A Study of Feedback Provided to Student Teams Engaged in Open-Ended Projects

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Introduction
Feedback has been described as “one of the more instructionally powerful and least understood features” of learning. Appropriate feedback can help to address student misconceptions, improve transfer of knowledge, and increase retention and satisfaction in school. However, both implementing and studying feedback is complicated; feedback content and effectiveness varies widely depending on the learning environment and the people involved in the feedback process. Feedback effectiveness can change depending on its timing, complexity, structure and content. Furthermore, students react to feedback differently based on differences in their personalities, backgrounds, academic capacities, and understanding of the material.

This paper empirically investigates feedback in a project-based learning (PBL) environment. In PBL, students encounter an open-ended learning environment, which differs considerably from traditional coursework in the university setting. Projects can require students to think and work more like engineers in industry as opposed to students in a classroom. Since this atmosphere is a complex, challenging and new experience for most students, feedback can play an important role in guiding them through the process. Effective feedback can be used to address misunderstandings and misconceptions at critical stages in the project and to encourage students to consider alternative ideas and solution paths.

In this paper, we focus on a project called the Industrially-Situated Virtual Laboratory Project. The Virtual Laboratory is delivered in the senior laboratory class during the final year of a chemical, biological and environmental engineering program at a large public university. Students choose between two different projects, a Virtual Chemical Vapor Deposition (VCVD) Laboratory Project and a Virtual Bioreactor (VBioR) Laboratory Project. Both projects require students to act as working engineers in industry, developing a process “recipe” for a new manufacturing process while managing a virtual budget. Throughout the three-week project period, student teams meet weekly with a course instructor who acts as a coach. These meetings are termed “coaching sessions.” At the first coaching session, called the Design Memo Meeting (DMM), the students are required to bring a memo that details their intended experimental strategy and their proposed project budget.

Previous work has studied subsets of student teams working with the VCVD Laboratory Project to understand how feedback proceeds in this PBL environment. These studies have illuminated the primary themes of the coaching sessions and the adaptability of the feedback that occurs. Now, we expand this characterization of the coaching sessions by considering an entire cohort of students and comparing the feedback in both Virtual Laboratory Projects. Such a study provides a more extensive basis for understanding and comparing the feedback that occurs. By increasing the scope and including a second project, we are better able to identify similarities and differences between teams and provide a reliable, more systematic assessment of feedback.
Ultimately, we seek to provide useful insight for engineering educators to apply feedback in PBL environments.

**Background**

*Feedback*

Over the past century, feedback has emerged as one of the most important aspects of student learning. According to one study that considers over one hundred factors on student learning, feedback consistently ranks among the top ten factors that influence educational achievement. In another study, instructor interaction and feedback are found to be the only variables significantly associated with enhanced student group skills, problem-solving skills, and engineering competence, while other considerations, such as gender, standardized test scores, and year in school, are not correlated. While feedback is clearly a powerful educational tool, the effectiveness of feedback is not the same for every student and its influence cannot be easily predicted. The execution and assessment of feedback is extremely challenging because learning processes are influenced by so many different institutional, interpersonal, and individual factors. Furthermore, the effectiveness of feedback can differ based on how it is delivered and then received, with something as basic as dialogue quality having more influence on feedback effectiveness than a learner’s ability and personality. Of course feedback is delivered with the intent of improving performance, but depending on the circumstances, feedback might improve performance, have no effect on performance, or negatively impact performance; clearly it is important to understand how to best tailor feedback to be effective in different situations.

In an educational context, feedback has been previously narrowly defined as information provided to a student to acknowledge correct versus flawed responses, such as when an instructor tells students if their response is right or wrong. More recently, the definition of feedback has broadened to be any information provided regarding some aspect of a student’s performance or understanding; it is often employed deliberately as a form of instruction to help students modify their knowledge, cognitive processes, behavior and skills. Instructors can use feedback to evaluate the current conceptions of their students, address errors, reinforce strengths, reduce the learners’ cognitive loads, encourage reflection and stimulate consideration of alternative solution paths. In other words, feedback allows for comparison between a desired educational outcome and actual student performance. The instructor can use feedback to facilitate learning and performance through interaction, information sharing, guidance, encouragement, and reinforcement.

Providing feedback for students has been found to be significantly and positively related to gains in engineering design skills and professional skills, such as communication, teamwork and critical thinking. Feedback is powerful because it can enhance self-awareness, inspire alternative ideas, broaden perspectives and increase effort, motivation and engagement. It can promote self-regulation by helping students learn to recognize their own errors. Students report that feedback related to understanding concepts, tasks, calculations, and graphs is helpful when they are learning to apply previously learned content in a new context. Furthermore, besides the actual content delivered in the feedback, it has been found that any interaction between a student
and a faculty member can lead to greater student development and satisfaction through increased comfort in the university atmosphere.\textsuperscript{15,16}

