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Carnegie Mellon's Multidisciplinary *Engineering Design Projects Course* Serves a Variety of Students and Project Sponsors

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Abstract

The *Institute for Complex Engineered Systems* (ICES) at Carnegie Mellon University, a continuation of the former NSF-funded Engineering Design Research Center (EDRC), sponsors several project-based engineering design courses that are open not only to Carnegie Mellon *College of Engineering* students, but also to the entire campus community.

The *Engineering Design Projects Course* is unique in that teams of upper class and graduate students from several academic areas, including humanities, business, and fine arts in addition to various engineering disciplines, work on design projects sponsored by industries, non-profits, government agencies, or organizations within the university. The intent is to give the participating students a hands-on, integrative, multidisciplinary experience in the important field of engineering design.

The success of this course is attested to by several project sponsors returning for repeated semesters with additional problems to be addressed by student teams, and by some students taking the course a second time, usually working on different projects. Students also indicate that discussions during job interviews have focused on this course experience. Not all student reactions are positive. While some students have enjoyed participating in well-functioning teams to achieve success on projects they found to be interesting, other students have felt that the minimally-structured independent course environment did not provide sufficient motivational support to keep them excited and focused. Some also appeared to be unready for the level of responsibility required to succeed in an empowered team environment, with a faculty team advisor acting in a purely coaching role.

This paper discusses the design of the course, the design process the students are encouraged to use, typical projects and their sponsors, how student teams are formed to maximize multidisciplinary composition, how student teams are matched with projects, how student work is evaluated and graded, and Liré, a locally-developed Knowledge Management tool used to collect and archive course design and process documentation.

Introduction

The *Institute for Complex Engineered Systems* (ICES) at Carnegie Mellon University, which continues the former NSF *Engineering Design Research Center* (EDRC), sponsors several project-based engineering design courses which are open not only to Carnegie Mellon's Engineering School, but to the entire university community. The topics addressed include *Integrated Product Design*, *Rapid Prototyping*, and *Design of Wearable Computers* (1).

The *Engineering Design Projects Course*, which is now in its fifth year, is unique in that teams of students, usually from many parts of the campus community, work on design projects sponsored by industries (both local and national), non-profits, or organizations within the university. The intent is to give the participating students a hands-on, integrative, multidisciplinary experience in the important field of engineering design—an opportunity for the students to practice synthesis, innovation, and creativity in contrast to other courses that are more focused on knowledge transfer. Associated classroom activities address design-related experiences not usually covered elsewhere in the curriculum, like team building, project management, the context in which design is carried out, and product realization processes.

One of the successes of the course is demonstrated by the fact that several sponsors have returned to sponsor additional projects. Students can take the course either semester or both, and several each semester do elect to return—sometimes to continue with the same project and sometimes to try another project and another sponsor relationship.

Course Organization and Design Methodology

Course Structure

The students who take the course are organized into teams of four to six, each of which works on a different project. Each team comprises multiple disciplines to the extent possible given the mix of students who register for the course. Each team is supported by a faculty *coach* and by an individual representing the organization sponsoring its project. The authors of this paper are or in the past were "core" faculty with overall course responsibility. Additional faculty members are recruited as needed to coach individual teams.

Students registering for the course are told that it meets two days a week (Tuesday and Thursday) for two hours. During the first two weeks the class actually does meet both days each week so that preparatory activities (e.g., organizing teams and matching teams with projects) can be completed and the project work can get under way as quickly as possible. During the rest of the semester the class meets only on Tuesdays; the teams are encouraged to use the Thursday time they had already set aside to meet with their coaches and sponsors. They usually schedule additional meetings each week, to pursue their work.

The general flow of work requires that the student teams

- follow a Design Methodology and Project Management process outlined in their text and discussed in class
- report their progress regularly
- produce a Final Report, and, if possible, a finished design and prototyped product

The design methodology described in the text emphasizes

- defining the desired product (outcome) carefully and thoroughly
- identifying *goals* and *constraints* (and understanding the difference)
- reaching agreement with the project sponsor on these three things before proceeding
- developing a *Work Breakdown Structure*
- preparing a schedule to which they can work
- allocating their resources to the work breakdown so that they can achieve their schedule
- executing their design
- reporting their results and the work they did to get there

Instructional Material

The class meets together once a week for two hours. Early classes are purely instructional; once the students get going on the projects the typical class includes some instructional material and reports by several student teams. Instructional content is arranged to support the design methodology.

