MAKING UNDERGRADUATE RESEARCH EXPERIENCE MORE PRODUCTIVE

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Abstract Problem analysis is taught in the classroom environment by having students solve problems that often have ready solutions. Because classroom problems are often solvable within an hour, problem analysis, as one CEAB (Canadian Engineering Accreditation Board) graduate attribute, may be viewed separately from other graduate attributes. Students participating in undergraduate research, however, learn problem analysis by also developing investigative skills, use of engineering tools (Matlab, Excel), even communication skills. In this paper we discuss our undergraduate research experience from perspectives of mentor and mentee. Mentor's motivation to recruit undergraduate research students could include (i) high probability of finding talented students to work on project of relatively short duration (i.e., one year) and (ii) producing solutions to a variety of problems that could lead to research problems. These motivations align well with motivations of undergraduate research mentees, i.e., experience in solving more realistic (open-ended) problems and strengthening their research portfolios. Generating "real world" problems can be achieved by introducing student-proposed design or analysis project component into a third-year course. Projects completed can then be continued into summer research projects. Results from the summer projects in turn enrich the third-year course content. To make undergraduate research experience more productive, mentor encourages mentee to write and present together a conference paper, such as CEEA 2018 Conference. National-level conference experience would strengthen student's research portfolio. Projects with higher technical content could even be presented to engineering conferences, which is what we are aiming for. We discuss ways to increase student participation. We provide a course project template for faculty members who are interested in adopting our experience into their teaching and research activities.

Keywords: Problem analysis. CEAB Graduate Attribute. Project-based learning. Undergraduate research.

1. INTRODUCTION

There are three types of problems: presented, discovered, created [5]. Within the context of undergraduate engineering programs, presented problem is one that a student typically has to solve in assignments and quizzes. Assignment and quiz problems can be difficult, but a student does not have to perform initial phases of problem solving: recognizing, defining, and representing. Such problem is set up usually similarly to what students have seen in lectures and textbooks, and relevant parameters of such problem are given in the problem statement. The recognizing and defining phases were completed or largely performed by course instructor. To solve the problem, student usually follows a solution template consisting of equations, charts, and tables given by class or tutorial examples. Presence of such template reduces the amount of representing phase needed to solve the problem.

Discovered problem is one that actually exists already but is never recognized as a problem until someone declares it [5]. Majority of problems in natural sciences has the discovered-problem character, where the best answer to a problem is one that can explain experimental facts in the simplest possible way. When solving natural-sciences discovered problems, a problem solver may encounter a created problem. For instance, Isaac Newton, when answering the discovered problem of gravity to explain planetary motion, had to invent differential calculus. Created problem is thus one that is invented and thus has not existed before. Ability to solve discovered and created problems can be regarded as a prerequisite for solving either problem type.

Engineering design problem is a created problem [1, 3]. Unlike the created problem that resulted in a differential calculus solution, a design problem may not have universal appeal and utility. Despite this difference, we would use engineering design problem as a proxy for created problem because solving engineering design problem require initial phases of problem solving: recognizing, defining, representing [4].

Canadian Engineering Accreditation Board (CEAB) defines problem analysis as "an ability to use appropriate knowledge and skills to identify, formulate, analyze, and solve complex engineering problems in order to reach substantiated conclusions" [2]. Engineering students in
Canada are thus expected to develop problem solving skills that can tackle all three problem types. This expectation may not be supported by undergraduate curriculum. To gauge whether such support is available, we can use engineering design content as a proxy for skill development in solving discovered and created problem types. Out of 39 required engineering courses in our Mechanical Engineering program, 4 to 6 have substantial engineering design content. If undergraduate engineering programs regard knowledge acquisition through solving presented problems is more urgent than knowledge application through solving discovered and created problems, then we might state that the proper course proportion is 3:1 for presented problems vs. discovered-created problems. Even under this knowledge-heavy proportion assumption, the amount of engineering design is still lacking.

