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An Adaptive Scaffolding Approach Based on Team Dynamics in an Integrated Masters and Undergraduate Bioengineering Capstone Design Course

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Introduction

Capstone courses in undergraduate engineering programs serve useful roles for both students and faculty. ABET criterion 5 essentially requires a summative project, which is often delivered through a capstone course [28]. For students, these courses represent an opportunity to apply their training and skills to a problem relevant to the domain of their studies. It could be argued that a capstone course is one of the most effective courses by design, given that the structure and content of these courses often represents practical experience more authentically than traditional lecture-based courses [5,24]. Pragmatically, these courses present several challenges for faculty and administrators. The curation and selection of projects, whether to deliver the course in one or multiple semesters/quarters, and assessment of student group work all pose significant challenges which must be addressed to deliver the curricular outcomes of a capstone course [1,2,3,20,22,26]. These additional challenges translate to capstone courses requiring high investments of time and effort for instructors and administrators [20].

At the University of Illinois at Urbana-Champaign (UIUC) Bioengineering Department, the Bachelor of Science (B.S.) program requires a one-semester capstone design course. In the same department, the Master of Engineering (M.Eng.) program curriculum also requires a project management capstone style course. This requirement is among several differences which separates the M.Eng. program, which focuses on preparation for industry, from a Master of Science (M.S.) which typically reflect more academic and research focus. Recently, UIUC combined the capstone program for undergraduates and the M.Eng. capstone program into a jointly offered course. The details of the merger can be found in an earlier article [11].

There are several key benefits to combining the two programs intended to enhance the experience for students and instructors. One benefit of a joint course is that sharing the pool of projects across both courses reduces the total number of projects required to be solicited and approved each cycle, allowing faculty to focus on recruiting a smaller number of higher quality projects. Another benefit in combining the courses is the increased alignment between the goals of the M.Eng. program and the undergraduate program. Whereas the undergraduate program fulfills many ABET criteria through the technical execution of a capstone project [27,28], the M.Eng. program objectives are amenable to providing management experience more representative of the kinds of industry positions M.Eng. graduates typically seek [22,25]. These two major objectives complement well and lend themselves to more complex team dynamics which are increasingly representative of practical experience in industry [12,25].

Undergraduate Roles

Undergraduate students’ roles in the capstone course are designed to be reflective of an entry level R&D engineer in industry. Students are expected to contribute to ideation and design early on by reading literature, searching for existing solutions, and communicating their findings to the rest of the team. The M.Eng. students and sponsors provide guidance, direction, and give feedback and input to the undergraduate students to assist in refining the plans for how the project will be carried out. The undergraduates take the lead in executing prototyping and testing project designs. The course dictates that every 2 weeks, the undergraduates summarize the details of the team’s past progress and their future plans in a short write up which gets sent to the M.Eng. student(s). These informative reports help the M.Eng. students stay fully aware of detailed progress. The M.Eng. students then pass along the information along with their considerations for timeline and resources to the project sponsors. Faculty are copied on these regular communications, and students are given credit for completing and sending these reports on time. The undergraduate teams meet with a course instructor every two weeks for a 30-minute check-in meeting, which serves to monitor team progress and help students stay on track as the semester progresses.

M.Eng. Roles

Throughout the course, M.Eng. students attend some of the course content including group presentations to help deliver high level overviews and answer questions. M.Eng. students are tasked with helping the teams to ensure their research and design ideas are thorough, reasonable and provide feedback to the undergraduate teams regularly regarding course progress. M.Eng. students also meet regularly with course faculty, where they are expected to provide updates to the faculty and receive feedback on how the projects are progressing. At the semester handoff after winter break, the M.Eng. students help to bring the new cohort of undergrads up to speed on the previous semester's progress. Helping to manage multiple teams of undergraduates gives the M.Eng. students opportunities to learn and practice their skills in communication, leadership, and creativity in how they help their team overcome obstacles. These skills, even more than technical competencies (programming, prototyping, data analysis, etc…) are commonly listed by industry as being the most important skills for graduate level hires [25].