The earliest sessions address class organization, mainly forming teams and matching teams with projects. The Project Management methodology to be used in the class is introduced, and proprietary-information forms are explained and signed.

Before they get started on their projects the students participate in two team-building activities. The first requires that each team build with Lego a device to perform a simple task, and than prepare simple documentation that another team can use to replicate their device. During the first half of the activity each team conceives and creates its own device implementation; the device is then broken down and the parts and instructions are passed to another team who are charged to re-assemble the first team's device. The second team-building activity is a published "Subarctic Survival" exercise. This is evaluated and managed so that it illustrates to the student teams that team performance typically surpasses the performance of most individual team members.

Typical Class Sessions

A "typical" class consists of several student team "Progress Reports" followed by an instructional lecture.

The student Progress Reports are a mix of project management status (e.g., "Our schedule is complete.") and project design status. Early in the semester project management issues dominate; later there is more to say about progress in executing the design. The rest of the students and the attending faculty coaches and sponsor representatives are encouraged to ask thought-provoking questions which may help guide the students towards better results..

To the extent possible, the lectures in these classes are synchronized to the place most students are in their design processes. The first presentation addresses Project Management in general, and as applicable to the sorts of projects done in the class and to the constraints of the class (e.g., duration and people resources more limited than degree of design completion). Following lectures address breaking the work into manageable, trackable parts, and creating a schedule.

Later in the semester, when all the teams are well under way on their projects, we offer some lectures that expand on the design process. Examples are

- Product Realization Processes (PRPs). This is typically presented by one of the sponsor representatives, based upon the PRP used in their company.
- Design in the context of an "ecosystem" e.g., business needs, regulations, cultural issues). This has been presented for several semesters by a venture capitalist with ties to the university.
- The role of Industrial Design. This is important to the engineering students who are the majority of class members. It is presented by a Professor of Industrial Design.

During several semesters student team members were given additional opportunity to make presentations to their classmates by having them present the lectures based upon the material in the text. This was felt to have the additional value of exposing them to a "teaching" experience. To further support this idea, in semesters when there were few teams, each team was asked to present two lectures, one using pre-prepared visuals and one using material created in real time on the blackboard. Each team was asked to use their own project as the source of specific examples, rather than the examples given in the text. At the end of their lecture, the team members were asked to spend five minutes each working with one other team, helping to insure that they understood how the concepts of the lecture applied to their project.

We recently assessed this approach and found that it had three problems:

- Preparation required setting up two additional times for each presenting team to meet with a faculty member, who would provide experienced help preparing their lecture. With teams already having difficulty scheduling meetings to work on their projects, this appeared to create an additional hardship.
- The time devoted to preparing to present these lectures might better have been used by the students on their design work.
- The time when the team members were supposed to be "helping" other teams apply the concepts of their lecture was not being effectively used.

As a result we have chosen to eliminate the student lectures. These presentations are now given by various members of the supporting faculty.

Special Class Sessions

Three classes during the semester differ significantly in that the entire time is devoted to student presentations. For these sessions, all sponsor representatives are urged to be present; some additional faculty may also be invited to participate.

Two formal *Design Reviews* are conducted at roughly the one-third and two-third points of the course. The intent is the same as for design reviews held during the course of design projects in industry: to elicit from people not directly involved in the particular project observations and questions that may illuminate critical issues and unidentified problem areas. Each student team makes a fifteen-minute presentation of the state of its design, after which all in attendance are encouraged to ask team members challenging questions.

In the last class period of the semester, the student teams make *Final Presentations* based upon the reports they have prepared for their sponsors. It has become traditional to follow this class with a celebratory meal served on campus.

Final Report

Each student team is required to prepare a "complete" Final Report, regardless of the progress they have made on their actual design. This report has two principal customers:

- the team's sponsor
- a team that may continue with the same project during a following semester

For the sponsor, this is the minimum they receive in return for their sponsorship. If work progresses far enough, they may also receive a prototype or even a finished design, but the report is still a key deliverable. In addition to an *Executive Summary* stating what the students accomplished, the Final Report is also required to include

- description of design work done—including paths abandoned, with an explanation of why they were abandoned
- research avenues pursued and information gathered, whether specifically useful or not.