In this paper, we propose to use undergraduate research experience to increase proportion of discovered and created problems in a course so that our students can acquire skills to solve complex engineering problems as expected by CEAB. We outline strategy to generate undergraduate research topics from a third-year machine component design course without relying on research program of faculty members. We introduce course project component into a machine component design course, which can be converted into summer research projects. Our student questionnaire data give 68% ± 6% approval that the course project component enhances their problem solving skills. The approval rating for the machine component design course teaches students problem solving skills is 82% ± 5%, indicating room for improvement. Such strategy should work for both largely undergraduate and also research intensive universities. In either case, the proposed implementation plan would require more work to set up in a third-year course, but the time required would revert to a typical course workload within 2 years once the undergraduate research program becomes a permanent course component.

2. Generating Research Projects

The most direct route to generate undergraduate research projects is to derive them from a research program a faculty member has. They could vary from designing and manufacturing of novel laboratory equipment to performing research experiments typically under the supervision of graduate student or postdoctoral fellow. We used this route for several years through NSERC Undergraduate Student Research Award (USRA). Two strong incentives for students to apply are (i) stipend amount comparable to a summer job income and (ii) research experience for graduate study. The minimum cumulative 3.0 GPA requirement is reasonable, but due to competition the actual minimum GPA threshold may increase to above 3.3. Thus, only few selected students can experience such summer research experience.

USRA students bring two advantages to the faculty member: (i) additional group members to speed up research progress and (ii) early recruitment drive of high quality students for graduate study. These advantages could motivate a faculty member to participate in the USRA program despite increased workload. Because this undergraduate research program is designed for increasing research activity of participating faculty members, their research areas are often not an integral part of undergraduate curriculum. Students often have to spend the first two months of summer studying relevant background before they can truly start their research.

Another route of generating undergraduate research project is through undergraduate courses. Not all undergraduate courses can efficiently host undergraduate research. Course selection rationale presented below uses mechanical engineering program as an example. It is almost given that first year mechanical engineering courses cannot be used as a platform for project generation. If engineering design is taught in first year, this design course is often to make students aware qualitatively on engineering design aspects and skills. Some second year mechanical engineering courses are good candidates, such as (i) probability and statistics, (ii) engineering graphics (CAD), (iii) numerical methods. They emphasize developing mastery of engineering tools, so it will be difficult for mechanical engineering research projects from these courses to have high research-oriented content. As comparison, using second year engineering mechanics course as a research project generation platform will also be difficult since students are learning fundamentals of mechanics and thus are not ready to work on research-oriented projects.

We recommend third year courses as the best candidates. Students have learned the fundamentals and the tools from second year courses. Most third year courses are continuations of second year courses in fluid and solid mechanics, engineering mechanics, and thermodynamics, in addition to new topics in heat transfer, manufacturing methods, materials engineering, and mechatronics. Fourth year courses are not ideal candidates because students are working on their capstone projects and students are more focused on their technical elective courses.

One main advantage of undergraduate course route is its slower pace. Students and faculty members have time to incubate research ideas when they work on course projects in Fall or Winter term before continuing their project as a summer research project. It is possible for students who would have to work in summer to start working on research project in Fall term. The slower pace can potentially include more students to participate in undergraduate research.
3. MACHINE COMPONENT DESIGN COURSE

We have used a third year machine component design course to generate research project seeds in the past five years. The course covers mechanical components: fasteners, springs, lubrication, bearings, gears, clutches, brakes, shafts, and is thus fundamental for mechanical engineering students. A review of solid mechanics and dynamics is usually given in the first few weeks to establish theoretical framework for their analyses.

The course could become procedural and uninspiring for a good portion of students if it had no project component; this was one author's experience when taking the course as an undergraduate student. Knowledge of performance and limits of mechanical components can be tested as presented problems if examinations are solely based on a set of class and tutorial examples. Aspects of engineering design can be covered as rules concerning safety factor, stress concentration factor, and failure scenarios.

To move beyond presented problems, a course project was introduced five years ago. The initial motivation for introducing the course project component was to not repeat the author's undergraduate experience. The first two years of the project implementation were difficult because of the breadth of knowledge covered; experience with assessing mechanical designs was acquired over 2-3 years and helped increase project quality. Course project component did not start becoming research project precursors until two years ago.