One challenge with combining these courses arises from the additional complexity of supporting more complex team dynamics which will heavily impact student experience [2,4,9]. A 2013 review of engineering team effectiveness from a psychological perspective found that while many reports focus broadly on teamwork, a smaller proportion focused on interdisciplinary or complex teams [4]. Another more recent (2019) review captured multiple strategies to team formation in capstone courses, highlighting the tradeoffs between student led and instructor designed solutions [20]. Early on, it became evident that providing clear and consistent communication regarding roles and responsibilities was essential to ensuring students' positive experience with the course. To address this, the course faculty introduced several interventions into the structure of the course to help improve team dynamics such as communication and work delineation. A more thorough explanation of the design of this structure can be found in [1]. These elements are intended, like scaffolding, to reside adjacent to the coursework but to support students in understanding and navigating challenges should they arise [2,22,23]. Through a team contract, we encourage students to engage actively in their role, creating "buy-in" to promote better outcomes and a framework to aid in conflict resolution [4,9,18,20]. The goal of this work was to investigate how these scaffolded elements have been received by students in the first three cycles they have been deployed, and to report on the themes identified from student feedback regarding their team dynamics.

Methods

Team Contract and Survey Design

The joint course follows a familiar format which combines the project work with structured lectures and workshops into one course [13]. Throughout the course, each team is responsible for several assignments and attendance which constitutes the assessments for the

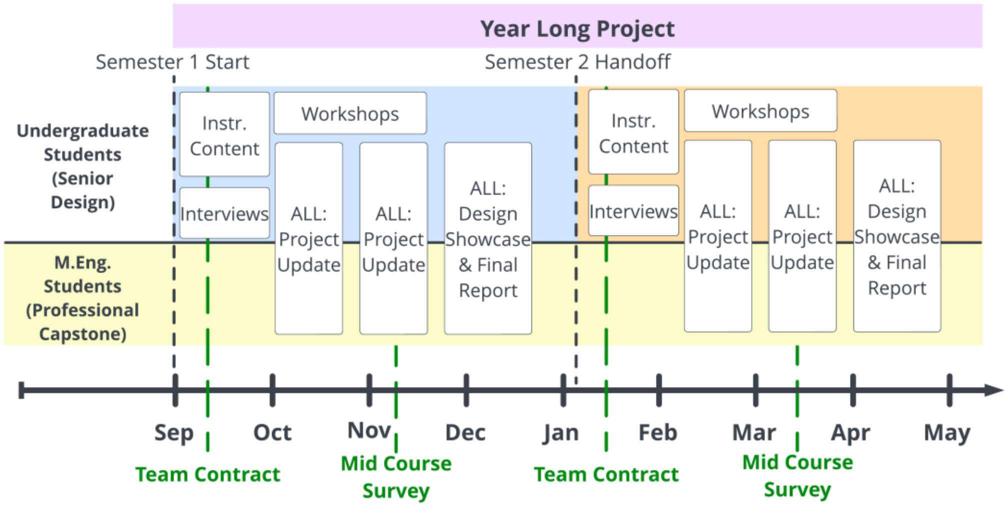

Figure 1. Course timeline. Team contracts are redone at the beginning of each semester with a new cohort of students (blue and orange). M.Eng. students remain with their projects all year, helping transition the project to a new cohort in January (yellow).

course. A snapshot of the semester timeline can be found in Figure 1. At the beginning of the semester, students review the available projects and submit their preferences for projects and teammates. Course instructors review student preferences and assign teams while trying to best accommodate student preferences while balancing team sizes, grouping minoritized students, and accounting for any other known student accommodations. Also early on, several lectures focus on team management and project management skills. These lectures provide baseline information and examples from past courses, which serve to justify and prime students for other course resources. After the lectures regarding team and project management, templates are provided to students for teams to draft their own team contract document. Within this team contract, there are 7 steps outlined with examples. The steps can be found detailed in Table 1. This provides students with a framework for outlining team goals and expectations, and students receive completion credit for filling it out as a team early on, and both undergraduates and M.Eng. students complete the contract together outside of class. The early lectures in week 2 contain advice and relevant examples for students to consider as they fill out their team contracts.

As detailed in Table 1, the team contract lays out the team's expectations. This contract forms the backbone of how teams self-organize and provides a means for faculty to scaffold the process of forming a healthy team dynamic without prescribing specific work.

Table 1. Team contract assignment outline. The 7 steps of the team contract completed by each team. Both undergraduates and M.Eng. students contribute to this assignment.