In order for feedback to be effective, it should be clear, direct, specific, relevant to the task or goal at hand, and not too strict, threatening, or overwhelming.\textsuperscript{3,7,19,20} It should verify current understanding, address misconceptions and include elaboration or explanation.\textsuperscript{21} Effective feedback also adapts the use of directive or facilitative methods to the situation. When students are learning new content, they may need more directive feedback that contains specific information about what needs to be done, while facilitative feedback that guides students without making specific demands may be more appropriate for more experienced students.\textsuperscript{12,22,23} However, even the most carefully structured feedback could work for one student but not another, because each student’s response to feedback depends on that student’s background and their reception of the feedback. How feedback is received depends on the structure, content, context, and timing of the feedback, whether the information is a review of previously learned material or completely new information, and on the student’s confidence and the perceived credibility of the instructor.\textsuperscript{20,21} The timing of feedback, or when the feedback is delivered relative to when a student completes a task, can affect how a student learns. Feedback can be ineffective if delivered before the student has a chance to attempt a solution individually, but immediate feedback can help the student to process errors more quickly while more effectively managing cognitively demanding tasks.\textsuperscript{9} Meanwhile, delayed feedback may be more effective in promoting the student’s long-term retention of material.\textsuperscript{4,24} In summary, feedback is an important educational tool that can be used to support student learning, but the characteristics of feedback are diverse and instructional use of feedback varies greatly in different contexts.

\textit{Project-Based Learning Environments}

Projects have become an increasingly prevalent component of engineering education because they promote critical thinking skills, better prepare students for professional engineering careers and enhance students’ personal development by increasing self-esteem, attitudes and persistence.\textsuperscript{25–27} In project-based learning (PBL), students work on a task that culminates in the creation of a final product that is demonstrated in a final report or presentation.\textsuperscript{28} PBL can differ greatly from school work to which students are accustomed. Typical homework and exam problems are usually well-defined and closely related to information presented in lecture, have one correct answer, and can be solved using algorithms that are explained in textbooks or by the instructor. These problems are often encouraged to be solved individually. In comparison, projects are more complex tasks and are often based on challenging, realistic, industry-relevant problems. These problems are usually open-ended and ill-structured, lacking a single “correct” solution.\textsuperscript{25} Additionally, students typically work in teams, rather than as individuals, and their teams are given more authority and responsibility over the direction and outcome of the project.\textsuperscript{25,28}

PBL has been shown to help students learn several professional skills relevant to industry, such as communication, conflict resolution, self-management, teamwork and time management.\textsuperscript{29–31} Projects that situate students within an industrial setting are especially valuable because most
tasks undertaken by practicing engineers are in the context of working on projects.\textsuperscript{32} In a university setting, authentic projects allow students to experience an industry-like atmosphere without many of the constraints present in industry.\textsuperscript{33} As students think more like practicing engineers, discovering how to work through problems on their own in the absence of a traditional lecture-homework-exam format and realizing how course content applies to real problems, they become more motivated to learn the material and work toward a project solution.\textsuperscript{25,34–37} This kind of experience also improves higher-level thinking skills in students, such as conceptual understanding, metacognitive skills, problem-solving skills, and transfer by requiring students to synthesize knowledge from disparate sources.\textsuperscript{28,38} In summary, by incorporating authentic problems and teamwork, PBL helps students understand how to apply what they have learned in school by approaching problems as engineers typically would in industry.\textsuperscript{32,39}

The Need to Study Feedback in PBL Environments

There is clear evidence that PBL enhances learning. However, instructors can be reluctant to implement this type of system due to the challenges that students have with the cognitively difficult tasks.\textsuperscript{40,41} Feedback can mitigate these challenges by reducing students’ cognitive loads while working on unfamiliar or difficult tasks.\textsuperscript{23} Feedback can also encourage student effort and persistence over time on complex problems.\textsuperscript{41} In a PBL environment, with a more student-controlled project, the instructor naturally adopts the role of a coach or supervisor rather than a professor, furthering the industry-like feel of the project and giving the students more authority to solve the problems on their own.\textsuperscript{30} However, feedback allows the instructor to continue to assess and monitor the progress of the students and guide students towards a solution while still allowing them to develop their own paths.

Given the complexity of executing effective feedback in a PBL learning environment, more research is warranted to understand feedback that is provided in this type of context in order to support the development of instructional recommendations for effective feedback with PBL. This paper characterizes how feedback proceeds for student groups engaged in two similar open-ended projects. The primary questions guiding this research are as follows: What are the most prevalent themes and types of themes that occur in the student-instructor interactions? How does feedback compare and contrast for different student teams, across different instructors and different projects? How do these themes vary among student teams? And finally, what do the findings imply about the nature of feedback in open-ended projects?

