. Establish concrete, measurable goals for each project and define how success will be determined.
8. Students will pick from among several projects, so the more challenging and stimulating a project, the more interest it will garner.

Interested sponsors assemble project ideas from their own internal sources. Some sponsors have an internal review committee that evaluates proposed projects based on company needs. In many cases, HMC alumni/ae are an integral part of the project review process. Sponsors then forward the project idea or ideas to the Clinic Director for further evaluation. In most cases the Clinic Director has some flexibility in picking from among many projects to fulfill the required project mix. During a typical year, 35 projects may be required. As a result, there is always some compromise among project mix, company needs and how well the projects meet the above guidelines.

DIFFERENCES AND SIMILARITIES BETWEEN CORNERSTONE AND CAPSTONE PROJECTS

Not surprisingly, there are some interesting similarities and differences in criteria applicable to E4 and Clinic projects. In both cases, a primary consideration is that a team of students be capable of completing the project within the available time and other resources. An interested sponsor who is external to the College is an important element of developing a sense of professional practice and responsibility among the team for both E4 and Clinic projects. Finally, a key element common to both is that the projects are evaluated primarily on the basis of their educational value to students, as defined in the goals for their respective courses.

The most significant differences are related to the level of preparation the students bring to the course, and the resultant degree of difficulty which is acceptable in a project. While the ideal E4 project is challenging to the students, it is unlikely that the teaching faculty would find them as excessively demanding or problematic. The same cannot always be said for Clinic projects. The best Clinic projects draw upon the full set of skills and

domain knowledge acquired by the students, and demand that the students engage in a great deal of additional learning specific to the project. In that sense, the faculty is often surprised by the solutions developed by the teams, and impressed by students' technical creativity.

Another significant difference is in the amount of design content in the two types of projects. Because E4 is specifically a design course, projects with little or no design content are summarily rejected. Clinic projects are not bound by this constraint, and often interesting and educationally valuable projects with very little design content are included.

How projects are generated represents another key difference between E4 and Clinic projects. Because the educational content is more standardized in E4 projects, and because clients are less directly involved in the definition of problems, metrics for 'good' projects tend to be applied initially by the faculty in E4. Clinic projects, on the other hand, are much more likely to originate with the client, and depend on their application of the supplied guidelines during the initial project definition.

On a final note, perhaps the least significant difference between the two project types is in the costs to sponsors or clients. E4 projects are done on a *pro bono* basis, with teams limited to a $125 budget per team. Clinic projects are usually sponsored for a fee in the thousands of dollars, with each team preparing its own budget and then seeking approval from their faculty advisor and the Clinic Director. Ironically, this seems to have little effect on the educational vitality of either type of project.

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