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Title: Characterization of the Feedback between the Instructor and Student Teams Engaged in a Virtual Bioreactor Laboratory Project

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This thesis characterizes the feedback between the instructor and student teams engaged in a Virtual Bioreactor (VBioR) Laboratory Project. The project allows senior-level chemical, biological, and environmental engineering students to apply their developing knowledge and skills in an industrially situated process optimization project. Feedback is an important tool for instructors to use to scaffold student learning, especially in the context of an ill-structured project. An ethnographic approach is taken for data collection; audio recordings and field notes are taken throughout the duration of the project. The characterization of feedback uses an episodes framework for discourse analysis to consider similarities and differences. Using this framework, thematic codes have been developed through a semi-emergent process to describe the content of Design Memo Meetings (DMMs) between an instructor and student teams. Student work products, post-DMM surveys, and post-project interviews are also considered as data sources for this research. The results of this research show that instructor feedback in this project is adaptable, conforming to the status of the student team at the beginning of the DMM. This adaptability is highlighted by differences in DMM themes that are supported by differences in the Design Strategy Memos that student teams bring to the meeting. Student perceptions of the DMM feedback are also presented.

Characterization of the Feedback between the Instructor and Student Teams Engaged in a Virtual Bioreactor Laboratory Project

by

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Jaynie L. Whinnery, Author

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1 Introduction

Engineering education is an emerging field of research, drawing from math and science education, engineering, and cognitive science. According to the National Science Foundation, each year over 100,000 engineering degrees are awarded in the United States (NSF, 2008). These engineers go on to design chemical processes, cars, airplanes, energy production systems, wastewater treatment facilities, roads, and bridges. Engineers play a key role in the functioning of society as we know it, ranging from aspects of basic safety to cutting-edge technology. For this reason, it is important to continually improve education for engineering students. Upon graduation, engineers need to be prepared to productively engage in their discipline. Beyond understanding what is written in textbooks, engineers need to be capable of selectively applying technical content and concepts effectively. They need to be ready to work in varied contexts with diverse teams under time and budget constraints (National Research Council, 2011). Therefore, it is important that engineering curricula support student development of these capabilities.

Feedback is commonly thought to improve student learning in educational settings, but research shows that results are mixed. Whether or not feedback positively influences student learning depends on factors including how and when the feedback occurs and the characteristics of the learner (Hattie & Timperley, 2007; Shute, 2008). For this reason, additional research is warranted to investigate feedback. This investigation is part of a broader effort to better understand student learning in virtual laboratories. As part of this broader effort, methodology has been developed for characterizing instructor feedback using an episodes framework for discourse analysis. This framework provides insightful descriptions of the feedback between the instructor and student teams (Gilbuena, Sherrett, Gummer, & Koretsky, 2011[a]). So far this feedback analysis has focused on students engaged in the Virtual Chemical Vapor Deposition (VCVD) Laboratory Project. The research presented in this thesis extends this approach to student teams engaged in the Virtual Bioreactor (VBioR) Laboratory Project. There are two key differences between the VCVD and VBioR Laboratory Projects, (1) the physical characteristics of the systems being optimized and (2) the instructor the students meet with for feedback. Given this background, the questions guiding this research are as follows:

1) In the context of the Virtual Bioreactor Laboratory Project, what role does instructor feedback have in the information gathering and problem formulation stages of the modeling process of student teams?
2) What similarities and differences can be identified for different teams?
3) How does an instructor's feedback change with time in this role?

2 Theoretical Framework

A theoretical framework can be considered as a lens through which to view the world. It provides specific perspectives for a given study or research program. It is thought that applying different theoretical frameworks in different cases is a meaningful way to illuminate specific aspects of a situation (e.g., activity, environment) that one wants to investigate. This research is studying feedback as it relates to student learning in the context of the VBioR Laboratory Project. The theoretical framework for this research is presented in three sections as follows: (1) Learning Theory, (2) Project-Based Learning, and (3) Feedback.

2.1 Learning Theory

A learning theory of constructivism is presented to highlight the subjective nature of knowledge. According to Bransford (2000), constructivism is a theory of learning in which "people construct new knowledge and understandings based on what they already know and believe" (p. 10). Constructivism is a prominent theory of learning in education research. There are two main constructivist perspectives – cognitive constructivism and the sociocultural approach – that are based on work of Piaget and Vygotsky. Cognitive constructivism is most closely associated with Piaget. From this perspective, learning builds on prior knowledge and occurs when the learner constructs new knowledge based on activity and experience. Glasersfeld (1996) explains that this theory assumes that "knowledge, no matter how it be defined, is in the heads of persons, and that the thinking subject has no alternative but to construct what he or she knows on the basis of his or her own experience…all kinds of experience are essentially subjective, and although I may find reasons to believe that my experience may not be unlike yours, I have no way of knowing that it is the same" (p. 1). On the other hand, the sociocultural approach has greater alignment with the ideas of Vygotsky and focuses on the "essential relationship" between mental processes and cultural, historical, and institutional settings in which the thinking is situated (Wertsch, 1991).

The main difference between these two constructivist perspectives is the extent to which knowledge resides in an individual versus in the social realm. For example, how should constructivists handle widely accepted knowledge, such as Newton's Laws of Motion? Is learning to be considered as the individual's interpretation of these laws or the relationship between the laws and the individual's mental processes? Phillips (2000) argues that "bodies of knowledge" such as Newton's Laws of Motion are important for students to learn if engineering students are expected to participate in and contribute to the engineering discipline in the future. Students must learn what the broader engineering community agrees upon and incorporate these "bodies of knowledge" as they develop their understanding of engineering. Sociocultural and cognitive constructivist perspectives in mathematics education research have historically been considered oppositional, but instead they can be viewed as complementary. In the latter case, the role of the instructor can be considered as mediating between students' individual meanings and culturally established meanings. (Cobb 1994).

In addition to the perspectives discussed above, there is a range of other constructivist perspectives. This paper does not attempt to provide every detail of the constructivism landscape nor does it try to reconcile the debates concerning constructivism as a theory of learning. Rather than claiming one perspective to always be true, what is most appropriate should be considered within context, based on what is most relevant to improving the educational process for the learner. Constructivism can be used to inform a pedagogical approach. Assuming students bring unique knowledge, attitudes, and interests to the learning environment, instruction should be adaptable to this diversity. Instructional design can provide experiences that allow students to construct their own understanding based on their individual perspectives (Howe & Berv, 2000), which can be accomplished within the social setting of school. Some specific principles of constructivist pedagogy include encouraging collaboration, promoting activity and exploration, respecting multiple points of view, and emphasizing authentic problem-solving (Burbules, 2000). The approach used for the VBioR Laboratory Project is aligned with these principles. The students are individual learners, but their learning takes place within the social setting of their team and their classmates. For the VBioR Laboratory Project, cognitive constructivism suggests studying the mental models that individual learners develop to understand the bioreactor. Sociocultural approach advocates analysis of contextual influences on individual learners to understand how social interactions, such as peer and instructor feedback, contribute to their understanding of the VBioR Laboratory Project.

2.2 Project-Based Learning

The intention of the VBioR Laboratory Project is to address the differences between the types of problems students work on in engineering school versus engineering practice. In the early stages of engineering education, problems may be simplified or isolated to promote understanding of specific concepts and theories. As students' knowledge of these concepts and theories mature, it is important for them to develop knowledge synthesis and transfer abilities. Synthesis refers to the capacity of an individual to blend information from disparate sources when approaching new problems or projects (i.e., an "integration of knowledge") (Bordogna, Fromm, & Ernst, 1993, p. 3). Transfer means applying concepts that have been learned in one context to other contexts (Engle, Nguyen, & Mendelson, 2011, p. 603).

In engineering practice, the problems faced are diverse and each problem may require the application of a different set of skills and knowledge. Students must learn when to apply which skills and abilities, and when to call upon others' expertise.