Methodology

The Virtual Laboratory project described in this paper uses PBL instructional design and incorporates a considerable feedback component. This project is employed to assist and motivate engineering students.\textsuperscript{42,43} The Virtual Laboratory environment is a useful addition to engineering curricula in that it allows students to optimize a complex system that would otherwise not be accessible at a university due to economical and equipment-based constraints.\textsuperscript{42} This learning environment advances different skills than traditional physical laboratory experiments. Students can focus more on experimental strategy and data analysis because the cognitive load associated with handling physical equipment has been eliminated. Furthermore, the students are situated as
engineers working in industry rather than undergraduate students doing an assignment for school. They are required to deliver industry-relevant work products such as memos, reports, and a process ‘recipe’ and they must think more similarly to a working engineer, employing teamwork, critical thinking and communication skills. This instructional design allows students to practice professional skills in a learning environment without all the demands or consequences of an actual industry project.\textsuperscript{44}

Project Structure
The Virtual Laboratory project takes place as part of a senior laboratory course in the final year of a chemical, biological and environmental engineering program. This three-week long project situates student teams in either a chemical vapor deposition fabrication laboratory or a bioreactor operations plant. The teams are tasked with optimizing process parameters to (1) create silicon nitride thin-films in the Virtual Chemical Vapor Deposition (VCVD) project or (2) produce recombinant protein in yeast or degrade waste with an acclimated bacteria consortium in the Virtual Bioreactor (VBioR) project. Throughout the project, students meet regularly with an instructor that is acting as an industry supervisor and project coach to discuss their progress. Students must work together to define an optimal set of process parameters (e.g., temperatures, flow rates, and times) while managing a set of applicable measurement tools and a self-generated, coach-approved budget. In order to complete the process optimization process, the students must develop their own strategy for all aspects of the project and produce five deliverables. The major components of the Virtual Laboratory project and details about opportunities for feedback are summarized in Table 1.

<table>
<thead>
<tr>
<th>Timeline</th>
<th>Key Project Milestones</th>
<th>Student-Coach Opportunity for Feedback</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project Begins</td>
<td>• Introductory seminar</td>
<td>The instructor delivers a presentation about the industry, relevant engineering background, the software interface, and project constraints, objectives and deliverables. Feedback is limited to in-class questions, discussion and interaction.</td>
</tr>
<tr>
<td></td>
<td>• Laboratory notebook is provided</td>
<td>--------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>End of Week 1</td>
<td>• First-run parameter set</td>
<td>In this first coaching session, feedback takes the form of a 20-30 minute meeting in which the coach and students discuss the team’s design strategy memo. If the initial parameter values, budget, and strategy are defensible, the team is granted access to the virtual laboratory equipment.</td>
</tr>
<tr>
<td></td>
<td>• Budget estimate</td>
<td>--------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td></td>
<td>• Experimental strategy</td>
<td>--------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td></td>
<td>• Design Memo Meeting</td>
<td>--------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>End of Week 2</td>
<td>• Progress to date on reactor performance achieved, strategy and budget</td>
<td>Another opportunity for feedback occurs during this second coaching session, which has the same format but is typically a few minutes shorter than the first coaching session. The coach and students talk about progress the team has made thus far, addressing issues and discussing future plans.</td>
</tr>
<tr>
<td></td>
<td>• Team Update Meeting</td>
<td>--------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>End of Week 3</td>
<td>• Final parameter set is released to production</td>
<td>Teams deliver a 10-15 min oral presentation (to the coach, two other instructors, and other students in their lab section) that is followed by a 10-15 minute question and answer session that allows additional feedback. Final project feedback consists of grades and written comments on final deliverables.</td>
</tr>
<tr>
<td></td>
<td>• Final Written Report</td>
<td>--------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td></td>
<td>• Final Oral Report</td>
<td>--------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td></td>
<td>• Laboratory notebook submitted</td>
<td>--------------------------------------------------------------------------------------------------------</td>
</tr>
</tbody>
</table>
Previous work in our group to characterize the feedback in these meetings has analyzed a subset of four student teams working on the VCVD project and demonstrated that feedback varies widely for each team depending on the students’ preparedness, abilities and team dynamics.\textsuperscript{18,45,46} To further characterize feedback content and structure for different student teams and instructors and to systematically compare analyses for both projects, this study expands the scope to a cohort of student teams working on either the VCVD project or the VBioR project. This paper focuses on the discourse in the first coaching session, or Design Memo Meeting (DMM), during which the coach and the students discuss the team’s design strategy memo.

**Participants and Setting**

This research examines a cohort of 16 chemical, biological, and environmental engineering student teams, comprised of 46 students in total. Each self-selected team consists of two or three students and is maintained throughout the entire course, which involves two physical laboratories followed by the virtual laboratory. The teams choose to work on either the VCVD Laboratory Project or the VBioR Laboratory Project. Biological and environmental engineering students generally choose the VBioR Laboratory Project, while chemical engineering students choose either the VCVD or the VBioR Laboratory Project. In this study, eight teams choose the VCVD Laboratory Project and eight teams choose the VBioR Laboratory Project, with all eight VBioR teams selecting the protein production option. The students work under the supervision of two coaches, who are faculty members in the unit. One faculty member is the VCVD coach and the other the VBioR coach and both coaches are content experts in their respective fields.

**Data Collection and Analysis**

This research study is an ethnographic case study using discourse analysis.\textsuperscript{47} The data is collected ethnographically by observing and audio recording participants while they are working on the project. This case study consists of sixteen cases, in order to explore similarities and differences for participants experiencing the same environment. Discourse analysis is used once data has been collected to characterize and interpret the interactions occurring during the Virtual Laboratory Project. This combination of these three methodologies is important because each one serves a different purpose within the context of this research: ethnography is used for the data collection, data is selected for analysis based on applicable case studies, and discourse analysis is how the data are examined.

