**INTRODUCTION**

Undergraduate chemical engineering students are required to develop strong analytical and numerical problem solving techniques. The analytical side is thoroughly covered through the entire calculus series and differential equations. However, numerical approaches for solving complex problems are an area that remains frequently underdeveloped. Numerical techniques are regularly needed in chemical engineering in circumstances when either the analytic solution is unobtainable or data is collected at discrete time points. Examples include analysis of non-linear functions, higher order reaction kinetics, advanced thermodynamics, and transient control applications [1].

The coverage level of numerical techniques across undergraduate programs varies greatly. Even when a numerical methods class is part of the required curriculum, it is not typically considered a key or core course. What students fail to recognize is that many higher-level engineering courses build upon a foundation of both strong analytical and numerical techniques. These upper-level chemical engineering courses, which are more mathematically challenging, are typically considered the core curriculum, including thermodynamics, transport phenomena, reaction kinetics, and fluid dynamics. Therefore, for students to succeed in these advanced courses they need to not only be proficient with numerical analyses, but understand how these techniques support the field of chemical engineering.

**THE CHANGING CHEMICAL ENGINEERING CLASSROOM**

In recent years, it has becomes increasingly apparent that the structure and delivery of engineering education needs to be modified, in order to match technological advances and developments in the workplace [2]. Some of the concerns raised include the need for incorporation of “real-world” engineering design, improvement of critical thinking and analysis capabilities, increased opportunities for students to develop written and oral communication skills, and promotion of teamwork [3]. Employers are seeking graduates who are able to undertake a challenging, multidisciplinary problem by applying both chemical engineering skills and creativity. In fact, the best chemical engineering graduates are the ones who can successfully connect real world applications, constraints, and considerations to a technically challenging problem [4].

The long-term goal of educational reform is to expand student problem solving approaches and confidence, acquire professional development essentials, and establish their own methods and metrics for success. To answer the demand for the evolving educational approaches, many novel teaching techniques have emerged, including flipped classrooms, problem-based learning, and collaborative learning [5]. Another approach that has shown tremendous potential in student development is the implementation of open-ended group projects [6,7].

**DESIGN AND IMPLEMENTATION OF CONNECTIVITY PROJECTS**

The chemical engineering curriculum at the University of Dayton requires students to complete a class focused on numerical techniques, entitled Advanced Mathematics for Chemical Engineers (CME 381). This junior-level class follows
a three semester calculus series and differential equations. The primary focus of this course is to promote student proficiency in numeral analysis techniques, which will be necessary in subsequent courses and in their professional lives. Table 1 provides a summary of numerical methods covered in CME 381 throughout the semester. However, because these topics are used at a later period, many students fail to grasp the importance of CME 381 while enrolled within the course. To improve student appreciation of course material, as well as enhance their technical proficiencies, we developed and implemented “Connectivity Projects” in CME 381 during the fall 2015 semester. The goal of Connectivity Projects was to help students recognize that the tools and applications learned in CME 381 were broadly applicable across the entire chemical engineering curriculum and in the real world.

Working in self-selected groups of two to four students, each group was responsible for 1) identifying a unique project that utilized numerical techniques but applied to another engineering course, 2) performing the required mathematical analysis to solve the selected project, 3) incorporating Microsoft Excel or Visual Basic into their solution, 4) writing a written report outlining their rationale for project selection, their solution approach, and final conclusions, and 5) presenting their project and results to the class. The programming element was included in Connectivity Projects in order to improve student proficiency and confidence in programming capabilities. Additionally, each group chosen Connectivity Project required instructor approval. The rationale for instructor approval was to ensure that selected topics could be successfully analyzed using techniques from the course and that each group developed a unique project.

To select a topic, the student team considered all engineering courses they had previously taken or were currently enrolled in, and identified a unique problem which could be solved using numerical techniques studied in CME 381. During this time groups also were required to determine how programming would be integrated into their solution. Once a group agreed upon a project of interest, they submitted a two paragraph proposal to the instructor which outlined 1) the selected problem for this project and what engineering course it was connected to, 2) what motivated them to choose this topic, 3) what numerical, and potentially analytical, techniques would be implemented, and 4) how programming would be incorporated in the solution.

The instructor criteria for approval were that the above points were all clearly and accurately outlined, the problem was complex enough to require multiple analyses, and ensuring that this project was unique.

Following instructor approval the groups were allowed to begin working on their projects. They had several weeks to perform the necessary mathematical analyses and computer programming to complete their project. It was required that all mathematical solutions submitted included a description of any necessary assumption and all intermediate steps. In addition, students were required to produce a final, written report that included all their mathematical work as well as a full explanation of the numerical processes and programming involved. In the report, students were to include a discussion on how the completed project applied to another course and the group’s project selection process. The last component of the Connectivity Project was a presentation that was prepared and delivered to the class. Evaluation criteria for these presentations included all the requirements in the written report as well as organization and preparedness. Through the joint written and oral aspects of this project, the importance of communication skills was reinforced to the students.

**PROJECT RESULTS**

Connectivity Projects were first implemented in CME 381 during the fall 2015 semester. During this semester 31 students were enrolled in the course, and divided themselves into 8 groups. As shown in Table 2, the groups selected a broad range of topics that spanned multiple chemical engineering courses, including thermodynamics, transport phenomena, and reaction kinetics. As thermodynamics is a foundational course for chemical engineering students and our undergraduates take two semesters of it, we were not surprised that many of the projects were thermodynamics-based topics.

In these projects students successfully demonstrated mastery of multiple techniques covered throughout the semester. For example, the group that developed the 2nd order momentum profile solved this problem both analytically and using a 4th order Runga Kutta numerical approach, generating nearly identical results. The group that used root finding techniques to predict system temperature from a complex thermodynamic equation implemented and compared four different methods: traditional graphing, using the solver function in Excel, the Secant method, and the Newton-Raphson method. They concluded that the graphing method was the least accurate, while the other three approaches arrived at the same answer. However, the numerical techniques (Secant and New-Raphson) both required an initial guess, which introduced extra iterations and therefore was more time and calculation intensive than using Excel. While curve fitting applications were the most frequently utilized in Connectivity Projects the format of fitted functions varied greatly, including, linear, polynomial (2nd and 3rd orders), and non-linear regression.

The class average on their Connectivity Projects, including the execution, written report, and presentation aspects was an 88%. The accuracy of the student analyses and results demonstrated their fundamental understanding and ability to perform these required numerical techniques. While we were exceptionally
pleased by the quality and rigor of the submitted assignments, it also appears that the students enjoyed this work themselves. For the first time, end of semester evaluations did not include student comments regarding a lack of course applicability or usefulness. Additionally, these evaluations included several student comments that expressed appreciation for efforts to connect course material to both industrial applications and other engineering classes. Therefore, we believe that implementing Connectivity Projects into our chemical engineering curriculum was an effective way to engage students in numerical methods and help them develop critical connections.

CONCLUSION

In an effort to engage undergraduate chemical engineering students and facilitate their development, we designed and implemented Connectivity Projects into CME 381, a class centered on numerical processes. During the design phase we focused on project aspects that would help students gain technical and programming competencies, emphasize the applicability of course content, and develop their communication skills. Eight student groups were responsible for choosing a problem that connected to a different engineering course, required multiple mathematical techniques to solve, and integrated computer programming. Following their analysis, students presented their work in both a written and oral manner. Based on the high class average of 88%, we concluded that Connectivity Projects were an effective and engaging way for undergraduate students to apply numerical techniques and identify where these methods are critical in the everyday life of chemical engineers.

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REFERENCES