Abstract
This paper reviews some recent major changes made to the Senior Mechanical Engineering Capstone Design Program at UBC. The program now consists of a two-term senior level design sequence where student teams work on open-ended design problems sponsored by outside clients. In order to reinforce relevance and ensure that practices parallel those of industry, the Department recruited local senior engineers to serve as engineering mentors to the students and work in concert with the course instructors. Several milestones were established during the duration of the program year to reinforce good design practice beginning from an agreement on client needs and proceeding through concept generation, selection, analysis and finally ending with prototype construction and evaluation. The paper highlights the improvements made to the program as a result of these changes and presents an example of a student design project developed under the new model.

1. Introduction
Similar to virtually all other engineering schools across North America, the UBC Department of Mechanical Engineering requires all students to complete a Capstone Design Program during the student’s final year of study. Most often, capstone design programs are intended to provide meaningful design experiences whereby students must not only apply their knowledge in the engineering sciences but must also utilize skills in design methodology, teamwork, project management, record keeping, etc., to solve a real need. A successful design capstone project embodies all aspects of engineering design starting from the problem definition and leading through to prototype construction and evaluation. A well-structured capstone design course coupled with motivated students provides an ideal learning environment.

UBC Mechanical Engineering has maintained a Capstone Design Program, in one form or another, since the formal establishment of the department in 1920. The capstone course, titled MECH 457 – Mechanical Engineering Design Project, is a six credit mandatory course that spans both academic terms of the final year. Historically, design projects were often sponsored by local industry involved in supplying equipment for the traditional west coast resource based industries of forestry, mining, and fisheries. As the department expanded into a full graduate research program during the 1960’s and 1970’s, the Capstone Design Program was altered to serve the needs of the research program for the department1. Project supervision and assessment was performed by all faculty members on a volunteer basis. Although this model for creating design topics and providing supervision produced several successful projects through the years, recently it was felt that this model could not provide all students with a meaningful design experience. It was felt that a more structured approach to the program would bring it in-line with the best programs in the country.

Deficiencies in the previous program included a lack of adequate engineering supervision and management of the student project teams, lack of outside industrial participation, lack of structure, and some discontinuity and fragmentation of design projects. An excessive number of project groups and project topics meant that, at times, the project topics were not adequately reviewed to ensure the students practice the full range of elements of the engineering design process. An insufficient number of target milestones and one-term projects often meant that students were unable to complete a meaningful project. In
addition, it was felt that there was a general decline in the quality of technical content and written/oral communication within the program.

A review committee, established to update the program, concluded that a meaningful capstone design program must be based upon realistic engineering problems posed by industrial clients and it must utilize a support structure of motivated faculty members with design experience. It was felt that having outside industrial clients would help to motivate students, and would best provide a complete design experience to the students.

2. Program Design

The Canadian Engineering Accreditation Board (CEAB) stipulates the mandatory application of a significant capstone design program using the following definition:

*Engineering design integrates mathematics, basic sciences, engineering sciences and complementary studies in developing elements, systems and processes to meet specific needs. It is a creative, iterative and often open-ended process subject to constraints which may be governed by standards or legislation to varying degrees depending upon the discipline. These constraints may relate to economic, health, safety, environmental, social or other pertinent interdisciplinary factors.*

The engineering curriculum must culminate in a significant design experience which is based on the knowledge and skills acquired in earlier course work and which preferably gives students an exposure to the concepts of team work and project management. A research project may be interpreted as engineering design provided it can be clearly shown that the elements of design, as noted in the definition, are fulfilled in the completion of the project.

Creation of a “significant design experience” within a university capstone course is itself, a significant design challenge. B.W. McNeill in his paper on design courses states: “Capstone design courses, if they are to be meaningful experiences, must be offered in a context which is consistent with the prevailing views of design pedagogy and design as practiced in industry.” Faculty members that are both experts in the latest engineering design research/teaching and experienced in the practice are extremely rare. Recognition of this deficiency is a primary reason for the establishment of the Canadian Design Engineering Network.