Consenting teams are videotaped during all interactions with the coach, including the Design Memo Meeting (DMM), Team Update Meeting (TUM) and final presentation. This study focuses on the DMM when the students meet with the instructor to review their initial reactor input parameters, experimental design and budget. Once the DMM videos are transcribed, the discourse is coded in ATLAS.ti and analyzed using an episodes framework, in which the discourse is broken into thematic units with a definitive start and end point.\textsuperscript{48} The length of the meetings analyzed ranges from 20 to 35 minutes, with an average length of 28 minutes. The hierarchy of themes used for coding the episodes has been previously developed\textsuperscript{46,49} and is shown in Table 2. Breaking the discourse into episodes based on themes allows for comparison.
between teams on the number of themes discussed, the proportion of discourse dedicated to each theme, and the depth to which each theme was covered.

### Table 2. Episode coding themes with descriptions

<table>
<thead>
<tr>
<th>Tier I</th>
<th>Tier II</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Student Engineering Objectives</strong></td>
<td><strong>Input Parameters</strong></td>
<td>Measurement strategy and reactor-specific control variables (e.g. temperature, flow rate, time, pressure, substrate concentration)</td>
</tr>
<tr>
<td></td>
<td><strong>Performance Metrics &amp; Project Objectives</strong></td>
<td>Budget and reactor-specific indicators (e.g., utilization, uniformity, productivity, process efficiency)</td>
</tr>
<tr>
<td><strong>Coaching Objectives</strong></td>
<td><strong>Core Technical Content &amp; Concepts</strong></td>
<td>Kinetics, transport, material balance, modeling, experimental design and strategy</td>
</tr>
<tr>
<td></td>
<td><strong>Professional Skills</strong></td>
<td>Communication, experimental documentation, teamwork, economic impact of engineering solutions, and project management</td>
</tr>
<tr>
<td><strong>Project Contextualization</strong></td>
<td><strong>Situate</strong></td>
<td>Relating the project to industry and engineering practice</td>
</tr>
<tr>
<td></td>
<td><strong>Instructional Design</strong></td>
<td>How the project is structured and why and comparison to traditional homework</td>
</tr>
</tbody>
</table>

While the discourse is coded at both Tier I and II levels, primarily Tier I data is reported in this paper. The themes are categorized into one of three Tier I categories: Student Engineering Objectives, Coaching Objectives or Project Contextualization. Themes that are part of Student Engineering Objectives have to do with the project requirements that must be fulfilled by the students to successfully complete the project, such as performance metrics and selection of recipe parameters. Coaching Objectives comprise themes that relate to the instructional goals of the project of applying fundamental engineering content to an authentic process optimization project. These themes include Core Technical Content and Concepts, which relate to the laboratory processes and experimental strategies, and Professional Skills, which include industry-relevant skills such as communication, teamwork and experimental documentation. Project Contextualization denotes themes that have to do with situating the project in relation to academic curriculum or industry.

After coding the transcript in terms of thematic units, the episodes are further broken down into stages of surveying, probing, guiding and confirmation, as seen in Figure 1.49 In the first two stages, the coach identifies the students’ competencies and deficiencies. In the surveying stage, the coach is becoming familiar with their approach by reviewing the memo and asking general questions about their strategy. The probing stage consists of more specific questions, asked in order to understand a particular conception or approach. In the next two stages, the coach helps to expand the team’s understanding. Coaches begin the guiding stage when they identify a misconception or weakness in approach, providing feedback to help students modify their knowledge and strategies. Guiding can be done using directive feedback, explicitly telling the students what to change, or with facilitative feedback, providing comments or asking questions.
intended to encourage students to consider additional information or alternative solution paths. The confirmation stage concludes an episode with the students and coach reaching a consensus on what was discussed. An episode may or may not consist of all four feedback stages and the stages may occur in different orders or multiple times. This staging scheme has been developed in previous work but is refined through this study. More detailed descriptions of each feedback stage are provided in Table 3.