Additionally, Jonassen, Strobel, and Beng Lee (2006) argue that students need to learn to deal with incomplete information, make assumptions as needed, and manage unanticipated problems. Students also need to develop the ability to set project goals and manage tradeoffs and contradictory objectives, such as integrating engineering and non-engineering goals, such as time limitations, budget constraints, and client satisfaction. Furthermore, engineers typically work in teams, so students need to learn how to productively participate in a team setting.

Project-based learning (PBL) is one instructional approach that can be employed to promote the diverse skillset described above. According to the definitions provided by Prince & Felder (2006), PBL involves students engaging in "one or more tasks that lead to the production of a final product – a design, a model, a device or computer simulation" (p. 14). Typically, project concludes with a final report and/or presentation in which the students communicate their procedures and results. Distinguishing features of PBL include the use of broad, open-ended problems, a resemblance to engineering practice, the application of previously learned knowledge, and a focus on the end product. PBL can be a challenging experience for students so it is important for instructors to provide guidance to the students during the project (Prince & Felder, 2006).

Instructor guidance is particularly pertinent during the problem formulation phase of a PBL assignment. Figure 1 presents the Virtual Laboratory Project Modeling Process (Buckley, Gobert, Horwitz, & O'Dwyer, 2010; Sherrett, Nefcy, Gummer, & Koretsky, 2012). This modeling process includes three stages, (1) information gathering, (2) problem formulation, (3) and iterative modeling and experimentation. Research shows that expert engineers spend significantly more time on all stages of the design process, but this difference is particularly pronounced for the problem formulation phase. Additionally, experts tend to seek out a higher quantity and variety of information and consider an increased number of alternative solutions (Atman, Adams, Cardella, Turns, Mosborg, & Saleem, 2007). Based on these empirical results, instructors should provide guidance to students to promote adequate information gathering and problem formulation approaches. One way to provide this guidance for students is through instructor feedback.

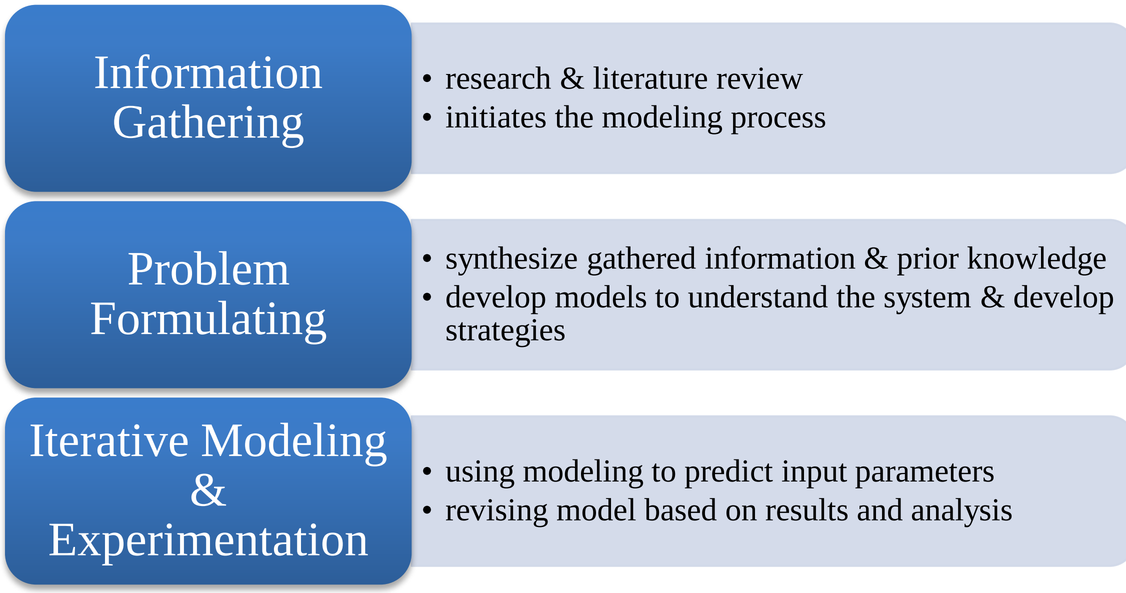


Figure 1 - Virtual Laboratory Project Modeling Process

2.3 Feedback

Feedback can play a valuable role in student learning, particularly in educational environments with high levels of ambiguity. According to Hattie & Timperley (2007), feedback is defined as information provided to help close the gap between current and desired performance or understanding. This definition is broad, as the extent of the 'information' given is unbounded. Through a synthesis of over 500 meta-analyses, Hattie and Timperley report that feedback is one of the most important factors for educational achievement, with an effect size that outranks factors such as students' prior cognitive ability, socioeconomic status, and reduction in class size. The most effective forms of feedback are specific to the topic or task at hand, with specific cues and reinforcement. More generic feedback, such as praise, rewards, and punishment, are much less impactful. There are a variety of possible feedback mechanisms, including assignment grades, peer review, and coaching; there are different approaches for each of these mechanisms. More understanding is needed about which types of feedback are effective for improving the quality of engineering education. Information gathered through research in this area can be used to make more intentional decisions regarding the educational culture being promoted.

People generally believe proper feedback has positive implications, but intentions and outcomes do not always align. Shute (2008) provides a thorough review of feedback in an attempt to define what methods are most effective at improving learning outcomes. Discerning effectiveness is complicated though, because feedback cannot be isolated from other factors including student achievement level, task complexity, and prior knowledge. The convolution of these factors leads to inconsistent results with substantial variation. In some cases feedback has even been found to have negative effects. According to Shute, is important to recognize two possible orientations toward tasks, learning versus performance. A student with a learning orientation is focused on personal development which is characterized by more internal motivators. From this perspective, cognitive ability can be increased. On the other hand, a student with a performance orientation is more concerned with external motivators, such as a desire to impress other people. In this case, cognitive ability is viewed as fixed. Students with a learning orientation are more likely to gain additional knowledge and understanding through feedback.

van de Sande and Greeno (2012) present three phases for alignment that can occur with individuals working together on a common project with initial misalignment as follows: the misalignment is realized, effort is made to achieve mutual understanding, and finally a satisfactory termination is reached. Shute (2008) presents three cognitive mechanisms related to feedback. First, gaps between current and desired performance can trigger motivation, and feedback can help by reducing uncertainty. Second, feedback can support learners by reducing their cognitive load. Third, feedback can be used to correct cognitive errors. “Effective feedback provides the learner with two types of information: verification and elaboration” (Shute, 2008, p. 158). While verification just confirms what is already understood, the purpose of elaboration is to guide the learner toward further understanding. Effective feedback should incorporate both of these aspects. Another major feedback continuum is facilitative versus directive. Facilitative feedback makes suggestions to guide the learner to make changes (e.g., asking leading questions). Directive feedback explicitly tells the learner what changes to make (Black & Wiliam, 1998). It is commonly thought that facilitative feedback encourages learning more than directive feedback, but Shute (2008) argues that it is not necessarily the case. Directive feedback can be more effective for students as they attempt to understand new concepts. Facilitative feedback tends to be more useful for building on previously learned material. Effectively blending facilitative and directive feedback is a balancing act.

Two instructional methods that can be integrated with a PBL approach are student-centered instruction and individualized instruction. Student-centered instruction includes the use of active learning experiences, open-ended and ill-structured problems, and team based learning. Students may also be held accountable for information that is not explicitly available in course materials (Felder & Brent, 1996). Felder & Brent (1996) also report that if student-centered instruction is implemented properly, it “leads to increased motivation to learn, greater retention of knowledge, deeper understanding, and more positive attitudes toward the subject being taught” (p. 43). Individualized instruction incorporates flexible assessment and continuous feedback, adapting to the unique characteristics of individual students (Chung, Delacruz, Dionne, Baker, Lee, & Osmundson, 2007).