The first task in upgrading the UBC Mechanical Engineering Capstone Design Program was to recognize that a team of experienced design instructors must replace the numerous faculty “volunteers.” Supervisors were recruited based on experience in design teaching, interest in the capstone design program, and representation of the various technology clusters within the department. A ratio of approximately one faculty supervisor per twenty-four students led to five faculty members being recruited. Faculty members were awarded formal teaching credit as supervisors. It was expected that the members of the team of design faculty, each of whom had slightly differing skill sets, could teach within “the prevailing views of design pedagogy.”

The faculty supervision team recognized that teaching “design as practiced in industry” required additional resources. Engineering mentors were recruited to assist the team. The engineering mentors were experienced practicing professional engineers recruited from local industry to serve as technical advisors to the student design teams. After an extensive search, three mentors were recruited representing a local medical device manufacturer, a forestry equipment manufacturer, and a vehicle design firm. Having experienced industrial engineers/project managers serve as technical advisors enhanced the professional atmosphere required for the students to complete their design tasks.

Finally, a technical communication consultant was recruited to provide guidance to student design teams in written and oral communication skills. The consultant was provided through the UBC Technical Communication Centre, a centre recently established in response to the need to improve the overall communication skills of undergraduate engineering students.

The faculty supervision team had five primary responsibilities: soliciting and reviewing projects for the students, developing a set of milestone assignments and course lecture materials that emphasize proper design methodology, establishing and guiding the student teams, facilitating the progress of the projects, and finally, evaluating the teams and assigning grades. The engineering mentors, while not directly responsible for any aspect of the program, provided valuable technical guidance, facilitated project progress, and
provided input on project evaluation. The technical communication consultant was responsible for reviewing project proposals and providing guidance to student teams identified as having deficiencies in written communication skills.

The organizational structure was based on a fictitious engineering consulting company (Figure 1). Design problem providers were deemed as the client with the student teams as “staff engineers” assigned to solve the client’s “design need.” Supervision was the responsibility of the faculty supervisor who normally had up to six design teams working on different client needs. Technical support was available to the design team through the engineering mentor assigned to the group as well as through the technical communication consultant. Although limited machine shop and instrumentation staff support was available to the student design teams, the expectation was that the student teams were responsible for the majority of the prototype construction and evaluation.

Figure 1. Capstone Organizational Diagram

In order to best simulate industrial design practice, projects were solicited from outside industries as much as possible. The “client” design needs were reviewed before acceptance as projects based on several factors:

- Design problems had to be adequate in scope and be deemed challenging enough for the skill level of a student team made up of four to six students. Design problems had to appear solvable within an eight month program.
- Design problems were to go beyond reproducing an existing design. It was important that the problem be open-ended so that design teams could experience the creative synthesis process required in tasks such as problem definition and concept generation.
- The design had to culminate in the construction of a prototype. The scope and type of prototype varied from project to project.
- The design had to solve a “real need” required by the client and not be based upon a fictitious problem as is often used for entry level design courses.
- The design problem should match the interests to the students.
- Whenever possible, the client was expected to provide financial and in-kind support for the student design team.

At the start of the year, students reviewed the project list and submitted a preference form to the supervisors who established the student engineering teams. Team sizes would normally range from three to six students depending on the scope of the project. Although students could suggest working partners, these requests were not automatically granted.

The student design teams were expected to attend weekly meetings with the supervisor. These weekly meetings were established to ensure team progress and to allow for discussion of specific technical challenges. In the past, these meetings were arranged in an ad-hoc manner between the student team and volunteer faculty supervisor. This often meant meetings were poorly attended or skipped all together. To solve this problem, a common two-hour block was secured in the schedule of all students enrolled in the program. This “tutorial time” was used for individual team meetings, as well as common “company meetings” where all design teams were present to provide input into all the designs. The engineering mentor attended the meetings on a bi-weekly basis (these meetings were deemed as formal meetings). If required, additional meetings with mentors and supervisors were scheduled at convenient times to discuss particular technical challenges as they arose throughout the year.

