A contextualized, experiential learning approach to quantitative engineering analysis

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***Abstract*—This work-in-progress, innovative-practice paper describes the creation and first two iterations of an experimental course which aims to develop a process-focused approach to integrated quantitative engineering analysis in early stage engineering students. The goal of this two-semester course is to improve the confidence and competence of our students in choosing and applying the tools of quantitative analysis to solve practical problems throughout their time in college and beyond, including in other course projects, senior capstone experiences, internships and in their careers. The course is led by an interdisciplinary team of faculty, in a project-based format, including in the presentation of fundamental concepts in mathematics. The course is run studio style, with emphasis placed on the process of engineering, improving students' self-directed learning skills, and encouraging peer and near-peer learning. Overall, we observed a high level of engagement in the course, with student-chosen final projects that involved significant analysis and self-directed learning of new tools and approaches.**

***Index Terms*—engineering analysis, project-based learning, cross-disciplinary team teaching, foundational courses**

I. Introduction

This work-in-progress, innovative-practice paper describes a prototype 16-credit, two-semester course open to first-year engineering majors at our undergraduate institution. This course has been run twice before, and is currently in its third iteration. The main goals of this course are to improve students' competence and confidence in applying the power tools of analysis in solving engineering problems. The course places a significant emphasis on the process of engineering analysis in addition to the tools of engineering analysis. Success of this course in achieving these goals will be indicated by students' comfort level and ability to effectively apply analytical and mathematical tools in their senior capstone projects and beyond. The purpose of this paper is to introduce the course structure and content and to share lessons learned. After participating students finish their senior year, we will assess and share the longer-term outcomes of this course.

In addition to the main goals of the course, other goals include improving students' self-directed learning, teamwork and presentation skills. We also view this course as a professional development opportunity for faculty to improve their abilities in working as part of an interdisciplinary teaching team and facilitating a completely project-based course.

In pursuing the goals of the course, we presented the vast majority of the technical material in the course in the context of tangible engineering projects and problems, including material typically covered in mathematics courses such as multivariable calculus and linear algebra.

A number of different institutions have implemented integrated mathematics, physics and engineering courses for early stage engineering students, including but not limited to the programs described in references [1] and [6]. Our institution has also experimented with integrating fundamental mathematics, physics and engineering since its inception. Relative to these courses, our approach has a larger semi-block structure, an increased emphasis on introducing the fundamental mathematics and physics material through the project rather than adding an interdisciplinary project on top of traditional presentation of the material, and delves deeper into connecting the fundamental material to more advanced topics that are traditionally presented in major-specific courses such as Fourier analysis and control theory.

II. Course Structure

This course is split over two semesters, starting in the students' second semester and continuing in their third semester. The course counts for 8 credits per semester, thus taking up the space of 4 standard courses at our institution. It is a designated alternative for Multivariable Calculus, Linear Algebra, Differential Equations, and Signals and Systems or Dynamics, which are courses that are typically taken in the first and second years at our institution.

The course meets twice a week for 3.5 hours per session, with a 15 minute break in the middle. Since this is an 8 credit course per semester, the students are expected to spend 17 hours per week on the course outside of class hours. 36 students enrolled by lottery in each of the first two iterations of the course sequence and in the current iteration, 62 students are enrolled which respectively, represents just over 40 and 70 percent of the student body per year at our institution. Approximately half of the students in the class identified as women. The course is taught by an interdisciplinary team of faculty which thus far includes a mathematician, physicists, computer scientists, electrical and mechanical engineers, a computational neuroscientist, and a systems engineer. In addition, the course had substantial support from undergraduate teaching assistants who participated in developing certain

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aspects of the course, running regular office hours, grading assignments, and weekly one-on-one check-ins with students.

In the first two iterations, the course met in a studio-style classroom with large tables seating 4 students each. Each table had a significant area of white board space next to it to facilitate group work and student-faculty interactions. In the current iteration, two such rooms are used in parallel.

This course is being run as a three-year experiment, during which time, the courses for which this course is a designated alternative continue to be offered at our institution. At the end of the three-year experiment, the faculty will collectively decide on whether to make this course the default offering either as is, or with some adaptation.