From this overview, it is clear than effective feedback can enhance student learning. How, when, and with whom feedback occurs are all important factors. The specific nature of the feedback provided can influence its effectiveness. In engineering PBL activities, students commonly engage in a modeling process, which includes information gathering, problem formulation, and iterative modeling and experimentation. The information gathering and problem formulation stages are a critical time for the instructor to provide guidance for students. Feedback is one way to provide guidance, but not all forms of feedback are effective. Recommendations for increasing effectiveness include providing verification and elaboration (Shute, 2008), use of facilitative feedback approaches (Black & Wiliam, 1998), student-centered instruction (Felder & Brent, 1996), and individualized instruction (Chung et al., 2007). This study considers these recommendations in relation to the instructor feedback observed.

3 Virtual Bioreactor Learning System

The intention of the Virtual Laboratory Projects is to provide a unique learning environment for the students involved and to supplement their experience with traditional physical laboratory exercises (Koretsky, Kelly, & Gummer, 2011). Although the importance of physical laboratory projects is not up for debate, the added value of virtual laboratories such as the VBioR can be illustrated by the different range of skills and knowledge engaged during the virtual laboratory project. Furthermore, the virtual laboratory setting is representative of engineering practice because it allows more focus on the modeling process while professional technicians and operators run the processes and experiments. The virtual laboratories are designed to allow students more extensive practice with the experimental design process. A schematic of the VBioR model is shown in Figure 2. It is a stirred-tank fed-batch reactor that can be configured for product production or waste degradation.

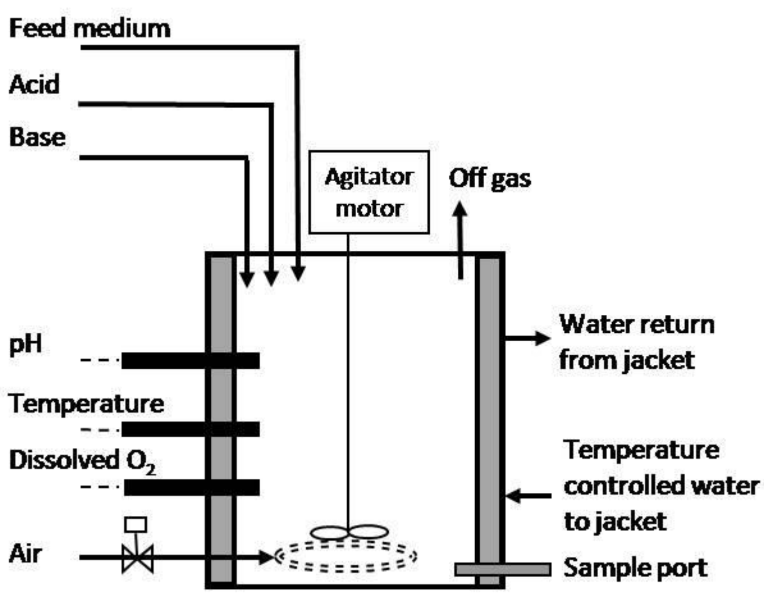


Figure 2 - Virtual Bioreactor Schematic

3.1 Computer Simulation

The Virtual Bioreactor (VBioR) simulates an industrial-scale bioreactor system with a first principles mathematical model along with added process and measurement variation. The VBioR has two interfaces, one for the instructor and one for the students. The instructor can set the reactor type (waste degradation or product formation), properties of the organism, and other reactor parameters. Also, noise can be specified for the product, cell density, substrate, and process to include variation in the laboratory output. This variation makes the output of the VBioR more representative of a real bioreactor, presenting students with an opportunity to practice statistical analysis. The student interface allows inputs for the bioreactor operating conditions and measurements. A screen shot of the student interface for the initial input parameters is shown in Figure 3. The operating conditions set by the students include the following: batch time, fed batch time, temperature, fed batch flow rate, fed batch feed concentration, inoculation cell density, and initial batch substrate concentration. To generate the desired measurement set, students first input the total number of samples they want to collect. Then, the next input screen allows them to set the times at which they want to collect data points for which parameters (substrate, cell density, and/or product). The student interface maintains a cost summary, experimental run data, and can be used to input the team's final recipe at the end of the project. The instructor controls access to the system through the use of a unique username and password. Each student team must gain approval from the instructor prior to completing any runs with the VBioR.

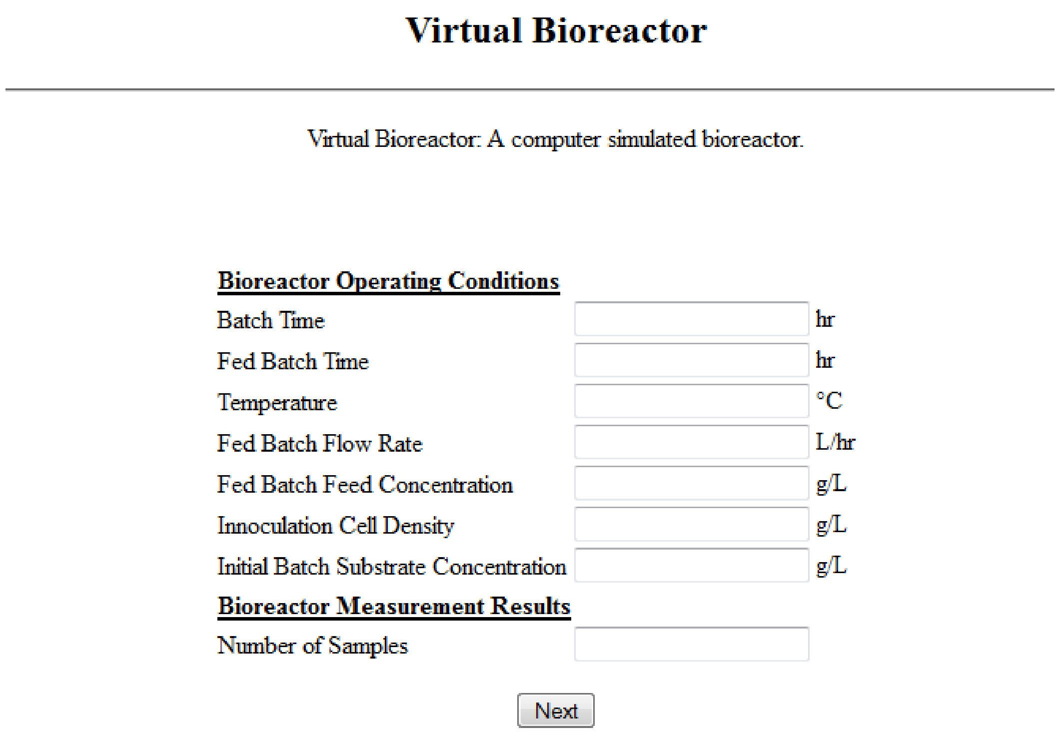


Figure 3 - Student Input Parameter Interface

3.2 Instructional Design

The VBioR Laboratory Project is presented to students as a process development task where they must determine the operating conditions of a bioreactor. The students can choose to optimize either a bioreactor producing recombinant protein in yeast or a bioreactor degrading waste by assimilated bacteria. The goal is to achieve the highest volumetric productivity or greatest waste degradation within the time and budget constraints. Because student teams are charged money for the reactor runs and measurements there is a financial constraint to the optimization process that students do not normally have to think about. There are five project deliverables as follows: (1) the Design Strategy Memo, (2) the Intermediate Update Memo, (3) the Design Notebook, (4) the Release to Production, and (5) the Final Oral and Written Reports. Table 1 provides an overview of the timeline and key elements of the VBioR Laboratory Project, and the nature of the student-instructor interactions.

Table 1 - Timeline of the VBioR Laboratory Project

Timeline	Key Elements	Student-Instructor Interaction
Project Introduction	Goals & Criteria for Success are introduced	The instructor provides an overview of the VBioR system, including a review of related technical concepts. An outline is provided that includes the VBioR Laboratory Project timeline and deliverables.
End of Week 1	Design Memo Meeting (DMM)	Student teams meet with the instructor to review their Design Strategy Memo. The instructor provides feedback to the students regarding their initial parameters and experimental strategy. Once the memo is acceptable, the instructor provides the student team with a username and password to access the VBioR Laboratory.
End of Week 2	Team Update Meeting (TUM)	Student teams meet with the instructor to review their Intermediate Update Memo. The instructor provides feedback to the students regarding their progress to date, issues they may have encountered, and the direction they are going.
End of Week 3	Release to Production, Final Oral & Written Reports, Design Notebook	Student teams deliver a brief oral presentation (10-15 minutes, followed by 10-15 minutes of Q&A) to the instructor, two additional faculty members, and the other students in the laboratory section. The teams also turn in a release to production, a final written report, and the design notebook.