Students were allowed access to a student machine shop, computer design/analysis lab, and instrumentation shop. Students were expected to fabricate their prototype on their own. However, for complicated components, student teams could submit detailed engineering
drawings to shop technicians for fabrication. For many of the projects, fabrication took place through access to client facilities or access though the engineering mentor. Access to other shop facilities was critical since shop demand often exceeded the capacity of the university facilities.

3. Program Activities

As mentioned previously, significant changes were adopted for the 2004 academic year in order to provide excellence in professional design practice and to bring the program closer to the CEAB capstone definition. The supervision team felt that the capstone design experience must provide a “complete design experience” beginning with a client need and leading through to prototype construction and evaluation. It was felt that the old course format, without proper program supervision and few milestone deadlines, would often lead to projects that could be interpreted more as research projects than design projects. For the new program, the supervision team established a set of milestone deliverables that follows accepted design procedures, and arranged deadlines to follow the entire UBC academic year (32 weeks).

Project Schedule

Most of the milestones deliverables required a written report submitted by the group to the supervisors for review and feedback. In some instances, an oral presentation was also required. The project schedule was as follows:

- **Engineering Proposal and Project Definition** – Three key elements were required in the design proposal. Students were expected to:
  1) Generate a detailed needs analysis and product specifications using techniques such as happiness charts.
  2) Develop detailed evaluation criteria to provide a comparison at the end of the design project.
  3) Develop detailed work plans using techniques such as a Gantt Chart, estimate resources required to solve the problem, and establish roles and responsibilities within the student groups. (Report due date: week 4)
- **Background Materials Exercise** – Student teams were required to gather relevant background materials through detailed patent searches, sourcing scientific and trade papers, finding relevant codes and standards, and examining the state of technology and practice in related areas. (Due date: week 6)
- **Analysis of Conceptual Alternatives** – Students were expected to develop detailed conceptual analysis reports consisting of: 1) Detailed product specifications using techniques such as top-level functional decomposition trees, benchmarking of related products, and QFD. 2) Generation of concepts using techniques such as morphological charts, and concept variants. 3) Concept selection using techniques such as weighting functions. At the completion of the report, student groups were asked to justify their proposed solution in a formal oral presentation to the class. (Due date: week 11)
  - **Formal Technical Analysis Report** – At this point, students were now embarking on the Embodiment Design stage of the program. Students were expected to identify the key performance variables/components in their project, use these variables to predict system performance, and maximize system performance through variable optimization. In many instances, students were expected to establish the product architecture of the design and perform a detailed parametric design using models and simulation packages such as common finite element analysis or computational fluid dynamics packages. Students were also expected to perform a failure modes and effects (FMEA) analysis on their design. (Due date: week 14)
  - **Formal Manufacturing Analysis** – A formal report was required which highlighted the required manufacturing processes for one or more critical components of the design including selection of machine type, operations, quality issues, and time requirements. In addition, a detailed manufacturing cost estimate was required. (Due date: week 18)
  - **Technical Drawings Exercise** - In order to highlight the need for good technical communication through engineering drawings, students were expected to submit a set of detailed engineering drawings including proper dimensions, tolerances, and bill of materials. (Due date: Week 18)
  - **Prototype Construction and Testing** – The development of a prototype was the largest
deliverable in the program. Students spent several weeks contacting vendors, acquiring parts, machining elements, and assembling the prototype. Final prototypes varied from proof-of-concept models (both physical and analytical) to functioning industrial units. Prototype evaluation was based on the type, suitability, and features of the prototype, as well as the quality of work and prototype presentation. Students presented their initial prototype for review by supervisors, clients, and fellow classmates near the end of term. Following this initial feedback, students had several weeks to complete their final prototype for public presentation following the exam period. (Due date: initial prototype – week 28, final prototype – week 32)

Final Report – The final report consisted of a summary of the project and a set of appendices that contain all the previous assignments, drawings, and photos. The governing philosophy for the final report was that it should be written for the client and should provide short, yet concise, information on the design and recommendations for future work. (Due date: week 31)

Logbook Assignment – Each individual student was expected to maintain accurate logbooks showing a clear path of development from initial design, through embodiment and testing to a complete workable design. The logbooks were used to track student’s time on the project and were signed by the supervisor at the completion of each formal weekly meeting. Logbooks were submitted along with the final report for evaluation. (Due date: week 32)

Lecture Series

A weekly lecture series in support of the milestone deliverables was developed for 2004 academic year. Previously, no lecture series existed for the course. As defined by CEAB, a capstone course should be based on previous knowledge and skills and not be venue for teaching new material. As such, most of the lectures were a summary of materials taught in the third year design program but emphasized the best current design practices. Much of the lecture material was based on the recommended course text, Product Design and Development, by Karl Ulrich and Steven Eppinger. At times, the technical communication consultant and engineering mentors were invited as guests.