<table>
<thead>
<tr>
<th>Stage</th>
<th>Description</th>
<th>Example</th>
</tr>
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</table>
| Surveying | The coach becomes familiar with the team’s approach to uncover weaknesses, misconceptions or incomplete understanding. In this stage, the students offer general information about their approach and the coach may ask broad questions, such as, “how did you select these parameter values?” | C: [upon conclusion of a mass balance episode] “And are you confident of these numbers?”  
S1: “Barely.”  
S2: “That’s just the minimum to get the deposition so that would require 100% utilization on only the wafers. So that doesn’t include the reactors.” |
| Probing   | In this stage the instructor asks the students more pointed questions to further assess their understanding of a particular core concept and how they plan to incorporate that concept in their approach to the project. Questions often take the form, “you explained optimization of X, but what is your plan for that in relation to Y?” where X and Y might be temperature, uniformity, substrate, biomass etc. | C: “So, [S1], you’re confident…so does that mean that you did the calculations?”  
S1: “Yes.”  
C: “I see. Did you do the calculations (to S2)?”  
S2: “No.”  
C: “And [S3]?”  
S3: “I didn’t work it out by hand.” |
| Guiding   | The guiding stage occurs after the coach has identified and confirmed a misconception or weakness in understanding or approach. The coach uses a blend of directive and facilitative dialogue to increase the team’s awareness of the coach’s concerns. Usually guiding consists of leading and rhetorical questions, but occasionally information or advice is given directly. | C: “Alright, so this is something where on your homework, or even more so, if you get a method right you get most of the credit, right?”  
S1+S2+S3: “Yes.”  
C: “On this thing, if you get a method right, do you get most of the credit. No. [S1] is generally very accurate. But what else do you think you can do?” |
During the confirmation stage, consensus or acknowledgement of understanding occurs. This conclusion can be a student statement that is confirmed by the coach, possibly followed by further justification or explanation, or short statements such as “I get it” or “right, okay” if followed by a change in topic. Reinforcement, repetition, and praise are also confirmation if no new information or ideas are presented.

S2: “Have everybody check and do it also.”

C: “Yeah, you could have independent checks on that. I mean, you don’t want to spend several thousands of dollars to learn that...Oh, I forgot to carry the zero. I’m not saying it’s right or wrong, that’s just more of a team strategy.”

In developing the coding protocol, an inter-rater reliability (IRR) analysis has been conducted for the themes and the stages coding. This process involves two rounds of coding comparison. First, two researchers who analyzing transcripts for this study review the coding protocol previously developed and then each researcher codes one full coaching session transcript for a single team. This first round illuminates ambiguity in the coding protocol, which is then reconciled by the raters through refinement of the protocol. Second, after reconciling, each rater analyzes one full transcript for a different team’s coaching session. Based on this second round of coding, two statistical metrics, Cohen’s kappa and Krippendorff’s alpha, are calculated using SPSS statistical software, with a unit of analysis of words. While Cohen’s kappa is more frequently cited and available as a standard analysis tool in SPSS, Krippendorff’s alpha has been proposed as the “standard reliability measure” for qualitative coding because it is the most comprehensive and flexible metric. In this study, Krippendorff’s alpha is the more conservative metric; both metrics are reported in Table 4. The stages’ codes are treated as mutually exclusive; therefore a combined IRR metric can be calculated. Individual stages IRR values are also provided for reference. The themes’ codes are not mutually exclusive so an average value is provided in lieu of a combined metric. Individual values are also provided for the Tier I theme codes.

Table 4. Inter-rater reliability metrics for coding themes and stages

<table>
<thead>
<tr>
<th>Codes</th>
<th>Cohen's Kappa (p&lt;0.001)</th>
<th>Krippendorff's Alpha</th>
<th>Average Word Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Themes Average</td>
<td>0.80</td>
<td>0.79</td>
<td>4229</td>
</tr>
<tr>
<td>Student Engineering Objectives</td>
<td>0.87</td>
<td>0.87</td>
<td>164</td>
</tr>
<tr>
<td>Coaching Objectives</td>
<td>0.93</td>
<td>0.89</td>
<td>3565</td>
</tr>
<tr>
<td>Project Contextualization</td>
<td>1.00</td>
<td>1.00</td>
<td>237</td>
</tr>
<tr>
<td>Stages Combined Metric</td>
<td>0.78</td>
<td>0.77</td>
<td>4229</td>
</tr>
<tr>
<td>Surveying</td>
<td>0.89</td>
<td>0.89</td>
<td>131</td>
</tr>
<tr>
<td>Probing</td>
<td>0.89</td>
<td>0.88</td>
<td>750</td>
</tr>
<tr>
<td>Guiding</td>
<td>0.87</td>
<td>0.83</td>
<td>2819</td>
</tr>
<tr>
<td>Confirmation</td>
<td>0.61</td>
<td>0.60</td>
<td>309</td>
</tr>
</tbody>
</table>

The IRR values for all of the codes show acceptable agreement between the two raters, demonstrating the reliability of the coding protocol used in this study. According to the results for the individual stages, it can be seen that the coding for Surveying, Probing, and Guiding is
more reliable than for Confirmation, which presents the greatest opportunity for further protocol refinement.

Results and Discussion
Prior case studies in our group have shown that feedback can vary greatly; however, those results are limited to four teams in the same project. In this section, we present results which show that the feedback differs based on the project and instructor delivering the feedback, shown by comparing the VBioR project and the VCVD project as a whole, and also on the students receiving the feedback, shown by comparing teams within each project. We provide a discussion of factors that appear to contribute to these differences.

Comparison of Virtual Laboratory projects
As seen in Figure 2, the proportion of discourse for each of the Tier I themes differs between the Virtual Laboratory projects. Overall, the Virtual Bioreactor (VBioR) Design Memo Meetings (DMMs) includes less discussion of Student Engineering Objectives, more of Coaching Objectives, and more of Project Contextualization.