For the sponsor, this means that should they choose at some later time to pursue the project topic further, they will have the benefit of *all* the information and knowledge the students gathered and developed. The value to a following team is similar: they can move forward without re-tracing old paths.

Liré—the Product Data Management Tool

Liré is a Product Data Management tool that was originally created in the EDRC/ICES to illustrate evolving concepts of how design data is captured, stored, and later accessed. To get application experience, it was tailored to the environment in several EDRC/ICES courses including this Engineering Design Projects course. Material is stored in *Liré* in nested folders, which can be accessed by different groups of users in ways easy for them to negotiate. It is set up so that particular stored items (e.g., documents) can be accessed from more than one entry point. This permits one item to be seen by different users in contexts specific to their needs. As an example, a student presentation (e.g., a Progress Report) can be "stored" in their specific project folder and can also appear in the appropriate folder in a stack representing the individual class periods throughout the semester.[1-4]

Before the start of each semester a base set of folders is created for the upcoming course; the student teams develop these further as they progress with their project work. The students are required to place into *Liré* all material developed for the course, including research findings, meeting minutes, design documentation, reports, etc. The completeness of their *Liré* documentation factors into each team's grades.

The Projects and their Sponsors

Recruiting project sponsors is a key activity. Enough projects are needed each semester to accommodate all of the students who sign up for the courses. For this course, we have found that working in teams of four to six is most beneficial. (Fewer than four severely limits the work that can be done and the results that can be achieved. Teams of more than six students have difficulty scheduling times to meet, work together, and ensuring that everyone is contributing to

the team. This made especially hard by the cross-campus mix of students; the different schools have different course lengths and frequencies, which leads to few free times in common.) Sponsors tend to be organizations already working with ICES in some other role, or organizations with whom participating faculty have existing connections. Sometimes a colleague who is aware of a faculty member's participation in the course will hear of a company or project that may seemingly fit the Project course model well. Projects sponsored by campus organizations are sometimes sought when there do not appear to be sufficient outside projects to provide for all of the students who have signed up for the course.

Sponsor Obligations

A sponsor must be willing to meet several obligations. The most important is that, along with the faculty mentor, they identify a problem that provides a pedagogical experience to the students and can be solved by an engineering design that can be completed by four to six college students working for one or two semesters. Project sponsors must be willing to provide sufficient information (normally under a confidentiality agreement) that the students can fully understand the need and make meaningful progress on a design to meet the need.

The next requirement is that the sponsor identify someone on their staff with whom the students can interact on a regular basis and when needed. For sponsors local to the Pittsburgh area, this interaction may be via the sponsor representative coming to campus to participate in some class sessions and team meetings, by having the students visit the sponsoring organization during the semester, and by exchanging E-mail messages. Sponsors remote from Carnegie Mellon may interact with the students chiefly by phone and E-mail and through a designated on-campus contact.

If the project involves hardware or software made or sold by the sponsor, the sponsor is expected to provide materials they and the students believe are necessary for conduct and completion of the design project. Often these are loans, with the materials being returned at the end of the project, often as part of the design solution.

Finally, a sponsor is asked to pay a modest fee. The money is used by the students to purchase materials they believe they need to pursue their design work, and sometimes to pay for travel to visit the sponsor's site. A small amount is provided to the project's faculty coach, usually in the form of an account which can be drawn upon for purchases in the campus computer or book store, or to voucher conference expenses and the like. The remainder is used to support course general expenses like copying course announcement posters or hosting visiting speakers.

A (small) Pennsylvania company that finds the fee difficult to pay may have up to half of the fee provided through a PITA (Pennsylvania Infrastructure Technology Alliance) grant obtained to support the course. ICES has a broad and strong interaction with the Commonwealth-sponsored PITA program.

The fee may be waived for a non-profit that offers a particularly appropriate or appealing project. Campus organizations sponsoring projects are also exempt from the fee.