A topic list for the 2004 academic year is presented in Table 1. As design is normally an iterative procedure, future lecture series will evolve to reflect the experiences gained from the first year and will better suit the objectives of the program.

Table 1. List of Lecture Topics, 2004-05

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<th>Week</th>
<th>Topic</th>
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<td>29</td>
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<td>Review of Report Writing</td>
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Evaluation of Student Performance

The new capstone design program involved a total of six written reports, a group oral presentation, two separate prototype evaluations (including a presentation aspect), evaluation of logbooks, and individual participation throughout the year. This was a significant increase in student assessment compared with the previous program which involved a proposal, a final report, and an oral presentation. Maintaining high expectations for the course required a high degree of feedback on student performance.

Since the faulty team were given teaching credit, student evaluation was the responsibility of the supervisors. However, it was important that the students received as much feedback as possible so other members of the program team were recruited to provide feedback. The technical communication
consultant was required to evaluate proposals in order to identify student groups that needed additional help with writing skills. The industrial mentors were required to provide input on prototype assessment and oral presentations. Although not required, the mentors would often provide input on several written reports, and engineering drawings as well. The clients were not required to provide student assessment but were asked to provide valuable feedback on whether the student developed prototype was able to solve the initial client need.

Peer evaluation was used for oral presentations and prototype evaluations. In general, the peer evaluation grades resembled closely the supervisor’s grading of the prototypes and oral presentations. In some projects, individual grades were adjusted based on feedback from team members. In the future, formal peer evaluation forms may be adopted to assess the individual participation of students within the project teams.

Except for the evaluation of logbooks, all assessment was based on group submissions. Based on results from the initial trial course, maintaining a high degree of group assessment over individual assessment better reflects industrial design practice where teams of engineers are often rewarded over individuals.

4. Example of a Student Project

A team of five senior mechanical engineering students were presented a design problem from the Cytogenetics Laboratory of the British Columbia Children’s Hospital. In general, a hospital cytogenetics laboratory is required to perform all types of chromosome studies to help diagnose congenital disorders. In this environment, the preparation of un-tainted quality samples is critical for accurate diagnosis of a patient’s health. Current sample preparation uses human operators which often lead to large variability in samples, and results in a higher incidence of errors. The students were asked to design an adaptable semi-automated fluid-handling subsystem that increased the efficiency of the laboratory procedures while not compromising the quality and quantity of the harvested chromosomes.

Working with the clients, the student team first established a set of minimum functional requirements. Some of the functional requirements included establishing the required volume of dispensed fluid, the associated maximum tolerances, number of test tubes to be filled per unit time, safety, and costing for the handling device.

Following a background study to understand the problem, (and two weekends in the hospital actually using existing test equipment) the design team established a formal function tree to help develop conceptual designs. Figure 2 shows the functional diagram for the design problem. The top of the chart represents the primary functions of the addition machine. The student team developed this line by starting with the end result, filling the container, and then repeatedly asking how this would be done to generate the following function. The vertical items represent secondary functions which are required to perform the primary function properly.