These differences appear to be due to different approaches the coach takes regarding feedback. The VCVD coach tends to nest episodes based on Coaching Objectives within episodes based on Student Engineering Objectives. VCVD DMMs are often structured as methodically going through the team’s design memo, in which the students generally detail the input parameters they are going to select and the measurement strategy they will employ. The coach usually discusses each input parameter presented in the memo and then asks how it was selected, at which point he will bring up Core Technical Content and Concepts to probe at how the students arrived at each value. For example, while discussing how to optimize the temperature in the reactor (an Input...
Parameter, part of the Student Engineering Objectives), the coach will incorporate fundamental course content, such as kinetics or transport. Conversely, the VBioR coach does not rely on the memo as much for the structure of the meeting. She tends to initiate episodes that are focused on Coaching Objectives, usually Core Technical Content and Concepts that relate to fundamental VBioR material. Therefore, the proportion of discourse devoted to Coaching Objectives is higher than that in VCVD DMMs, and the proportion of discourse devoted to Student Engineering Objectives is lower. The VBioR coach also tends to situate the project more within industry, which leads to a higher proportion of discourse devoted to Project Contextualization. Further investigation is needed to assess the effect of each overall approach on student performance and learning.

The different feedback approaches are also reflected in differences in the percentage of words spoken. Figure 3 shows the comparison of student and coach talking time for the two projects. The VBioR coach speaks 73% of the words in the DMMs, while the VCVD speaks 57% of the words.

The two projects also differ in the proportion of discourse devoted to each episode stage, as seen in Figure 4. The VCVD teams engage more in surveying and probing, while the VBioR teams are provided with more guiding.
The feedback approaches described previously explain these differences in proportion of discourse spent on the different episode stages, and are elaborated as follows:

- **Surveying**: The VCVD coach tends to verbalize reading through the memo while the VBioR coach reads the memo silently before questioning the students. Therefore, the proportion of discourse devoted to surveying is higher in the VCVD DMMs, although that does not necessarily mean that the proportion of time spent on surveying is higher.

- **Probing**: Since the VCVD coach tends to let the design memo guide the topics discussed, the students tend to have more influence over the structure and content of the meeting. This means there is more discourse related to Student Engineering Objectives, as previously mentioned, and also that there is more discourse in the surveying and probing stages than in the VBioR meetings. The VCVD coach usually probes the students rather than initiating episodes and immediately directing the students toward a certain point, as is done in guiding episodes. He asks questions and allows more time for them to attempt to reach conclusions on their own before jumping in to guide them.

- **Guiding**: However, as the VBioR tends to focus on certain core concepts in the DMMs as a way to structure the meetings, there is generally more discourse in the guiding stage. Rather than probing to assess what the students understand, the coach may lead students through certain calculations, graphs or sketches in order to guide the students to consider different solution paths and to encourage conceptual learning.

- **Confirmation**: The VCVD and VBioR meetings tend to have the same proportion of discourse devoted to confirmation. The VCVD coach typically allows the meeting to flow from one topic to another, leading to less confirmation episodes, but when confirmation does occur, it generally includes repetition of the students’ conclusions, leading to more words per episode. The VBioR coach confirms more often, frequently...
encouraging the students and acknowledging correct statements, but uses more concise statements, like “okay” and “good” as confirmation.

Comparison of student teams
The previous section demonstrated that the different feedback approaches of the two coaches clearly leads to differences in the characteristics of how feedback is delivered. This section provides data from individual teams, examining how the teams’ discourse varies within each project in terms of which themes are discussed and which episode stages occur most frequently.

Virtual Bioreactor Laboratory
Figure 5 presents the Tier I themes discussed in each VBioR team. On average, 66% of the discourse for the bioreactor teams is devoted to Coaching Objectives, ranging from less than 50% to over 90%. For Student Engineering Objectives, the average proportion of discourse is 29.6% and ranges from 5.0% to 47.4%. Project Contextualization ranges from 0% to 10.9%, with an average of 4.8%. Team B2 has the highest proportion of Student Engineering Objectives, B6 has the highest proportion of Coaching Objectives, and B4 and B5 have the most Project Contextualization. B6 is also the only team with no Project Contextualization.

Figure 5. Comparison of themes for the VBioR teams

Figure 6 displays the proportion of words for each VBioR team by episode stages. On average, 5.0% of discourse is surveying, 16.6% is probing, 70.9% is guiding and 7.5% is confirmation. Teams B2 and B5 are at the extremes, with B2 having the least amount of guiding and B5 having the most guiding. The episodes stage distribution for B8 and B7 are similar to B2 and the distribution for B5 and B6 is remarkably different than the rest of the teams.
Figure 6. Comparison of stages for the VBioR teams

Figure 7 shows the proportion of words spoken in the DMM by person, including the coach and all three students. All of the VBioR teams had three students. There is variation from team to team according to team preparation and prior knowledge, team dynamics and the team’s interaction with the coach. For example, in team B4’s coaching session only two of the students talked during the meeting and the coach spoke more than 80% of the words. By comparison, with team B2 the coach spoke much less, around 60% of the words, while the three students spoke more substantial amounts of 10% to 15% each.