Team Contract Section	Description
Step 1: Get to know each other	Asks students to list strengths, interests, contact information
Step 2: Clarify group purpose	As a team, lists out personal expectations and expectations for the team

Ste 3: Community guidelines	Instructs the team to write out the conduct they will hold themselves to. Examples include conflict resolution, time management, attendance/tardiness.
Step 4: Time commitment, meetings, communication	Team lays out expectations for meeting structure, meeting schedules, and commit to a platform (in person, Zoom, other)
Step 5: Individual roles and responsibilities	Each team member lists out their role and what responsibilities they will commit to. Examples include what they will focus on (electronics vs packaging, etc…) and also communication (take notes at meetings, follow up after major updates,…)
Step 6: Conflict and accountability	As a team, list out checks and balances and expectations for failing to meet team commitments.
Step 7: Timeline	Teams must commit to a project tracking tool (Excel, Teams, Slack, other) to keep track of deadlines and meetings.

At several points in the semester, teams meet with course instructors and are prompted to reflect and comment on their team dynamic. These touchpoints can be formal (initial submission of the contract, mid-course survey, CATME end of course survey) and informal (verbal feedback during check-in meetings). Each of these touchpoints is intended to promote reflection and proactive measures for students to manage their team dynamic and project. The idea behind these supportive elements is that the framework and resources provided help define and inform the team contracts, and check-ins throughout the semester initiate a feedback cycle between course instructors and student teams [1,2,4,22]. This feedback cycle helps scaffold teams' navigation of issues and solutions throughout the semester and provides direction and motivation for students to learn and engage with the course instructors and each other [4,5,23]

Each semester, lectures are adjusted to focus or clarify elements of team dynamics, undergraduate and M.Eng. collaboration, and project management based on student feedback. Examples of changes made include: (1) adding more details around motivation for project management, and (2) the inclusion of more specific examples of how and why certain elements of project management are deployed the ways they are. In regular check-in meetings between instructors and students, instructors also continued to define and clarify roles and responsibilities for new situations as they arose, which improved the information and guidance instructors could offer to students in subsequent cohorts. Our hypothesis was that improving these scaffolding elements would enhance the student experience, and lead to more positive feedback during formal touchpoints. After initially deploying the team contract and early lectures, mid-course data were collected over three course cycles.

At the halfway point of the semester, all undergraduate students are given a brief survey asking them to reflect on the team contract. The questions on the survey include:

(1) "What is your general feeling about the dynamic of your project group so far this semester?" [Likert 1-5]

(2) "Take a moment to review your group's contract. How well do you feel your group (as a whole and as individual members) is adhering to the guidelines you agreed on in your contract?" [Likert 1-5], and

(3) "Is there anything specific that you think you or your group needs to work on to have a better experience in the remaining weeks of the semester?" [Free response].

All questions were programmed to require some text response, so no responses collected were blank.

Data Analysis

We analyzed the Likert-style responses, aggregating responses by team and by cohort. The resulting plots show how team sentiment varied between teams, and also how the distribution of total cohort responses changes over time as the course evolved (Figure 2, Figure 3 respectively). We note that the mid-course survey had fewer responses in the second cohort; likely due to a holiday break being scheduled at approximately the same time as the survey. This has a potential impact on our findings, which we considered in our results and discussion.

To analyze the free-response feedback, we applied a sentiment analysis software model, Valence Aware Dictionary for sEntiment Reasoning (VADER) via a custom Python script [14]. This sentiment analysis model employs empirically constructed lexical features tied to human-rated sentiment, followed by a rule-based system for analyzing syntactical pattern conventions for expressing sentiment intensity, such as emphasis by capitalization, exclamation marks, or adjective/adverb modifiers [14]. The python library used for the analysis [17] provides breakout estimates for presence of positive, neutral, and negative sentiment which collectively sum to 1.0, such that each category ranges from 0.0 (no text supported that sentiment) to 1.0 (all text supported that sentiment). Compound sentiment scores are also produced ranging from -1.0 (strongly negative) to 1.0 (strongly positive) which is calculated separately from individual sentiment scores [17]. A score near 0.0 indicates a neutral sentiment (e.g. *"haven't made up my*

Table 2. Additional rules used to process feedback text for VADER sentiment analysis. Different survey questions may require different rules.