![Figure 2. Functional Diagram for Fluid Addition](image)

Next, a morphological analysis for the fluid addition was developed to aid in the selection of the conceptual alternatives. The morphological chart for filling the container is reproduced on Figure 3. The importance of both the formal functional trees and morphological charts was stressed to the students as part of the new capstone design program. These concepts are often a challenge to teach and require open ended problems in order for students to properly understand and apply the procedures.
Once the students developed several design concepts, they were required to make a formal oral presentation to their supervisors, mentors, client, and fellow students to defend their methodology and present their final design. Following this, the student team began the embodiment design phase of the program. A solid model of the proposed prototype is shown on Figure 4. The design consists of a custom designed test-tube indexing carousel controlled by a stepped down servo-motor. An inert solenoid-operated self-priming micro pump delivers the test fluid to the test tube through a dispensing needle tip. Optical sensors and associated logic was developed to control the liquid levels within the required tolerances. The student design team was responsible for the design of all the mechanical components of the system as well as the development of the simple logic control system for fluid delivery.
Following numerous design reviews with the supervisor and mentor, the students began the prototype construction phase of the program. As mentioned earlier, the prototype phase of the program is heavily weighted so that students experience the challenges of achieving a working prototype from their detailed designs. Several “real world” design challenges were encountered by the student team including: funding constraints, minimum time lines, underestimating the required levels of detail to complete a prototype, the impact of tolerances on the construction of a prototype, the value of using standard parts over custom designed parts, and perhaps most importantly, the critical role of communication within the team as well as with the supervisor and client. During this phase of the program, the students relied heavily upon the experience and support of the supervisor and industrial mentor along with technical support from machine and instrumentation shops.

It was found that holding two formal prototype evaluations were very valuable to the design teams. In this example, the student team worked hard to complete all the mechanical components before the first prototype deadline. At this first showcase, the students received valuable advice on all aspects of their design. Following the first deadline, the student team refined the prototype by concentrating primarily of the completion of the control systems before the final prototype showcase at the end of the academic year. It was felt that if only one prototype deadline was used (normally, the end of the academic year), the student teams would not achieve the same level of completion as was experienced in this case.

5. Important Considerations for Further Improvement of Program

From the inaugural capstone design program, a number of key observations were made by the authors that will require consideration for future years:

1) It was observed that were significant differences in design skills, experiences, and motivation levels between the students. In general, it was felt that students who were involved with the engineering co-op program were superior in design skills than those students who were not enrolled in the co-op stream.

2) In general, students were quite reluctant to apply the design methodologies they were learning. Often, the instructors and mentors were required to provide significant guidance at these stages of the program.

3) Some students had difficulty in maintaining proper engineering logbooks.

4) In many cases, the technical drawings produced by the students did not meet engineering drawing standards. It was felt that this is a reflection of the reduction in engineering drawing courses at the first and second year levels.

5) It was felt that in certain situations, students were reluctant to apply any form of technical analysis to their problem. This could be the result of not understanding the basic fundamentals of the design problem.

6) It was felt that students often possessed naïve optimism with respect to the work involved and the cost of constructing the prototype. This usually reflected the lack of experience of students in manufacturing components.
7) There was often an imbalance of effort between individual team members of the same design group.

6. Conclusions

A well designed student capstone design program is critical in the teaching of engineering design to undergraduate students. This paper reviewed the program delivered during the 2004 academic year, which brought a more professional design experience to the students. Supervision of project teams, review of potential design projects, and evaluation of the numerous reports was greatly enhanced through the formal establishment of a five-member faculty supervision team. The recruitment of three practising engineers as engineering mentors to the student design teams provided an industrial focus to the program and added a significant design resource to the students. The establishment of ten distinct milestones, including the requirement of completing a prototype, ensured that students followed an accepted design methodology to solving a client need. Through these changes, the quality of student design work has significantly increased over the work that had been performed in previous years.

Future work includes expanding the client base of industrial sponsors to ensure high quality open-ended design problems for the student teams, increasing the number of industrial mentors, refining the milestones and supporting lecture series to better reflect best design practices, improving the technical support for the teams, and continuing to work with design organizations such as CDEN that strive for excellence in engineering design education.

7. Acknowledgements

Funding for the development of the new capstone design program was made possible through a grant from the UBC Teaching and Learning Enhancement Fund. The successful delivery of a capstone requires the dedication and effort of a large number of people. A special thanks to all the students enrolled in the program for their patience and hard work during the development of the new program. A special thanks to Albert Ng, Laura Neels, Thomas Lau, Sherwin Wong, and Tuan Truong for use of their project as a design project example.

8. References