The first deliverable is referred to as the Design Strategy Memo. This memo must meet the approval of the instructor before the students receive their username and password to access the VBioR. A typical team meets several times to develop a strategy which they report in the Design Strategy Memo. Next, they schedule a time with the instructor for a semi-structured coaching session, known as the Design Memo Meeting (DMM). During the DMM, the instructor reviews the team's memo and engages them in a feedback process. The DMM is situated as a meeting engineers have with their boss in industry. At the end of the meeting, the instructor requires some teams to revise their memo and return at a later time for additional memo review and feedback. Once the memo conveys appropriate starting parameters and experimental strategy the instructor provides the team with their access codes. At this point the team can access the VBioR and complete as many runs as they want to (within their budget and time constraints). The next deliverable is the Intermediate Update Memo which is reviewed by the instructor during a Team Update Meeting (TUM). This meeting is also situated as a meeting between engineers and their boss. The Intermediate Update Memo allows the instructor to review how each student team is progressing and provide additional feedback while the team is working through the iterative modeling and experimentation process for their bioreactor.

During the entire laboratory project, the students maintain a design notebook to keep track of run parameters, output summaries, data analysis, explanations, and general notes as they make progress. The notebook must be turned in at the end of the project, but the instructor also reviews the notebook at both meetings the student teams have with the instructor (DMM and TUM). The notebook is required to encourage documentation habits similar to what is often expected of practicing engineers. The notebook also provides the instructor with more information about the process the team went through to arrive at their final process recipe. At the end of the project, the team releases the final recipe to production and delivers Final Oral and Written Reports. The reports must include the team's final process recipe, achieved productivity or waste removal (depending on reactor type), expected variation, and final experimental cost.

4 Research Design

4.1 Methodology

To answer the research questions, this study provides a detailed description of the interaction between an instructor and different student teams. There is also a temporal component related to how the approach of the instructor changes over time because student teams are from different cohorts. According to the classification of emerging methodologies in engineering education research by Case and Light (2011), this research is an ethnographic case study using discourse analysis. The data is collected ethnographically by observing and audio recording participants at all times while they are working on the project. Detailed field notes and records of all group work and team meetings are also taken. Case and Light note that a case study can consist of several cases in order to explore similarities and differences for participants experiencing the same environment. For this research, four distinct cases have been selected for further analysis. Discourse analysis is used once data has been collected to characterize and interpret the interactions occurring during the VBioR Laboratory Project. This combination of three of Case and Light's methodologies is important because each 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 is examined.

Recall that information gathering and problem formulation are critical stages in the modeling process for the influence of feedback. The four student teams observed in this study were chosen in order to focus on information gathering and problem formulation aspects of the VBioR Laboratory Project. Limiting the study to a small number of teams allows for more in depth analysis. In this case, information gathering and problem formulation is defined as the initiation of the project until the team accesses the VBioR to begin performing experimental runs, at which point they transition to the iterative modeling and experimentation phase. This period of time is when student teams are developing their understanding of how the bioreactor works. During these phases of information gathering and problem formulation, teams typically come up with their initial run parameters, measurement strategy, experimental strategy, and decide on a budget that they will adhere to for the remainder of the project. Instructor feedback can help guide students through this highly uncertain aspect of the project.

4.2 Participants & Setting

The participants in this study are students and instructors associated with a chemical, biological and environmental engineering program at a large, public research university. The virtual laboratory project is one of three projects student teams complete in their capstone laboratory class. They can choose between the VBioR Laboratory and the VCVD Laboratory. The course also includes two physical laboratory projects. Therefore, during the 10-week quarter, there are three distinct laboratory projects including (1) double-pipe heat exchanger, (2) ion exchange chromatography, and (3)

VBioR/VCVD. Bioengineering and environmental engineering students typically choose the VBioR Laboratory Project, while chemical engineering students have the option to choose either the VBioR or VCVD Laboratory Project.

Through this class, approximately 80-120 students participate in the Virtual Laboratory Project each year. The students work on the project as part of a small student team, typically consisting of three students. Approximately half of the student teams choose the VBioR Laboratory Project. Students are asked if they are willing to participate in the research study through an informed consent process. Each year two instructors also participate in the study by engaging the student teams in feedback processes during the project. The four teams analyzed in this study were selected based on the availability of verbal data for the entire information gathering and problem formulation phases. These teams are referred to as Team A, Team B, Team C, and Team D. Team A is from an earlier cohort than Team B and Team C, which are from the same cohort, and Team D is from a later cohort. These are designated as the first, second, and third cohorts. A feedback guidelines document was developed in between the first and second cohorts. Although there are other cohorts that have completed the VBioR Laboratory Project, they are not included in this study due to data limitations. Also, focusing on a small number of teams allows a richer description of the data. The four teams considered in this study are composed of seven female students and five male students. All of the teams interacted with the same instructor for feedback.

4.3 Data Sources

The following process is used for ethnographic data collection. Consenting student teams are paired with a graduate student researcher for the duration of their VBioR project experience. The researcher attends all team meetings as a neutral observer, taking notes and audio recordings. Students are instructed to voice their thoughts as much as possible. Records of student work products are kept for research purposes, including memos, notebooks, reports, and presentations. Interviews are also conducted after the project has concluded. Audio files are transcribed as needed for analysis. Each student is assigned an anonymous but unique identifier; the letter indicates the team while the number is assigned based on the order the students speak at the beginning of the DMM (e.g., Student A1, Student B3). The portion of the discourse dedicated to information gathering and problem formulation is determined by looking for the first instance of a team logging into the VBioR to complete a run. The discourse leading up this point is isolated for analysis.

The discourse data used for analysis is listed in Table 2. The data is described in relation to the DMM, during which the student teams engage with the instructor to receive feedback. For this reason, the majority of the discourse analysis focuses exclusively on coding the text of the DMM transcriptions. However, Pre-DMM, Post-DMM, and Follow-Up DMM discourse is considered in an attempt to understand the role of feedback in the information gathering and problem formulation process. The amount of time spent post-DMM prior to running the VBioR varies the most, since some teams are required to modify their Design Strategy Memo while others are not.

Table 2 - Details of verbal data used for discourse analysis

Cohort	Team	Meeting Phase	Time(s) [Hr:Min:Sec]	Word Count(s)
First	**A**	Pre-DMM	2:45:00	n/a
		DMM	12:33	1,868
Second	**B**	Pre-DMM	48:52	4,989
			1:00:13	4,738
		DMM	18:26	2,086
		Post-DMM	25:33	1,557
	C	Pre-DMM	2:07:19	7,899
		DMM	19:45	2,216
		Post-DMM	1:48:36	5,745
		Follow-Up DMM	17:23	1,254
Third	**D**	Pre-DMM	3:29:31	n/a
		Pre-DMM	1:49:53	n/a
		DMM	28:05	5,688
		Post-DMM	1:20:00	n/a
		Follow-Up DMM	7:00	n/a

Another source of data for this research is from another cohort. A total of 53 students engaged in the VBioR Laboratory Project were asked to reflect on the DMM by individually responding to the following questions:

1. What are the top three things you are taking away from this meeting [the DMM]?
2. What interaction with your supervisor do you remember most and why?
3. Is there anything that happened during the meeting that
    a. especially helped you understand something?
       and/or
    b. was especially confusing and you wanted to discuss more?

Student answers to these reflection questions were hand written and returned to the instructor. Responses were received from 44 students for a response rate of 83 percent. Student responses to the above questions provide insights regarding student perceptions of feedback from the DMM. However, because the reflections are labeled by team number and returned to the instructor voluntarily, the responses could be more favorable than if the data was collected anonymously.