III. Course Content

The course is split into 7 modules: 3 in the first, and 4 in the second semester. Each module is focused on an engineering challenge which was designed by the faculty specifically for this course to be appropriate for a student's first exposure to the mathematical tools they are learning, and for scaffolding the quantitative analysis process in a variety of domains (see Fig. 1). Over the course of a module, the students are first introduced to the engineering challenge (problem identification). They then break the challenge down to understand the specific underlying questions and the topics they must learn in order to answer these questions (deconstruct, identify concepts) . This question breakdown phase motivates a period of core content learning where students study the topics necessary for the challenge and practice them in smaller scale applied problems (identify accuracy $\rightarrow$ apply and calculate). Then, following and sometimes in conjunction with the core content learning phase, they attack the final challenge, applying what they have learned to complete this engineering task successfully. While each module contains substantial core content learning, the engineering challenges are intentionally interdisciplinary and the core material is not intended to be a complete traditional presentation of the topic at hand. Rather, different modules may contain different pieces of a particular topic or different applications of a particular analytic technique.

The first module challenges the students to build a boat. The boat must float flat, carrying a cargo and supporting an aluminum mast, and it must be stable when inverted to an angle between 120 and 140 degrees off the vertical, but must not be universally stable. On the first day, the students attempt this challenge in two hours, which provides a compelling introduction to the problem, demonstrates the difficulty of this seemingly simple task, and builds community in the class. The core content learning in this module includes forces and torques, statics and stability, functional curves and surfaces and multidimensional integration.

In the second module, students are asked to write two pieces of software for facial recognition. Students learned major topics in linear algebra and introductory statistics and data science in this module. For their projects, students were tasked to implement the eigenfaces algorithm (starting from the original source [7]) and another algorithm of their choosing.

The third and last module of the first semester is focused on robotic navigation and is structured slightly differently. The students face three sequential challenges which build on one another and on material from the first two modules. The three challenges are to navigate a robot on a path defined by a parametric curve, up a hill, and through a maze of obstacles to a goal. The students study core material related to parametric curves and their derivatives, kinematics, gradients and optimization framing, scalar and vector fields and potentials.

For the fourth module at the beginning of the second semester, the students work on controlled heating, motivated by a senior capstone project at our institution on designing low-cost warming bassinets for newborn babies. In this module, students were introduced to differential equations, Laplace transforms, block diagrams and basic control theory. In their projects students design and implement control algorithms according to criteria that they chose (e.g., minimizing power consumption or response time).

In the fifth module, students designed motion sensing systems using accelerometers in their mobile telephones for an application of their choosing. The main ideas of signal processing including time-frequency analysis, Fourier transforms, filtering and sampling theory were introduced in this module. Additionally, students were also introduced to concepts from dynamics such as rotating reference frames. Projects that the students implemented include systems to analyze rowing, arm motions of conductors to provide feedback to visually impaired musicians, gait, and golf swings.

In the sixth module students were tasked to design and implement a control system for an inverted pendulum robot which would compete in different events in a robotic olympics. The inverted pendulum is a classic problem in control theory which is typically only demonstrated by an instructor, whereas in this course, students designed, analyzed and implemented the algorithms themselves using a commercially available robot platform with a modified chassis. This module enabled students to advance their understanding of control theory, Laplace transforms and dynamics, as well as expose them to real-world phenomena such as sensor noise and drift.

The last module in the course is a student-proposed project where students design a project to go deeper in one of the core learning areas from the two semesters of the class. This module enables students to exercise the approaches to self-directed learning that they learned throughout the course to teach themselves new concepts and apply these ideas in a tangible project. Projects that were completed in the last iteration of this course include a Sudoku solving program using semidefinite relaxation, a passive, dynamic walker, an image compression algorithm based on the JPEG standard, magnetic levitation, and a multiple-input, multiple-output acoustic modem.

IV. Module structure

The general structure we use for the modules is shown in Figure 2. Each module lasts between 4 and 6 weeks. The first day of a module starts with an introduction to the project with a significant emphasis on generating student excitement and

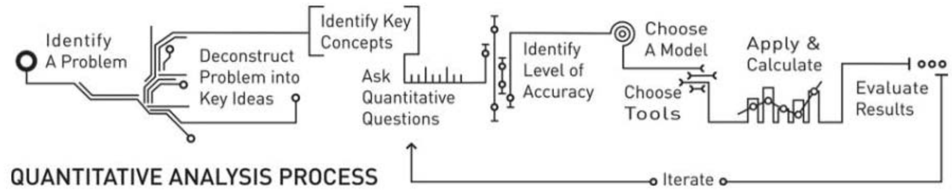

Fig. 1. Illustration of the process of solving an engineering problem.