Student Interaction with Sponsors

As indicated above, we encourage close interaction between a representative of each project's sponsor and the team of students working on the project. This can work especially well when the sponsor is local to the Carnegie Mellon campus. The level and nature of the interactions varies with team and with sponsor representative.

One nearby sponsor, which had a multi-faceted relationship with ICES and sponsored projects for several semesters, actually established an "office" (a cubical with a desktop computer) for use by Carnegie Mellon students working on their project. Even this did not insure frequent and comfortable interaction: one semester the team visited the sponsor's facility only once. Another semester the team visited every week, used their office, and interacted with a number of the sponsor's engineers. This paid off in an unexpected way: the students actually brought two of the sponsor's engineers together who had not realized that they were working on similar problems.

Sponsor participation in class varies greatly. We ask that the sponsor representatives come to class at least four times during the semester:

- at the start, to describe their projects to the students, so that teams can indicate on which project(s) they would like to work.
- to participate (ask questions) in the two Design Reviews
- on the last day of class, to hear the Final Reports of all the teams

Occasionally a sponsor representative will manage only the first and last of these. At the other end of the spectrum, some sponsor representatives come to nearly every class. These people often get drafted to make a presentation during the semester on some topic relevant to Engineering Design, such as describing the Product Realization Process used in their company, or speaking about Intellectual Property issues.

The Projects Themselves

Projects have mostly sought a design solution to a hardware problem. A few have looked for software solutions, and a very few have asked more open questions like "what's a possible new use for this material we make?" Not all result in actual implementations, even after two semesters. Even without completed and implemented designs, the sponsors find value in the R&D work done by the students, as an aid to their own future work should they decide to press forward to solve the problem themselves. Sometimes the methodology developed by the students as they pursued their solution is useful to the sponsor, and sometimes just the knowledge of dead ends not to pursue further is helpful.

Project definition varies greatly. Some start out well defined, with clear goals; *what* is desired is spelled out, *how* to get there is the challenge presented to the students. At the other extreme, one sponsor essentially asked the students to "look around in this specific category of things we do, and find a design problem you can try to solve." While some students enjoyed this open challenge, some of us felt that the students spent too much time thrashing around seeking a problem, and not enough time experiencing working on an engineering design project. Most projects are presented to our students somewhere in between these two extremes.

Team Formation and Project Matchup

Recruiting Students

We recruit students in several ways. The course is listed with the other courses open to students each semester. Since it is listed with other courses offered not by individual engineering departments but with those sponsored by the Engineering College, not every engineering student sees the listing. This mode also does not attract the attention of non-engineers.

We create each semester a colorful page-sized posted describing the course, and send copies of this to both undergraduate and graduate advisors in all of the engineering departments plus other departments and programs whose students might be interested: Computer Science, Human Computer Interaction, Industrial Design, Architecture, Business, and Technical Writing (English).

We also find that word of mouth brings us a good number of students—as it does in many places, *networking* pays off here, too. Students have fun taking the course, and since it is offered every semester, students who took it in the fall urge their friends to take it in the spring. A few students opt to take the course a second time (different course numbers each semester insure that they will get credit for both times they take it)—some to continue work on the same project and some specifically to work on something different!

Forming Teams

Several methods have been tried for forming teams, from semi-random to highly structured. The method used in recent semesters has proven to be quite successful in creating effective teams:

- Determine an average team size based upon the number of projects available and the number of students registered. Ideally this will be four to six, for the reasons already described.
- Organize the list of registered students by discipline.
- From the most-represented discipline (often Electrical and Computer Engineering, which is our largest engineering department), assign a student to each team. Continue this until all students in this discipline are assigned.
- Repeat this for the next most represented discipline, which is often Mechanical Engineering. (MechE students tend to like design project courses.)
- Distribute the remaining engineering students to balance the number on each team.
- The numbers of Technical Writing and Industrial Design students vary from semester to semester. Distribute them among the teams to get the best distribution of these key non-technical students.
- Balance the teams with any students still not assigned (e.g., Business students).

The students do have the freedom to make a small number of team changes after projects and teams are matched, to either meet special interests (like a student returning to continue work on a particular project) or to better match student skills with needs (perhaps a Materials Science and Engineering student moving to a project with a heavy need for materials knowledge).