4.4 Analysis Methods

Discourse analysis using an episodes framework is the method of analysis for this research. This analysis method was developed using data from the VCVD Laboratory Project (Gilbuena, Sherrett, Gummer, & Koretsky, 2011[a]). One of the primary aims of this thesis is to extend these analysis methods to the VBioR Laboratory Project. The VCVD learning system is the same as the VBioR learning system in terms of instructional design, but the computer simulation is different. Students engaged in the VCVD Laboratory Project are optimizing the uniformity of a deposited silicon nitride film and the utilization of a reactant gas while minimizing development cost. The cost aspect is similar between the VBioR and VCVD, but the input parameters and processes are different than those of a bioreactor. The analysis methods developed by Gilbuena et al. (2011[a]) use an episodes framework to allow discourse analysis by themes and by feedback stages, which will both be discussed in more detail in this section.

van Dijk (1981) laid the foundation for the consideration of verbal data using an episodes framework, defining the concept as follows: “episodes are characterized as coherent sequences of sentences of a discourse , linguistically marked for beginning and/or end , and further defined in terms of some kind of 'thematic unity'” (p. 177). In written text, episode markers might be visible through the use of paragraphs but in verbal discourse other markers must be identified. Each episode should be cohesive and stand apart from other episodes in the discourse, having a specific theme or topic. In the course of time, there should be a distinctive beginning and ending to each episode. Furthermore, it is possible for episodes to have a specified hierarchy, considering the entire discourse under analysis as one episode that comprised of a set of sub-episodes. Additionally, each sub-episode could have further sub-episodes, and so the tendency continues until sub-division no longer makes sense. van Dijk provides a list of signals that may indicate the beginning of an episode, including pauses, hesitation, time change markers, place change markers, changing predicates, and change of perspective markers. These signals are all considered in the analysis of the VBioR discourse. Research previously conducted for the VCVD Laboratory Project shows that the Design Memo Meetings (DMMs) seem to have a common structure, consisting of 10 to 20 primary episodes and many sub-episodes (Gilbuena et al., 2011[a]). In the process of coding the transcribed textual data, each episode is categorized thematically.

Chi (1997) presents methods for analyzing qualitative data in a more quantitative way, making a distinction between protocol analysis and verbal analysis. Both protocol and verbal analysis can be used for coding the contents of verbal data, which can then be counted and compared in a quantitative way. The coding of episodes is based on content, and not necessarily based on words of the text verbatim. Some key aspects associated mainly with protocol analysis include focusing on verbalizing thoughts but not explaining those thoughts, comparison to an ideal solution path, and focusing on the strategy of problem solving rather than knowledge representation. Students in this study are working in teams, so they cannot focus on verbalizing their thoughts because they also have to listen to their teammates. When they do verbalize their thoughts, they tend to also explain those thoughts to their teammates. Furthermore, the VBioR Laboratory Project does not have an ideal solution path for comparison, although expert engineers have identified some solution paths as stronger than others (Sherrett et al., 2012). For these reasons, this study uses verbal analysis. The steps for verbal analysis, as conducted for the VBioR Laboratory Project data, are captured in the eight steps listed below (Chi, 1997, p. 283).

1. Reducing the data to focus on information gathering and problem formulation and selecting sample teams.
2. Segmenting the reduced, sampled data into episodes.
3. Developing a coding scheme.
4. Operationalizing evidence in the coded data and mapping it to the coding scheme.
5. Depicting the mapped data with the coding scheme.
6. Seeking patterns in the mapped data.
7. Interpreting the patterns.
8. Repeating the whole process to find additional evidence and investigate other schemes.

The process of determining a hierarchy of thematic codes for the VBioR Laboratory Project was semi-emergent, using the words of the participants to aid in the development of the themes. However, the framing was explicitly within the domain of chemical, biological, and environmental engineering. Many of the theme names were straightforward, such as “memo” and “budget”. In the case of episodes focused on bioreactor-specific technical principles and nomenclature, the variety in wording for discussion of the same concepts made determination of common theme names more challenging. It was also found in many cases that the emerging list of thematic codes aligned with similar codes developed for the VCVD Laboratory Project. The existing VCVD theme names were adopted as appropriate. The list of thematic codes was finalized in consultation with instructors that use the Virtual Laboratories and other research team members. The final set of themes used for coding the VBioR discourse is presented in Table 3.

Table 3 - VBioR Episode Theme Hierarchy

I	II	III	IV (VBioR Specific)
Student Engineering Objectives	Input Parameters		Inoculum
			Temperature
			Batch Time
			Fed Batch Time
			Total Time
			Initial Substrate Concentration
			Fed Batch Flow Rate
			Fed Batch Feed Concentration
			Measurement Strategy
	Performance Metrics/Objectives		Productivity
			Budget
Instructor Objectives	Core Technical Content & Concepts	Kinetics	Biomass Growth
			Substrate Utilization
			Product Formation
			Temperature Dependence
		Transport	Oxygen Mass Transfer
			Substrate Limitation
		Experimental Design (Strategy)	
	Professional Skills	Sources	
		Memo	
		Notebook	
	Affective		
Project Contextualization	Situate		
	Instructional Design		
Other	Administrative		
	Research Study		

The episode theme hierarchy consists of four tiers. On the right-hand side of Table 3, the VBioR tier is the most specific and is most closely related to the verbal data. These context-based themes can be categorized in meaningful ways to aid in the analysis of the data. The specificity of the categories decreases from right to left in Table 3. *Student Engineering Objectives* are defined as the numerical values of parameters that the student teams must determine in order to run the VBioR (i.e., input parameters) and the explicit performance metrics of the system. In other words, these are the inputs and outputs that the students will manage when interacting with the VBioR system. *Instructor*

Objectives are defined as the knowledge and skills that are integrated and reinforced through participation in the VBioR Laboratory Project. This category includes understanding relevant core technical content and concepts, developing professional skills, and experiencing ambiguity, teamwork, stress, etc. *Project Contextualization* includes discussion relating the VBioR Laboratory Project to industry and engineering practice (i.e., situating) and explanations of how the project is structured and why (i.e., instructional design).

The use of these categories is especially useful for comparisons between the VBioR and VCVD Laboratory Projects because Tiers I, II, and III are equivalent. The "other" category includes administrative talk (e.g., when the instructor provides the students with their username and password) and any direct mentions of the audio recording or research study process. Discourse coded as "other" is not included in the feedback analysis because it is not considered part of the feedback process. Note that in the method of discourse analysis used for this research, any given episode can have multiple thematic codes, due to the hierarchical nature of the themes as well as the existence of nested episodes. In an extreme example, Table 4 shows a sub-episode from Team B that is directly coded with five themes, including Experimental Design, Kinetics, Transport, Oxygen Mass Transfer, and Situate.

Table 4 - Example of discourse with multiple thematic codes

Participant	Discourse	Word Count
Instructor:	"That's not going to happen at the beginning because I am certainly not going to let you put that many cells in… and why wouldn't I let you? I'll tell you why: Because..."	33
Student B2:	"That's a lot of cells that we would have to grow beforehand."	12
Instructor:	"Right. You would have had to of bought two bioreactors right? And if I am trying to get you to use the most efficient operating parameters then dividing by bioreactor volume because we had to pay for that bioreactor. You know you would have had to of had another one then pour it in to there so it messes up our evaluation parameter."	63

However, because of the hierarchical nature of the theme codes, this sub-episode also associated with Core Technical Content & Concepts and Instructor Objectives. The presence of sub-episodes means that these 108 words are associated with seven different theme codes and are accounted for five times in the discourse analysis. This overlap happens because the broadest episode has a theme of Experimental Design, but that discussion subsequently led the group to discuss Kinetics, Transport, and Oxygen Mass Transfer. This particular sub-episode is situating the discussion with respect to industry and engineering practice. Counting an episode multiple times if it has multiple themes is a practical and useful way to represent the data for the purposes of this analysis.