Rule	**Rationale**
Replace short, negative responses ("No", "Nope", "N/A", "Nothing") with "Neutral"	Given the wording of the question, a "No" or equivalent answer should be interpreted as a neutral or weak positive.
Replace longer negative responses ("Not at this time", "Nothing at the moment") with "Neutral"	Again given the question wording, these types of responses can reasonably be interpreted as neutral.
Remove the leading "No," from longer comments starting with "No, …"	There were several positive comments where the leading "No" skewed the VADER interpretation negative. For example, *"No, I think it's going well"* would be interpreted as -0.26, where *"I think it's going well"* scores 0.27, which we felt was more reflective of the actual sentiment communicated.
AFTER SCORING: If "negative" >0 and "neutral" > "pos" and "compound" > 0, "compound" = -"compound"	This was added to more accurately represent what we perceived to be negative feedback. Many students who wrote constructive but negative feedback registered the negative feedback, but the compound score was overwhelmed by neutral or slightly positive phrasing.

mind”). These types of techniques have been employed to study opinions about education from unstructured text. In one example, researchers looked at tweets during COVID-19 [19], and in another recent example, researchers visualize end of course student feedback using sentiment scoring [8]. We applied a rule-based pre-processing specific to our survey structure to improve the quality of the results [19,21]. The intention of these preprocessing steps in our case was to ensure text was formatted correctly for analysis and correct answers for the positionality of the survey wording. Common preprocessing steps include removal of non-text characters, trimming of unnecessary spaces, and ensuring similar formatting.

Some responses to the question of whether students felt they needed to fix anything included: *“No”*, *“Nothing”*, or other similar responses. These responses would normally score negative in VADER sentiment analysis, but the wording of our survey implies those responses should score a neutral or slightly positive. We chose to code these responses as true neutral (0.0). We also added a post processing step to correct for longer text with constructive criticism, which tended to score higher positive scores than our team perceived them to be upon manual review. We devised a simple rule to check for the presence of negative sentiment score in longer, positive responses which allowed us to correct for this effect in our dataset. An overview of all analysis rules can be seen in Table 2. Code files which produced the analysis and figures can be made available upon request.

In addition to computational processing with VADER, we also performed an inductive thematic analysis of the student feedback [6,7]. We initially reviewed the student responses to the midpoint check-ins and grouped responses together based on the most prominent focus of the text. Groups of responses were refined iteratively until consensus was reached amongst the research team. Throughout the process, we sought to organize the similar elements which emerged from the data [6]. The purpose of this additional coding was to provide insight into the variation and trends which may have motivated some of the sentiment analysis results. Six different categories emerged from the undergraduate student feedback which we combined into three major themes. In Figure 5, we show word clouds of the six different categories we identified in the undergraduate feedback.

Results

Overall, we observed a slight, positive trend in both Likert-style responses to our mid-course survey and also in the sentiment scores from cohort to cohort. In Figure 2, the bar plot shows the results of Likert question 1 asking about students’ perception of their team’s group dynamic. We see a slight improvement from semester to semester, with a noticeable jump in average response sentiment in the second semester. Also of note is that from the first tothe third cohort, the responses trended towards neutral, producing fewer “bad” responses, but also fewer “very good” responses. This effect appears small, and a Wilcoxon signed-rank test fails to demonstrate a significant difference in the two cohorts ($p=0.715$), and a t-test also fails to identify a significant difference in cohort means from the first to third semester ($p=0.915$). Comparing the Likert ratings shown in Figures 2 and 3 from the second to the third semester, the Wilcoxon test gives a p-value of $p=0.067$, significant at the $\alpha=0.10$ level, for both Likert questions. We chose to apply a significance threshold of 0.10 given the relatively small sample sizes, and also to account for the relative complexity of what we were asking students to consider. Figure 3 paints a similar picture to Figure 2 for the second Likert question, which asked