Fig. 2. General structure of a module.

motivation. The project introduction activities typically include a hands-on component, such as constructing model boats out of foam, and collecting accelerometer data on their mobile phones while doing different activities.

A. Problem breakdown

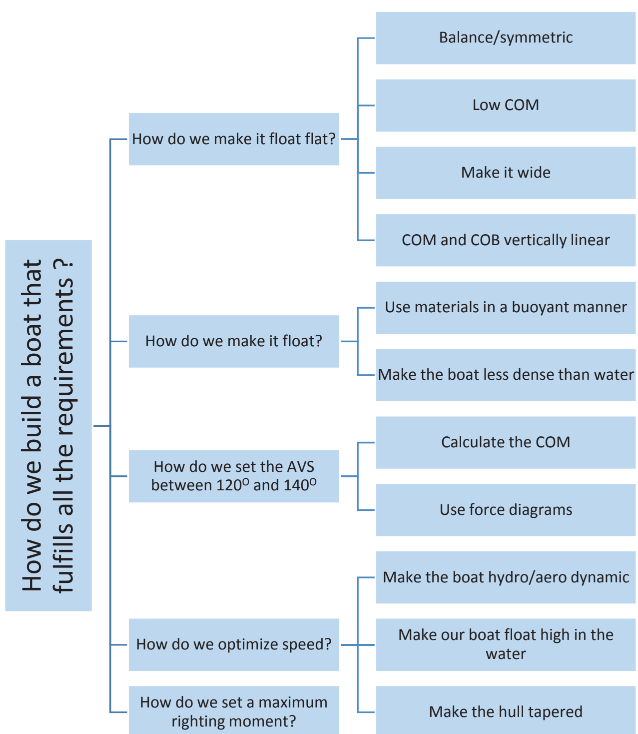

Fig. 3. Illustration of Problem Breakdown adapted from student response.

The second half of the first day in each module is spent on problem breakdown activities, where students are asked to do some background research through the web and/or a list of recommended sources on the topic of the module. Working in pairs in class, students are asked to break down the project into a set of smaller addressable problems and so on. This activity is facilitated by faculty instructors who circulate in the room providing feedback and prompts where necessary. Students are asked to provide a graphical representation of the problem breakdown, a generic example of which is shown in Figure 3. Students are also asked to identify keywords and concepts that are related to the project, and produce a simple concept map of the main subtopics that they need to learn about to complete the project. These activities help scaffold students' learning and their work on the project.

The following 2 - 3 weeks are spent in a cycle of acquiring new skills and knowledge as detailed in Section IV-B. The last 1 - 2 weeks are spent working on the project, followed by a final presentation, and/or demonstration, and reflection.

B. Acquisition of skills and knowledge

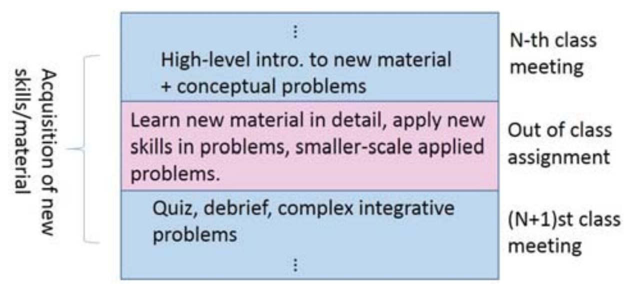

Fig. 4. General structure of in-class and related out-of-class activities.

In each module, the students build skills and knowledge through a cycle of in-class and out-of-class activities (illustrated in Fig. 4), which are guided by handouts. A typical cycle starts in the latter half of a class period, when students are introduced to a new topic area (e.g. eigenvalues and eigenvectors). An in-class handout introduces the main ideas through a combination of text, links to external web resources and videos (both home made and external). The students typically work in groups on a set of problems designed to highlight the main ideas of the new topic. These problems include hand calculations typical of standard problem sets (e.g. students are asked to calculate the eigenvalues and eigenvectors of a 2 x 2 matrix by hand), and computer-based exercises (e.g., to verify hand calculations). The students work in groups of 2-4 and are strongly encouraged to do their calculations on the whiteboards adjacent to their tables, which enables the instructors to quickly scan the room to assess where students are in completing the assigned work. The students are required to take photos and upload their in-class work.