Project Matchup

This, too, has been tried in different ways. Simply asking each team on which project they would like to work has not been successful; most teams name the same attractive-sounding

project. The opposite has also been tried: asking each team to name the project they would *least* like to work on**.** Recently these have been combined, with each team being asked to name their number one project choice and also the project they would least like to work on. This has worked quite well. In a recent semester four of five teams got their first choice, and no team had to accept the project they did not want.

As mentioned above, minor shifting of students among teams is permitted after teams are matched with projects, to strengthen some teams and satisfy some individual desires.

Evaluation and Grading

The course is graded using five inputs:

- The quality of the Final Reports each team prepares. "Quality" includes
  + clarity of presentation of principal findings
  + completeness of description of the recommended design
  + completeness of description of design alternatives considered
  + completeness of supporting material (research findings, etc.)
- The Faculty Coach's assessment of student performance (as a team and individually)
- The Sponsor Representative's assessment of student performance (as a team and individually)
- Team member ratings of their team colleagues.
  + We ask each student to start with 10 points for each member of their project team, and re-assign those points based upon their perceptions of how much each team member (themselves included) contributed to their success.
- The completeness of their "design history" as they captured it in the Liré system.

The faculty course director considers all of these inputs, and assigns a final grade to each student.

Because too little project work has actually taken place by mid-semester grade time, no grades are given at mid semester.

Student Reaction

Student reaction to the course, as evidenced by end-of-semester Faculty-Course Evaluation scores, is typically below average, with unusually high variability. Seemingly while a few students participated in a well-functioning team that achieved success on a project that proved to be as interesting as it originally sounded, many have found the course too loosely-defined and unstructured for their tastes.

Some of the students do enjoy the course and try to take it a second time. To support this, it is offered in both fall and spring semesters. Having a different course number each semester makes it easy for students to get credit for taking it twice. Some of the returning students elect to continue on the same project, while others specifically ask to work with a different sponsor to get a different experience.

Some of the most interesting responses to the course have come from the non-engineering students who participate. In a recent semester, several Technical Writing majors from the

English Department took the course. One student participated with the technical members of her team in the initial web-search research, but came fairly quickly to a point where she acknowledged that the technical expertise needed to continue this part of the work was beyond her skill level. She volunteered to her teammates that she would take responsibility for documenting their work—including preparing for the significant Final Report that is required of each team. She performed these roles excellently—and in fact provided the driving force that kept the others working close to schedule. While most teams were assigned uniform grades, she ended the semester getting a higher grade than her teammates because of her overall contributions to their work.

Students who appear to like the course least seem to encounter one of these obstacles:

- the project to which they are assigned (which may or may not have been their first choice) turns out not to excite them as much as they thought it would;
- their team never "jells" into a well-functioning, supportive team;
- the minimally-structured independent course environment does not provide sufficient motivational support to keep them excited and focused;
- they are not ready for the level of responsibility required to succeed in the *empowered team* environment, with the faculty advisor to the team in a *coaching* role.

Next Steps

The *Engineering Product Design* course is well received on the Carnegie Mellon campus, and will continue for the foreseeable future. Successful as we have been up to now, we continue to make minor adjustments so that both project sponsors and students will find it an ever-improving experience, worth their commitments of time and resources.

Summary

This paper has described Carnegie Mellon's *Engineering Design Projects Course* in which teams of upper class and graduate students from engineering and other academic areas, including humanities, business, and fine arts, work on design projects sponsored by industries, non-profits, government agencies, or institutes within the university. The course provides the participating students a hands-on, integrative, multidisciplinary experience in the important field of engineering design, together with instruction in key design-related topics not usually addressed elsewhere in the curriculum.

The course's success is demonstrated by both projects sponsors and students returning to experience the course for more than one semester. At the end of the most recent semester, fall 2003, four of five project sponsors plan to return in the spring, and more than 20% of the students have signed up for a second semester (under a different course number).

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Biographical Information

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Cristina Amon is the Director of the Institute for Complex Engineered Systems and the Raymond J. Lane Distinguished Professor of Mechanical Engineering at Carnegie Mellon University. As Director of ICES, she acts as the sponsor for the *Engineering Design Projects Course.* Professor Amon has developed outreach programs for female and minority students and her research focuses on heat transfer and computational fluid mechanics.

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