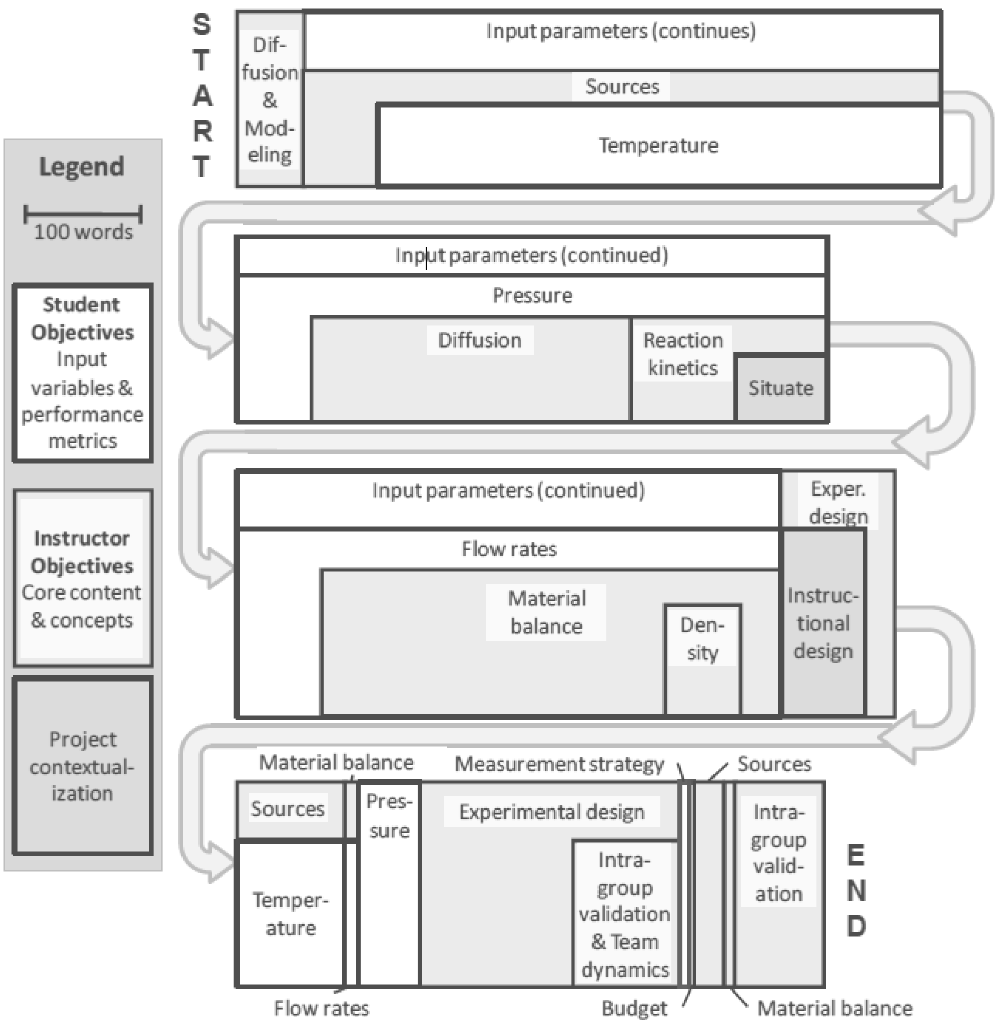


Figure 4 - Chronological Representation of DMM Episodes (Gilbuena et al., 2011[b])

As show in Figure 4, a nesting diagram has been developed to illustrate the flow of a complete DMM, including all sub-episodes. This technique for illustrating the data was developed with data from students engaged in the VCVD Laboratory Project, but it can also be applied to data from students engaged in the VBioR Laboratory Project. The diagram shows a legend of 100 words, which means that the width of the episode box is proportional to the number of words for that episode. The DMM discourse flows from left to right and continues down the page as directed by the arrows (Gilbuena, Sherrett, Gummer, & Koretsky, 2011[b]).

Episodes in the context of the virtual laboratory projects are commonly composed of up to four distinct feedback stages, surveying, probing, guiding, and confirmation, as shown in Figure 5 (Gilbuena, Sherrett, Gummer, & Koretsky, 2011[a]). During the *Surveying Stage*, the instructor becomes familiar with the student team's approach toward the VBioR Laboratory Project, looking for misconceptions or lack of understanding. This stage usually involves reading the memo, asking broad questions, and letting the students explain their approach to the project. During the P*robing Stage* the instructor asks more specific questions to more thoroughly understand the students' conceptions of the VBioR and the team's experimental strategy. The *Guiding Stage* begins once the instructor has identified a misconception or lack of understanding. From here, the instructor provides feedback until the students are aware of the issues and moved toward increased understanding. The guiding stage is often highly facilitative, using a series of leading questions. However, the feedback can be more directive, providing specific advice and instruction and answering questions. Finally, in the *Confirmation Stage*, the instructor and students reach consensus on the issue(s) being discussed. Confirmation is signified by instructor validation of explanations provided by the students or by the students agreeing with statements made by the instructor. Confirmation signifies the end of an episode and this process repeats for the next episode. This analysis method of considering feedback stages is an additional coding scheme used in this research.

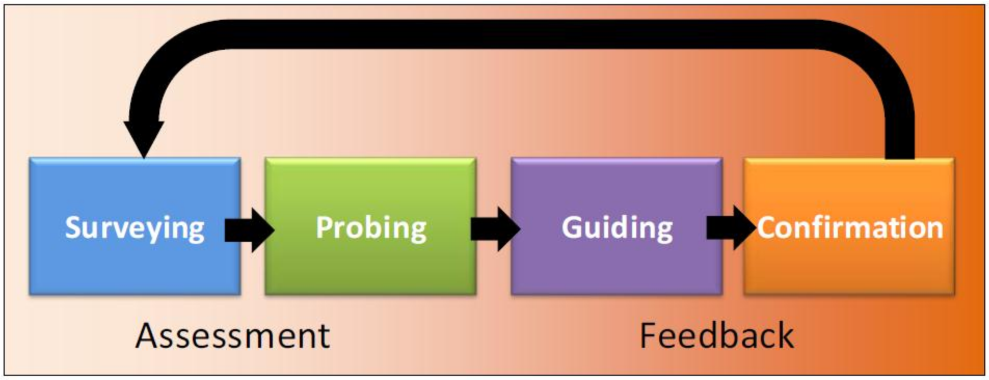


Figure 5 - Stages of Feedback

The survey data analysis involved the identification of themes. All handwritten student responses were grouped by team and reviewed for commonalities and differences. These responses were coded using the Theme Hierarchy presented in Table 3 to allow for a theme-based comparison. By using the same Theme Hierarchy for the survey data, future analysis will be able to compare the composition of themes in student reflection responses to the composition of themes identified through coding the DMM discourse by team. This analysis will allow correlation between these two perspectives, the student's reflections and the researcher's observations. In addition to the Theme Hierarchy, an emergent process was used to identify commonly cited instructor techniques.

5 Results and Discussion

The DMM discourse has been coded using the episodes framework as explained in the analysis methods section. The episode-delineated data is coded in three different ways as follows: (1) by participant (student or instructor), (2) by themes, and (3) by feedback stages. The coding results are presented for the entire DMM for all four teams for feedback themes and feedback stages. Additionally, specific episodes are compared across teams using these same coding strategies. The final section of the results codes student reflection responses by themes and by instructor techniques cited.

First, the average rate of words spoken during the DMM ranges from 112 to 203 words per minute. Because different teams have different rates of speech for the DMM, proportion of words spoken is used to allow a more direct comparison between teams. In some cases word counts are presented for reference. Figure 6 shows the distribution of words spoken during the DMM by participant type (i.e., student or instructor). The proportion of words spoken by the instructor is fairly consistent, at around 80 percent, except for Team D for which the proportion is 70 percent.