The in-class activity is followed by a more in-depth treatment of the topic in an out-of-class assignment. The out-of-class assignment is given in the form of a electronic handout which combines text describing the new material, links to resources including videos and written material on the web, and exercises. Depending on the module and topic, the exercises are a combination of derivations, hand calculations, and numerical and experimental challenges. Each student is required to submit a write-up with the solutions to the exercises before the start of the next class, and group work is encouraged. These assignments typically include a number of activities where students are required to turn problems described in words into a set of equations that they then solve.

The next class period typically starts with a diagnostic quiz (i.e. the results do not impact grades) that touches on all the main areas covered in the previous out-of-class exercise. The quizzes are administered electronically with instructors and students getting immediate feedback on topics students had difficulty with. The quiz is followed by a debrief activity where students work in groups of 4 to discuss the quiz and previous out-of-class assignment. The students first list the topics that they learned and areas of confusion on the board next to their tables, and then try to work out points of confusion in their groups. During this phase, the instructors circulate around the room and help answer questions. If a particular topic is found to be causing widespread difficulty, the instructor will present a mini-lecture (limited to 15 minutes) on the topic. If the confusion persists (which happened very rarely), we either include further clarifying material in the next out-of-class assignment or provide a time for discussion with an instructor after class. Finally, students complete 1-2 problems which are designed to synthesize the material covered in the previous out-of-class assignment. The quiz, debrief session, and the synthesis problems typically take up one half of a class period. The second half used to introduce a new topic.

This process of introducing new material helps build the students' self-directed learning abilities as they acquire knowledge primarily through reading written materials, online resources and interactions with their peers, and near-peer teaching assistants. As the course progresses, the instructors provide less scaffolding for the self-directed learning by providing progressively fewer suggestions for sources, culminating in a self-designed project for the last module where students chart their own courses for acquiring the skills and knowledge required to complete their projects.

V. Student Assessment

Student assessment in the course was based on a constructive engagement rubric. Students were expected to be engaged in best practice behaviors and learning management to achieve course objectives and their personal learning goals. Both quantitative and qualitative assessments were conducted. Quantitative assessments included scores on written assignments, project presentations and reports, attendance in class and in weekly check-in meetings with teaching assistants. Qualitative assessments were based on level of engagement in class, professional behavior, willingness to seek help when needed and professionalism in responding to feedback. Students were provided with a brief narrative of their assessment and a letter grade at the end of each semester in the course.

In addition to faculty assessment of student performance, we provided opportunities for student self-assessment which is useful given the emphasis on self-directed learning in the course. These opportunities include in-class diagnostic quizzes, modules which included multiple challenges which students could attempt progressively, and written reflections.

VI. Observations and Lessons learned

Preliminary data on student motivation collected in the current iteration of the course indicate that the course supports positive student motivation, i.e. students had a strong sense of interest and enjoyment, and of value in the course. Additionally, there were no gender differences in the measured variables for student motivation in the preliminary data.

This class was designed in part to improve the willingness of students to use quantitative analysis in their senior capstone program, so this is our primary target for outcome assessment. At the time of this work-in-progress paper, we do not yet have these results, but we do have a large amount of observational and qualitative data on student behaviors from within the class and quantitative skills attained by the conclusion of the class. We plan to asses the outcomes of this course from our first cohort of students who will begin their capstone projects at the time of this publication and publish our findings.

We observed a high degree of student engagement in the course including dynamic in-class participation, completion of deliverables, attendance at office hours and performance on projects. We also observed a high degree of self-directed and peer learning as intended by the designed learning environment of the course. The classroom for the course was a dedicated space, and students frequently spent time outside of class hours in the classroom working on the course and getting help from fellow students and course assistants. Further, students appreciated faculty efforts to make our thinking visible to the class, both in terms of course work, e.g. by explicitly stating the goals of each part of an assignment, and in explaining to them the principles behind the design and delivery of the course. The latter part was accomplished via regular communication with students regarding the flow of the class and why certain decisions were made.

The students attained a high level of quantitative abilities over the course of the two semesters. This was most visible in the last module of the course, where students designed their own projects. Each project was backed by detailed mathematical analysis which students were required to include in their final deliverables. The technical content of students projects was at a very high level for third semester students, which indicates that the approaches we took in this course have promise for training early students to use sophisticated analytical tools to design and implement systems that solve engineering problems through self-directed learning.

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