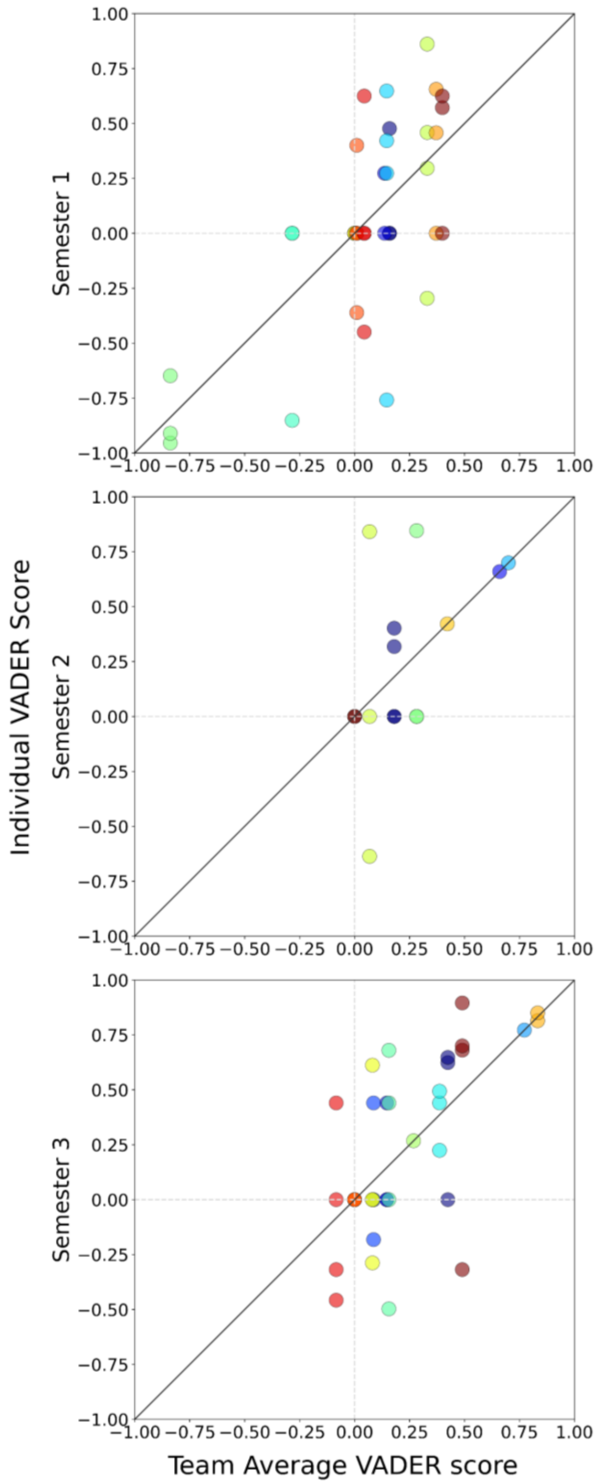

Figure 4. Individual VADER sentiment scores of undergrads (Y) from free-response midpoint survey plotted against the team average VADER score (X). Y=X indicates team agreement. Lower scores indicate negative sentiment, higher scores indicate positive sentiment.

about student's perceptions of the team contract.

We also observe a similar pattern between the second and third semesters in the sentiment analysis, where we see a slight positive trend over time and a noticeable bump in the second semester. The mean sentiment scores rose from 0.046 in the first semester, to 0.222 in the

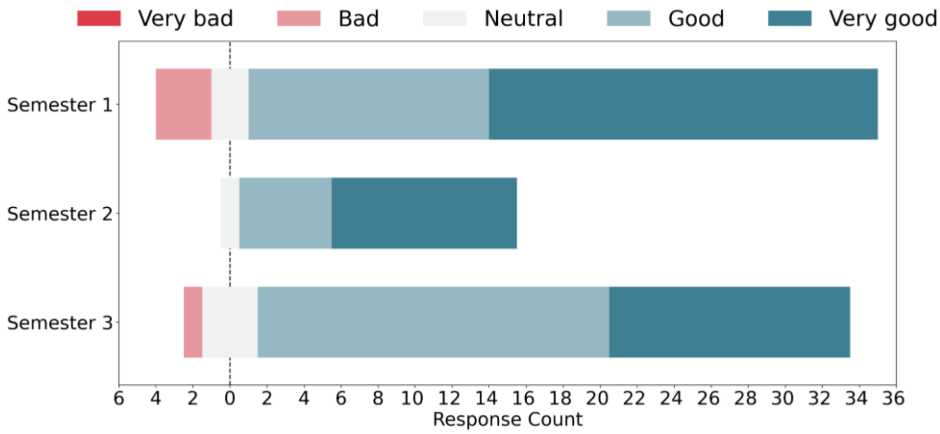

Figure 2. Perception of group dynamic as rated by individual undergraduates at course midpoint survey. No "Very bad" responses were recorded.