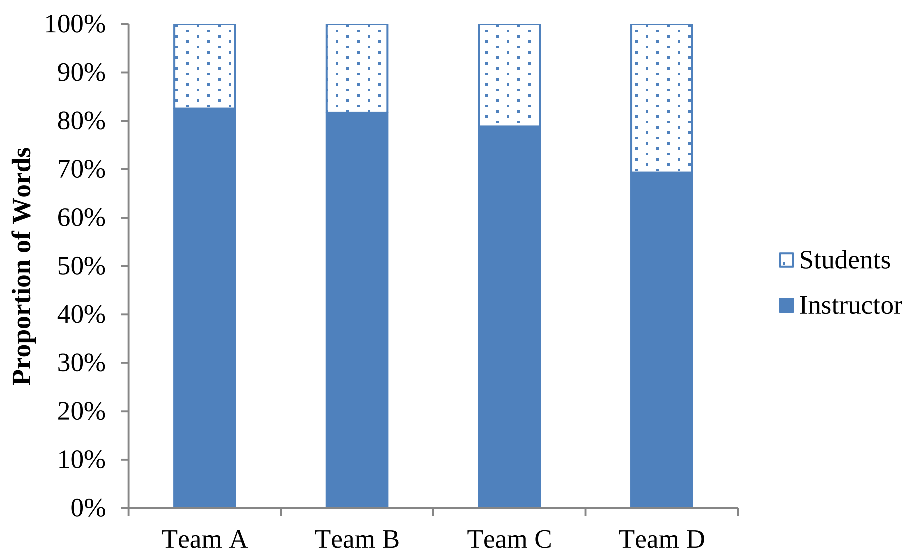


Figure 6 - Proportion of Words by Students versus Instructor during DMM

Next, Figure 7 shows the proportion of words spoken by each student with the words spoken by the instructor removed. Each team has a unique distribution of words spoken among team members. For Team A, Student A1 has significantly more words than Student A2 or Student A3. Next, Team B students B1 and B2 speak equal proportions of words, but Student B3 does not speak at all. All three Team C students speak about one-third of the words. Finally, Team D is similar to Team A in this comparison, with Student D1 having significantly more words than D2 and D3. Note that for both Student A1 and Student D1 not only did they speak the most, they were also first to speak.

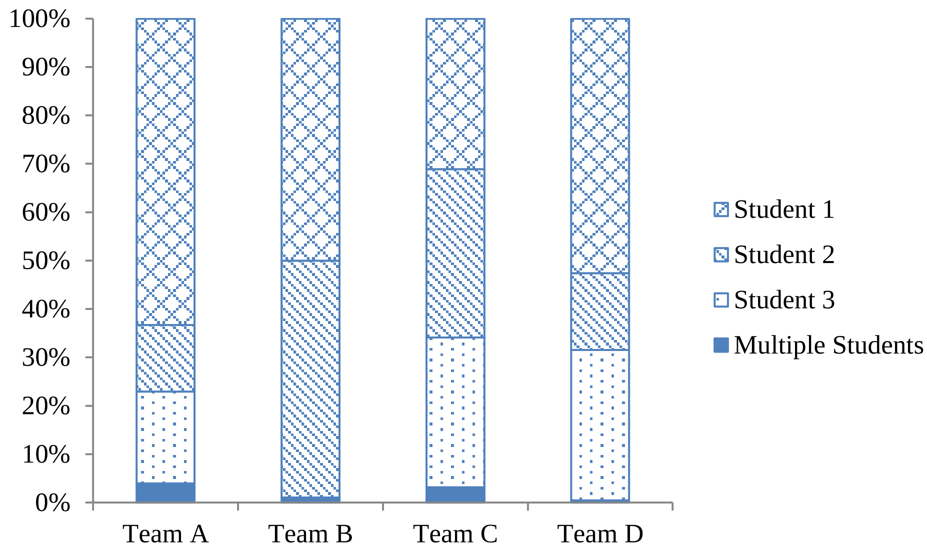


Figure 7 - Proportion of Words by Student Participant during DMM

5.1 Feedback Themes

Figure 8, Figure 9, and Figure 10 are nesting diagrams that have been generated for the four teams analyzed. The nesting diagrams are based on the Theme Hierarchy episode coding presented in Table 3. These diagrams give an overview of the flow of the DMM for each team. The episode size as shown in the diagram is proportional to the number of words associated with each episode. The Tier I discourse analysis themes – Student Engineering Objectives, Instructor Objectives, and Project Contextualization – are shaded differently to highlight the different theme categories.

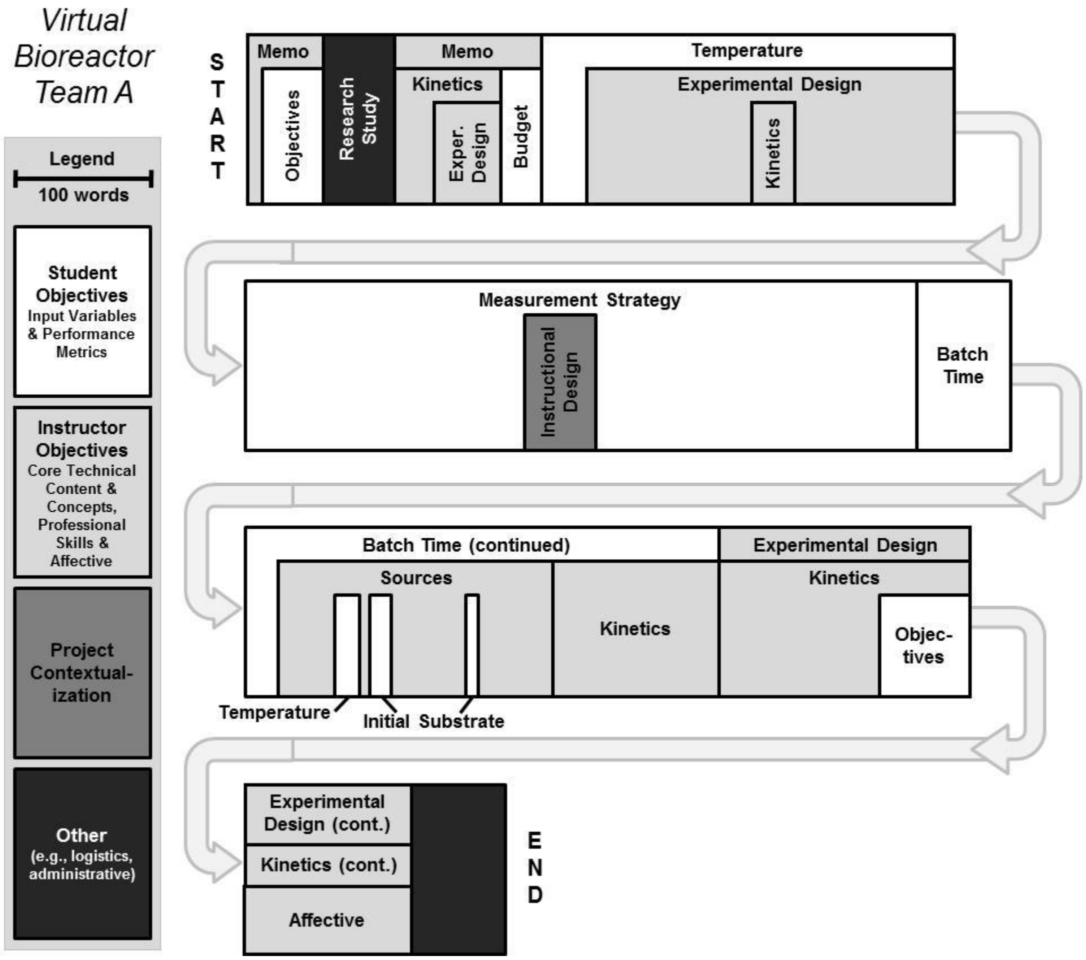


Figure 8 - Chronological Representation of DMM Episodes for Team A

Figure 8 shows that Team A has a fairly even distribution between Student Objectives and Instructor Objectives themes, however there is only one Project Contextualization episode. In contrast, Figure 9 indicates that the Team B has substantially more Instructor Objectives episodes. There are also fewer Student Objectives episodes and they are mostly sub-episodes within an Instructor Objectives episode. Team B also has more Project Contextualization. It is also evident that Team B has a longer DMM than Team A.