Most important lessons learned from 5 years of teaching experience are (i) course project has to be student-proposed to create genuine students interests, (ii) project proposals have to be vetted through one-on-one meetings, (iii) project deliverables have to be simplified to reduce course instructor and students workloads. Based on these lessons, turning such course project into a summer research project requires detailed course planning. Students receive project information package in their first class (Week 1) on (i) project expectations and (ii) project deliverables. This package contains examples of previous course projects and project ideas.

3.1 Project Expectations

Students are expected to work on either analysis or design project. Analysis project analyzes commercially available machine components or machine system, while design project proposes a mechanism using mechanical components. The number of critical components in either project should not exceed 4 in order to keep a project manageable.

Results of analysis project are calculation details combining theoretical and numerical analysis. To compel students to work on research-oriented topic, analysis project is only approved if the critical machine component involved is not found exactly in course textbook. One goal of analysis project is thus obtaining physical (mathematical, engineering) explanation of how the machine system studied works or gains its special property.

Results of design project are design drawings for the mechanism with calculations to predict its performance (strength, performance, stiffness). The proposed design may be arrived at by comparing available mechanisms (at least one) or by a creative engineering process involving identifying a problem that the proposed mechanism is supposed to solve. It is acceptable for the calculations in a design project to be less rigorous, but design project calculations have to give a reasonable indication on the proposed mechanism's performance.

Purpose of a project, which will guide the flow of analysis or design work to a practical recommendation or conclusion, has to be practical-oriented. Stating such clear purpose for a project idea compels a team to carefully assess why it is interested in a project idea. A project is only accepted if it has a clear and practical purpose. It is not sufficient for a team to work on a project that only explains how a mechanical component or system works. This is in keeping with the spirit of machine component design course, which uses mathematical analysis and mechanical design to come up with a practical device or practical technical advice.

A list of selected course projects in the past two years (2016–2017) is provided as reference:
1) Improving the Performance and Efficiency of an Existing Plastic Shredder;
2) Sprag Clutch Design;
3) Design of Bicycle Elliptical Chainring;
4) Design of Tail Rotor Driveshaft for Bell 206 Helicopter;
5) Power Requirement of Drilling Rig Tube;
6) Analysis of Deformable All-Season vs. Winter Tires;
7) Analysis of Motorcycle Dual Clutch Transmission;
8) Fall and Safety Factors of Grigri Device and Elastic Rope in Rock Climbing.

3.2 Project Deliverables

Maximum 5 students can form a team. For a class of 95 students, 21 teams were formed. To keep workload manageable for course instructor, project deliverables have to be kept concise. Except for Project Report due at the end of the term, the other three written deliverables (Project Charter, Project Proposal, Progress Report) are designed to be easy to write in order for teams to focus more on completing tasks and achieving project goals. Templates for all deliverables are provided with the project information package. Project Presentation for each team is limited to 8 minutes each and is held in Week 14.
Each student is estimated to spend on average 4 hours per week. The total number of hours per project thus ranges from 208 to 260 hours. Using an average 240 total hours per team, the estimated hours for different activities are as follows: (i) 30 hours of team meetings; (ii) 10 hours of external meetings; (iii) 80 hours of literature search and reading; (iv) 80 hours of analysis and/or design; (v) 40 hours of writing.

(a) Project Charter. Each team submits a 1-page Project Charter that contains members' agreement on (i) Role Distribution and (ii) Communication Protocol. The team has one week to reach the agreement so that Project Charter is submitted in Week 2. Project Chapter reduces significantly member conflicts during project execution.

(b) Project Proposal. Project Proposal has a maximum of 2 pages and contains 3 Sections: (i) Project Goal, (ii) Tasks to Complete, (iii) Results List. These Sections in essence captures team discussion (vetting meeting) with course instructor in Week 2. Section Project Goal outlines the main goal of the project. Section Tasks to Complete outlines the tasks required with their deadlines in order to reach the main goal. This Section can be presented as a numbered list and should provide sufficient details on what a team is doing to achieve the goal. A generic phrase "Performing Numerical Calculations" for a task does not have sufficient details. Week 2 Meeting with course instructor should cover these planned tasks since this discussion helps size up the project and ensure that the project will be likely manageable. Section Results List outlines the results with sufficient details the team wants and can be presented as a numbered list. Deadline for Project Proposal is at the end of Week 3.