We next discuss teams at the extremes of these data sets and associate the analysis with differences in the teams’ preparation and prior knowledge. Teams B5 and B6 clearly have the highest proportion of discourse spent on guiding and a similar distribution of stages. Unlike
many of the other teams, B5 and B6 present a relatively complete and well considered experimental design so minimal time is spent addressing common issues such as budgeting and sampling frequency. Consequently, the coach encourages the students to think about the system conceptually through various “what-if” scenarios. This type of guiding is evident in this subset of an Experimental Design and Kinetics episode in Team B5’s coaching session.

Coach: What else do you get from this besides just Ks, from a plot of this [referring to a Lineweaver-Burk plot]?
S3: $\mu_{\text{max}}$.
Coach: Yeah $\mu_{\text{max}}$. What else could you get, if you actually had all this data? Because really all these are individual $\mu$s that you calculate.
S3: You could get...
S2: Well if you had two runs...
Coach: Well yeah. Could you get all this data with one run? Maybe.
S3: Batch maybe.
Coach: Yeah because right, you have to go from a high S all the way to a low S.
S2: Yeah.
Coach: What could happen at really high S?
S2: Substrate inhibition.
Coach: How would that look?
S2: Not good. It would come up here and then...[drawing a plot of $S$ versus $\mu$]
Coach: Right, right, right.
S3: Do we know if it's substrate inhibition for just growth? I thought substrate inhibition would only act for our product formation.
Coach: No definitely it can act on growth.

In comparing these two teams, B5 is one of two teams with the most Project Contextualization while B6 has no Project Contextualization. In terms of themes, B5 has a Budget-themed episode and a Measurement Strategy-themed episode early in the meeting. These episodes mostly consist of guiding through clarification and elaboration. B6 has a comparable episode about Measurement Strategy, but does not have any discussion about the budget. The coach tends to use a lot of situating during budget discussions, as is the case with B5, contributing to discourse devoted to Project Contextualization. Team B6 is the only VBioR team without a Budget-themed episode, and also the only one without Project Contextualization.

B2 represents another extreme, having the highest proportion of Student Engineering Objectives, the lowest proportion of guiding, the lowest proportion of coach discourse, and the most even distribution amongst team members. In contrast to Teams B5 and B6, this team required a high level of basic help in the project. Three episodes contribute to over 90% of the Student Engineering Objectives discourse for this team. First, the DMM for this team starts with the students stating that they are “all very confused” about the budget and economic analysis component of the project, which leads into a lengthy Budget-themed episode. Second, later in the meeting, the coach initiates a Measurement Strategy episode regarding the high sampling
frequency the team has planned. During this episode, the team realizes that fewer data points can still provide the information necessary to analyze the bioreactor’s performance and that reducing the sampling frequency will also lower their budget. Third, toward the end of the meeting, the coach discusses the project expectations of the students, in terms of biomass, substrate and product concentration, constituting an episode about Performance Metrics and Objectives. Most of the episodes in this team’s meeting begin with substantial surveying and probing. For example, the Budget episode is more than half surveying and probing, as the coach works to understand and address the team’s confusion and misconceptions. The team also included several bioreactor textbook equations in their memo, which the coach uses to probe the students’ understanding of Core Technical Content and Concepts.

Virtual Chemical Vapor Deposition Laboratory
Figure 8 presents the Tier I themes discussed in each VCVD team. On average, 29.6% of the discourse is devoted to Student Engineering Objectives, 65.6% to Coaching Objectives, and 4.8% to Project Contextualization. Team C4 has very little discourse devoted to discussion of Student Engineering Objectives (11.2%) while teams C1 and C7 have the highest proportion, 49.6% and 47.1%, respectively. Teams C4 and C7 have no discourse devoted to Project Contextualization.

![Figure 8. Comparison of themes for the VCVD teams](image)

Figure 9 shows the distribution of episode stages. For every team, the majority of discourse is devoted guiding. On average, 5.0% is devoted to surveying, 16.6% to probing, 70.9% to guiding, and 7.5% to confirmation. However, as with the VBioR teams, there is considerable variation. Team C7 stands out as differing from the average most: this team had far less guiding than average (43.0%) and far more surveying (14.0%) and probing (37.8%).
Figure 9. Comparison of episode stages for the VCVD teams

Figure 10 shows the distribution of percentage of spoken words in the VCVD DMMs. On average, the coach provides 57.1% of the discourse. Teams C7 and C8 had only two students, which is why there is no discourse associated with S3. While there is always variation in students’ contributions within a team’s discourse, Team C4’s is drastically unbalanced and dominated by S1.

Figure 10. Comparison of percentage of spoken words for the VCVD teams

Again, the variation shown in Figures 8-10 can be understood in response to team specific characteristics. Team C4 is unique in that the DMM is driven mostly by the students, and in particular, student S1. Rather than waiting for the coach to read the memo and ask questions, the team launches into a verbal description of their strategy. Interestingly, the student’s discussion is structured by Coaching Objectives, as opposed to Student Engineering Objectives: rather than listing out how they picked their reactor parameters, they discuss how they considered transport and kinetics when developing their experimental strategy and used a mass balance to determine flow rates, as illustrated by the following excerpt.
S1: Yeah. We started with the mass balance to find the amount of DCS and ammonia. And then, we knew that it wasn’t going to, 100%, 100% of the DCS was going to react and create film. And then also we knew that the chamber, it was going to build up in the chamber as well.