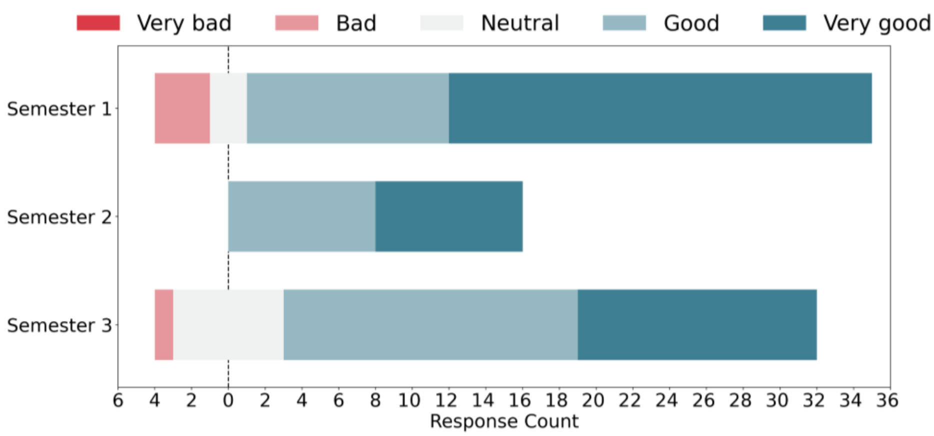

Figure 3. Perception of team contract as rated by individual undergraduates at course midpoint survey. No "Very bad" responses were recorded.

second, and finally 0.234 in the third cohort. From the first semester to the third semester, we find a significant increase in positive sentimentality at a significance level of alpha=0.10 (p=0.061). We note that the number of teams responding to the mid-course survey dipped in the second cohort, likely due to the interruption of a holiday break around the mid-course survey point. It is possible that teams who did not respond to the survey may have tended to have less

Figure 5. Six word-clouds from undergrad mid-course feedback. Three larger themes represented in each row. Top row: technical details. Middle row: Roles and responsibilities. Bottom row: Communication and collaboration. Word size corresponds to prevalence.

favorable opinions of the course, so we plan to investigate future cohorts to determine whether this may have been an outlier.

Figure 4 depicts compound sentiment scores organized by team. Each point represents an individual student response sentiment score (Y axis) plotted against the team average sentiment score (X axis). The line Y = X indicates the line of team agreement; the further points spread from this line indicates a larger difference in sentiment. Looking at the clusters of Figure 4 chronologically (top to bottom), the shift in points up and right in each subplot semester-to-semester indicates more positive sentiment scores over time. We also see a significant bump from the first to the third cohort. To help interpret these score values, some selected feedback includes: *"I think my group is doing a great job following the guidelines of the contract"* which scores 0.62, and another students' feedback: *"I think that we need to get better on the communication side of things. One of our group members regularly doesn't show up to class or meetings so we spend a lot of time trying to catch them up"* registers a score of -0.44 when using our adjusted rules applied to VADER.

When we qualitatively sorted the undergraduate responses to our mid-course survey, we identified six main categories based on the content of the text [5,6]. Each student's feedback was thematically coded as belonging to one, unique category based on which category was most prominent. The categories which emerged were: ‘project details’, ‘goals and timeline’, ‘M.Eng. roles’, ‘collaboration’, ‘communication’, and ‘sponsors’. ‘Project details’ tended to focus on the technical aspects of the project, e.g. *“[We want to] develop the device further.”*. For ‘goals and timelines’, students usually commented on how they wished to be more proactive, such as *“Getting started on assignments a little earlier”*. In ‘M.Eng. roles’, we saw a bit more confusion, with comments such as, *“Better articulation of what the M.Eng. students’ responsibilities are”*. ‘Collaboration’ comments focused more on delegation and team organization, with comments such as, *“Working together more. We kind of split up the work but then I sometimes feel lost with what’s going on with other parts.”*. In the ‘communication’ theme and the ‘sponsors’ themes, we saw students highlight their desire for more direct and more frequent communication. These six categories we categorized into three broader themes of feedback: technical details, roles and responsibilities, and communication. These themes are highlighted in the rows of Figure 5.

Additionally, the M.Eng. course collected midpoint feedback and asked M.Eng. students to communicate the most challenging element they had encountered in the course. Eight M.Eng. students provided text responses. The same three themes of ‘details’ (2/8 responses), ‘roles’ (2/8 responses), and ‘communication’ (4/8 responses) emerged from the M.Eng. midpoint feedback. When we compare the M.Eng. self-reflection and the undergraduates’ comments, the prevalence of communication as a theme was most pronounced. While several comments called out specific behaviors or technical issues (attendance, setting meeting agendas ahead of time), many comments focused on the regularity and expectations of communication (desire for more communication, more clarity, more proactive planning, and guidance).