(c) Progress Report. Progress Report aims to motivate teams to reach two milestones by the end of Week 8. The first milestone is completion of literature search and reading (literature review). The second milestone is obtaining governing equations for achieving the project goal. For design project the second milestone is obtaining proposed design drawings. The maximum number of pages for Progress Report is 3. In Progress Report each team classifies findings from literature review into two Groups: (i) Useful (Critical) and (ii) Interesting. Each Group can be presented as a numbered list. Usefulness of a finding for design project is present if the finding directly affects design specifications. Interesting Group lists findings that are not directly related to achieving the project goal but have potential for a different goal or changing the project goal if the finding is adopted. Course instructor will evaluate Progress Report by forecasting what the end product (Project Report) would look like based on the submitted Progress Report.

(d) Project Presentation. Project Presentation is held in Week 14, the same week Project Report is submitted. It aims to share the main results to the class. Each Presentation including questions from audience lasts maximum 12 minutes and should focus on useful results.

Project Presentation should not focus on methods. Suggested Presentation duration is 8 minutes so that audience has 4 minutes to ask questions.

(e) Project Report. Project Report should aim to present project results logically. It should start by recalling the project goal and providing an executive summary that ties all results together toward the goal. It then proceeds to describe methods used. Project Report has maximum 12 pages.

3.3 Course Instructor Workload

The busiest week is Week 2 when all teams meet with course instructor: about 15 hours for 21 teams from a class of 95 students is spent. Subsequent weeks typically require 2 hours per week for team consultation. Project Charter marking requires 2 hours. 21 Project Proposals require 4 hours. 21 Progress Reports require 6 hours. Project Presentations occur during classes so they require no additional hours. 21 Project Reports require 12 hours. Administrative tasks take about 7 hours. The total number of hours is thus 70 hours.

The 70 hours total time is roughly equivalent to preparing and marking a midterm exam. Our machine component design course has neither midterm exam nor laboratory. Four 30-minutes quizzes are administered, in addition to final exam.

3.4 Course Grade Components

Course project takes up 45% of final grade, while the 4 quizzes are worth total 24%. Final exam takes up 31%. They are intended to send a strong signal to students of the course project importance.

The 45% for course project is divided as follows: (i) 3% Project Charter, (ii) 5% Project Proposal, (iii) 5% Progress Report, (iv) 8% Project Presentation, (v) 24% Project Report.

4. CHALLENGES AND GOALS

First challenge is to motivate third year students to convert their course projects into summer research projects and to continue working on the summer projects. Most students after completing their third year would like to work on one-year internship. For example, one project from Winter 2016 term, which continued in Summer 2016, could not gain traction because the number of students participating dwindled to two by July as the rest moved to internship. Another project in Summer 2016, which was committed to, didn't start because all team members had internship. The surviving project continued to Fall 2016 term it didn't progress sufficiently because the remaining two members were on internship in that term.
This year we are applying for internal university funding for providing stipends to students working in summer research projects. It is important to be realistic as not all students are interested in undergraduate research, but there are students who are interested in moving beyond solving presented problems. We would also like to know the fair expected number of summer research projects. We are going to distribute a questionnaire to the course students to establish a baseline proportion estimate of students interested in converting their course projects to summer projects.

One solution we are experimenting is to invite entering third year students to participate in summer research projects of the outgoing third year students. This has happened for one Summer 2016 project, where one entering third year student (i.e., one of the authors) participates after learning about the project from engineering student society's online ad. Entering third year students can start in summer or Fall term.

Second challenge is to achieve above-average quality course projects and thus to produce at least conference papers from summer projects. Third year students have a maximum of 8 months (two terms, including summer). If within the 8-months period a project cannot produce at least a conference paper, then the project should be able to enrich the course content as database for discovered and created problems.