C: Yep, yep good.

S1: So then we, and I didn’t know exactly how, like what the efficiency was going to be for that conversion. We tried looking up some rates online. To find the growth rates and such like that. And so we kind of just made an assumption that we scaled up the amount from the mass balance.

M3: So we chose what we thought would be a relatively low pressure, so um. We're kind of just guessing from the ranges that we found, to increase uniformity along the height and the radius. Because if the pressure is low for a really low flow rate, the gas velocity will be faster, so that will make more get up to the top before it's reacted near the bottom, and hopefully increase the amount that actually makes it to the top and deposits.

Figure 9 also demonstrates that team C4 is unique in that they have a large proportion of surveying episodes, most likely due to the student-driven structure of the meeting. Usually, the coach reads the memo and surveys on his own before beginning the meeting, but in this case, the students start discussing before the coach had a chance to read. Therefore, more verbal surveying is done to make up for the lack of reading done at the beginning of the DMM. It is also interesting to look at team C4’s division of discourse, in Figure 10; the students’ distribution of discourse is extremely uneven, as the meeting was mostly driven by S1, while S2 and S3 only contribute when prompted by the coach.

Teams C1 and C7 have the highest proportion of discourse devoted to Student Engineering Objectives. This characteristic can be associated with either poor conceptual understanding (team C1) or poor communication in the design memo (team C7). Team C1’s DMM is guided mainly by the coach; the students simply answer questions that the coach asks without elaborating or providing new information. They also appear unconfident when discussing their proposed strategy.

Team C7 shows extreme characteristics. Figure 9 shows that team C7 has far less guiding than average and far more surveying and probing. This high amount of probing, along with the high amount of discourse devoted to Student Engineering Objectives, correlates to the fact that they appeared to have poor communication in their design memo. Team C7 devotes 20% of the coaching session discourse to Communication, compared to the average of 9%. There are many episodes with the coach asking probing questions to determine the team’s strategy, as evidenced by the large proportion of probing in Figure 10 (37.8% compared to an average of 23.9%). Even after discussing the team’s strategy at length, the coach seems perplexed at the team’s ideas; he asks the team to describe how they came up with their strategy near the end of the meeting. The discourse is noticeably disjointed; episodes rarely have a clear ending point and there is little
confirmation given to end a topic. There is more direct feedback than with other teams, perhaps because the students seem to be struggling in response to guiding questions or because the team appears to be missing major portions of the memo. Additionally, this team has no Project Contextualization episodes, as all discourse is devoted to the actual completion of the project goals without referencing how the project fits into the industrial scenario or the student’s curriculum.

**Implications**

The learning environment studied provides an extremely rich source of data for analyzing feedback delivered to student teams engaged in an open-ended project. The analysis presented gives a general summary of how feedback progresses in two similar PBL projects, in terms of what topics are discussed, how the feedback progresses in order to assess and guide the students’ understandings, and how discourse may be divided between the instructor and students.

Differences are observed between the feedback that occurs in the two projects. These differences appear to be due to different approaches the coaches take regarding feedback. The VCVD coach tends to nest episodes based on Coaching Objectives within episodes based on Student Engineering Objectives. This approach imbeds the application of scientific principles in the engineering objectives that are desired. It also affords students more influence over the structure and content of the meeting. Conversely, the VBioR coach tends to initiate episodes that are focused on Coaching Objectives, usually Core Technical Content and Concepts that relate to fundamental VBioR material. This allows greater focus on illustrating calculations, graphs or sketches and can guide the students to consider different solution paths and to encourage conceptual learning. Further investigation is needed to evaluate the benefits of each approach for student performance and learning.

There is also considerable variation between teams as feedback is adapted to the uniqueness of each team and the interaction of each team with the coach, although there are also similarities in coaching session discourse for certain subsets of teams. The flexibility of the coaches during these meetings allows them to provide adaptable feedback that is tailored to the concerns and preparedness of each team.

This work provides a starting point for many areas of future research to further characterize and understand feedback in PBL environments. Although this paper focuses on the broad Tier I themes, more specific Tier II (and Tier III) themes, such as Performance Metrics, Professional Skills, and Core Technical Concepts and Content, still need to be characterized. The quantifying of coach and student talking time also provokes additional investigation; what causes some students to talk more than their teammates in these meetings? What techniques can the coach use to effectively ensure an appropriate level of engagement for the less vocal students? Lastly, this paper presents the feedback that occurs in the DMM but does not attempt to analyze its effectiveness. By linking this analysis to performance of each student team in future work, it may be possible to identify how these meetings progress differently for high-achieving or low-
achieving teams, and also to define what feedback strategies are more or less effective in this PBL environment.

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