Discussion

Overall, we found the team contract in combination with a midpoint check-in to be an effective way to gauge how students perceived their experience working with their team. Group work can be challenging to design and implement, and we feel these scaffolded elements provide valuable frameworks for students to build from. Interestingly, our most common issues with teams were too little communication (Figure 5 row 3) and lack of clarity over the roles of the M.Eng. students (Figure 5 row 2) on the projects. By comparison, other researchers interviewing faculty about common student team dysfunctions found that “lack of participation (slacking)” was the most common complaint [4,22]. While the M.Eng. participation is quite unique to our program, we note that we collected very few complaints from teammates not contributing. A closer inspection of the team communication cloud in Figure 5 (bottom left) reveals a focus on time management (time, deadline, regularly) as well as managing multiple modes of communication (chat, message, emails, meeting), The teamwork roles (middle right) cloud has more references to time management (time, initiative, early schedules) and collaboration (together, everyone, contribution). This may point to more issues arising from time management and expectations of communication than from absenteeism. Without a more rigorous model to study the specific impacts of our team contract scaffolding, we cannot comment on potential causes for this difference. In future work, it would be beneficial to explore in more detail how the students perceive each aspect of the team contract at formation, and how that perception may change throughout the semester. We anticipate there are many potential opportunities to refine the way in which our team contracts are constructed and enforced.

As seen in Figures 2 and 3, students reported similar perceptions of the team contract document and their perceived group dynamic. This was an expected result, as we hoped that possible issues which could be addressed through the team contract would correspond to better perceptions of group dynamics. Likewise, where the team contract failed to address team issues, we expected to see both perceptions of the contract and the group dynamic trend negatively.

We see small but noticeable improvement in the VADER sentiment scores and Likert question responses over time. If we look at the average sentiment scores amongst only the positive sentiment scores (>0.0) for each cohort, we still observe an increase from 0.50 in the first cohort, to 0.60 in the second cohort, and finally to 0.58 in the third cohort. This indicates that having fewer dissatisfied student team(s) alone does not explain the increased sentimentality year-to-year. This finding highlights one specific advantage of using the VADER analysis in addition to the Likert style survey items, which is that finer-grained analysis can be performed to give more insight into each student cohort's experience over time. For example; students on the same team who responded identically to the Likert scale items but described different experiences in the free response can be distinguished from one another in a way that would be difficult or time consuming to manually quantify. One area for further investigation is in exploring how the variation seen within and between teams in Figure 4 aligns to individual students' experiences.

The methods we employed carry several notable limitations. First, we did not have the ability to establish a control cohort which did not receive the scaffolded elements (lectures, check-ins, and team contract) to compare effects directly. We could not test whether the improvements in student responses were causally connected to our scaffolded elements. The M.Eng. mid-point check-in survey did not follow the same format as the undergraduate check-in, and we had far fewer responses to analyze, which gives our analysis a lopsided perspective from the undergraduate side. However, we believe our analysis captured interesting variation within teams as well as between cohorts which is relevant to the course instructors and administrators. Second, we recorded a low number of responses from the second cohort, and as a result, some of the cohort-to-cohort trends we identified may be influenced more strongly by response bias. The projects which were run in the first and second semesters were the same projects, but the third semester had different projects, so some of the effects observed may have been impacted by the nature of the projects. Different projects from different sponsors can also have different pacing, complications, and expectations; all of which may impact student perceptions of their team. However, our course does provide a strong framework and timeline which is the same for all teams in the course regardless of projects.

In summary, we find that providing scaffolding around team contracts and team management may provide some small benefit in student perception of their group dynamics. We also demonstrate how VADER sentiment analysis [14], when used with several simple processing rules, was capable of capturing student sentiment from text feedback which enables easy visualization of student feedback at scale, which would have previously required time-intensive manual qualitative analysis [21]. The VADER scores of the text feedback aligned well with the Likert style questions and provides a blueprint which may be of interest to other capstone programs or other large courses which rely on group-based work. Having the ability to process student free-response text for sentiment provides additional capability for exploring more subtle differences in student experience, as well as providing more fine-grained analysis of student perceptions. Applying these scaffolding elements such as a team contract and follow-up surveys to group based work, especially with interdisciplinary or hierarchical groups, not only supports individual students to find success but also provides a dataset detailed enough to evaluate the course over time.

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