To achieve a goal of at least a conference paper, course instructor has to ensure the project has such potential in terms of topic and students quality before the project continues to become a summer project. Course instructor thus has to select candidate projects based such criteria during course delivery. It is possible therefore that motivated students may not be given approval to continue their project into a summer project if the project is not selected.

Course instructor may have to perform literature search and to provide additional research materials to work together with students to accelerate the project progress. This additional work would be performed by course instructor if course instructor is motivated to becomes a co-author. Another motivation for course instructor is that students performing in such summer projects could be interested in pursing graduate study. It is important that this collaboration starting in summer does not create conflict of interest during regular term when the course is delivered. Conflict of interest can be prevented by clear statements of project expectations and marking rubrics for all project deliverables in the project information package. Course instructor thus acts as a mentor when a course project becomes a summer research project. Course instructor doesn't have to act as a (close) academic supervisor.

Figure 1 shows that the conversion from a course project to a summer project funnels through several filters. In addition to students motivation and possibly funding availability, project topic has to have potential and course instructor needs to be research-prepared. Realistically, there may be 1-3 summer projects that can be generated from 15-21 course projects, with 3 being the maximum number due to time and research commitment demanded from course instructor. Most course projects thus become course database to enrich course content. Such database can be developed to become case studies that next cohort of students can learn in classroom as simulated machine component design practice.

5. IMPLEMENTATION PLAN

The two challenges in Sec. 4 Challenges and Goals are translated into the following action plan. The list below orders the items from the most easily achieved. This action plan could represent a chronological to-do list if a faculty member is interested in adopting our course project experience. After the last step the plan is cycled back to the beginning.

1. A third year (mechanical engineering) course is the most ready to have a course project component as discussed in this paper. Main reasons are outlined in Sec. 2 Generating Research Projects.

2. Structure the third year course so that the final grade weight of course project is 40-50%. The overall time commitment is similar to preparing and marking a midterm as explained in Sec. 3.3 Course Instructor Workload.

3. Provide detailed course project information package to students at the start of term. Types of information in the package are detailed in Secs. 3.1 Project Expectations and 3.2 Project Deliverables. Key points are student-proposed project; each project idea vetted; clear marking rubrics; simplified deliverables;
maximum 5 students per team for accountability and student experience satisfaction.

4. Connect course materials to project topics along the course duration. This also reminds and motivates students to keep working on their projects.

5. Identify candidate course projects for summer research projects based on their topic potentials and also course instructor's background and interest. This prospect evaluation can be performed after Progress Reports are submitted in Week 8.

6. Announce to students during their Project Presentation that students motivated to continue in summer can inform course instructor. Provide information on funding availability and research expectation. Emphasize continuity of the course projects and how they could benefit next cohorts of students.

7. Put discontinued course projects into course database. Some could be converted readily into case studies next cohort of students could study. Some that have great ideas but require more work can be repurposed into course projects next year.

8. Mentor students in summer to work on their projects further. Set a clear target in early May on what each project should deliver by end of August. If a project continues in Fall term, set a clear target in early September for December target. This activity could continue to Winter term if desired.

9. Starting end of summer, search for conferences in both engineering education (such as CEEA and ASEE) and relevant technical engineering areas (ASME, SAE, CSME, even APS) to give students venues to present their works.

One additional step that will help attract students to participate in summer research is to register the summer research program to a Faculty's co-curricular leadership program. Research activity and community services are often viewed as aspects of leadership initiative, and participating students can have transcript citations of their summer research activities. We have started providing students with these transcript citations.

6. CONCLUSIONS

Third year course can accommodate undergraduate research component through course projects. Students can continue these projects into summer and next academic year. This research activity model focuses on students' curiosity and innovative ideas and can complement NSERC USRA model that focuses more on faculty members' research programs. Course instructor will spend more hours designing such course, but from our experience workload will return to normally expected after 2 years. We provide course project template for interested faculty members. Two main challenges are motivating students to continue their course projects into summer and enhancing project quality. Steps to overcome them are being implemented and discussed.

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References