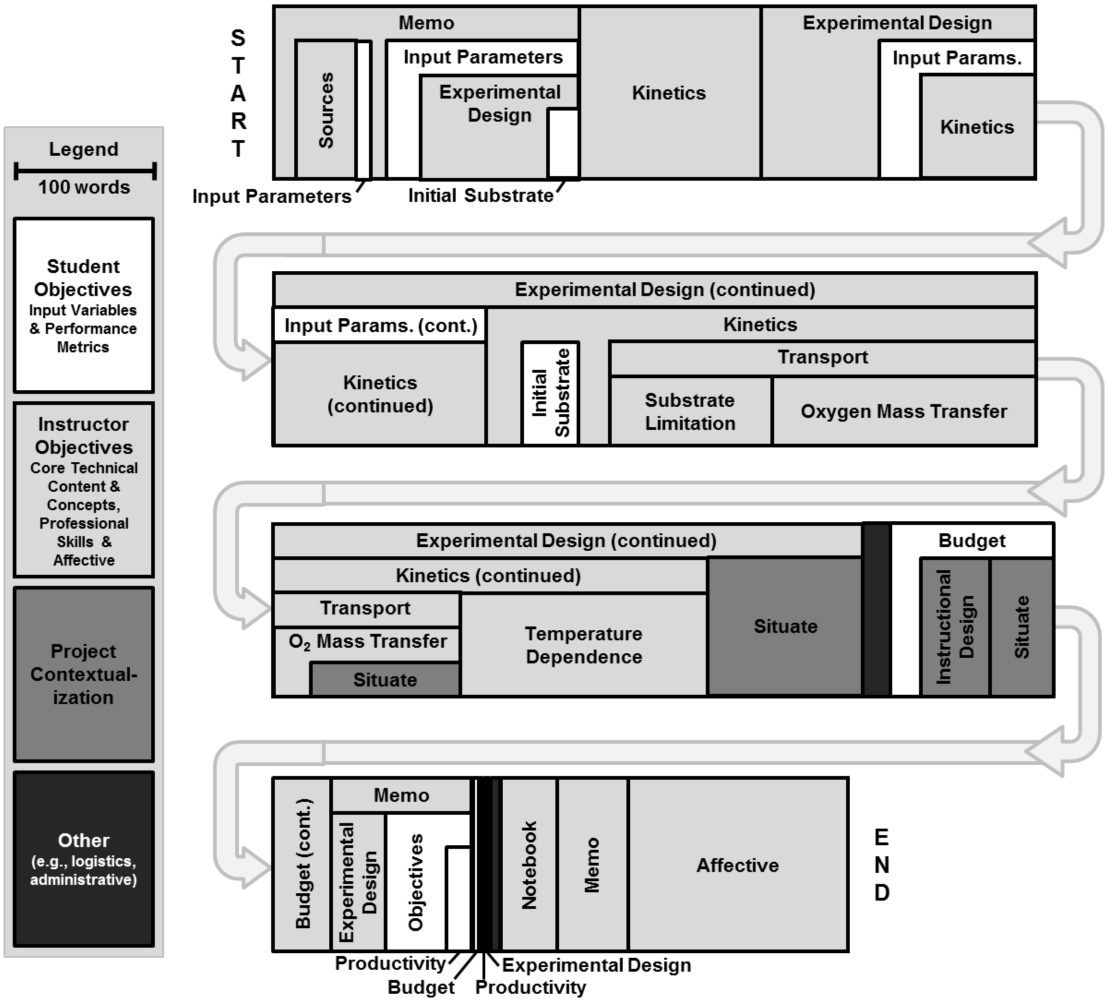


Figure 9 - Chronological Representation of DMM Episodes for Team B

Figure 10 displays the nesting diagram for Team C. Similar to Team A, the episodes for Team C are more evenly distributed between Student Objectives and Instructor Objectives, in comparison to Team B. There is also much more Project Contextualization, largely due to the Instructional Design episode. It is also evident that Team C's DMM is slightly longer than Team B's DMM. The time limit for the initial DMM for this cohort is 20 minutes.

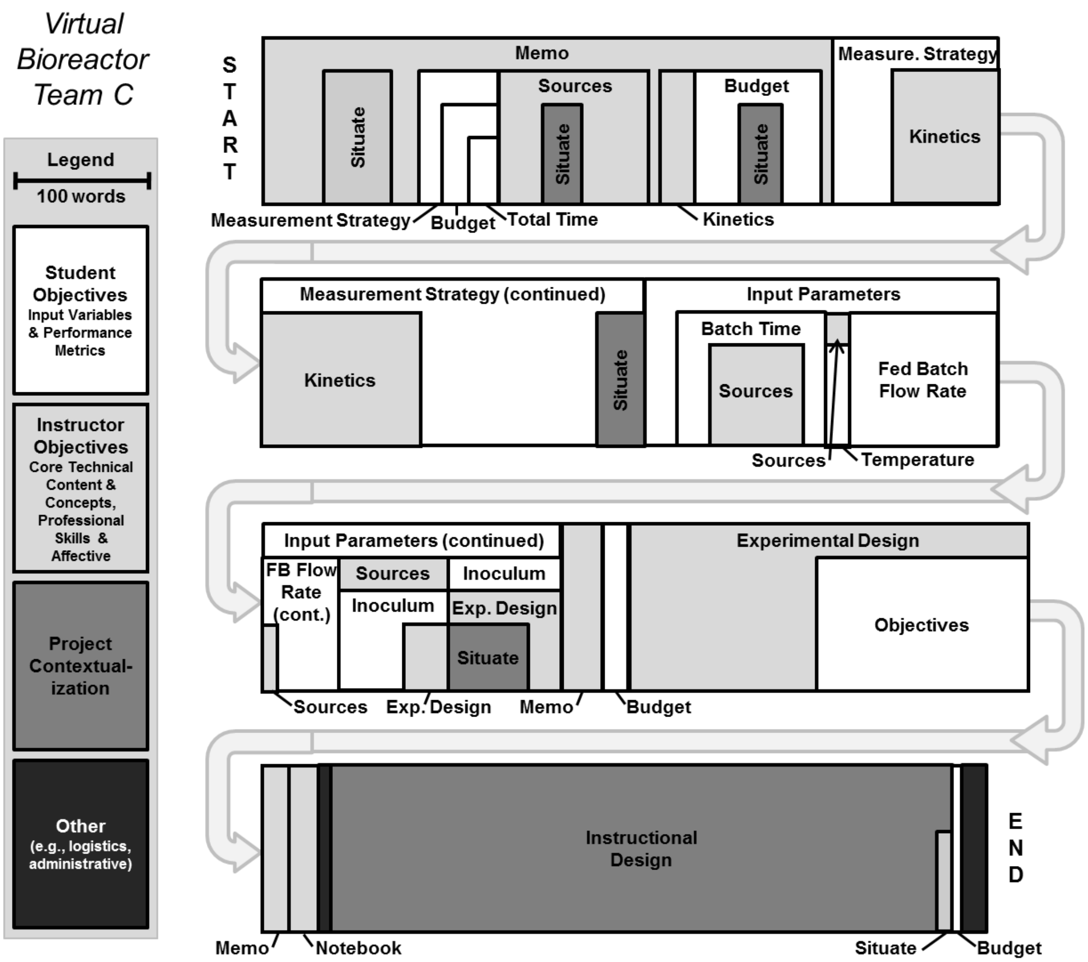


Figure 10 - Chronological Representation of DMM Episodes for Team C

Figure 11 shows the nesting diagram for Team D. The DMM time limit of 30 minutes for this cohort is longer than for the other cohorts. Because of this increased meeting time limit, the nesting diagram for Team D is longer than that of the other three teams considered in this study. Also, similar to Team B, Team D's DMM is largely focused on themes associated with Instructor Objectives. Discussion of Student Objectives is limited and there is only one instance of Project Contextualization.

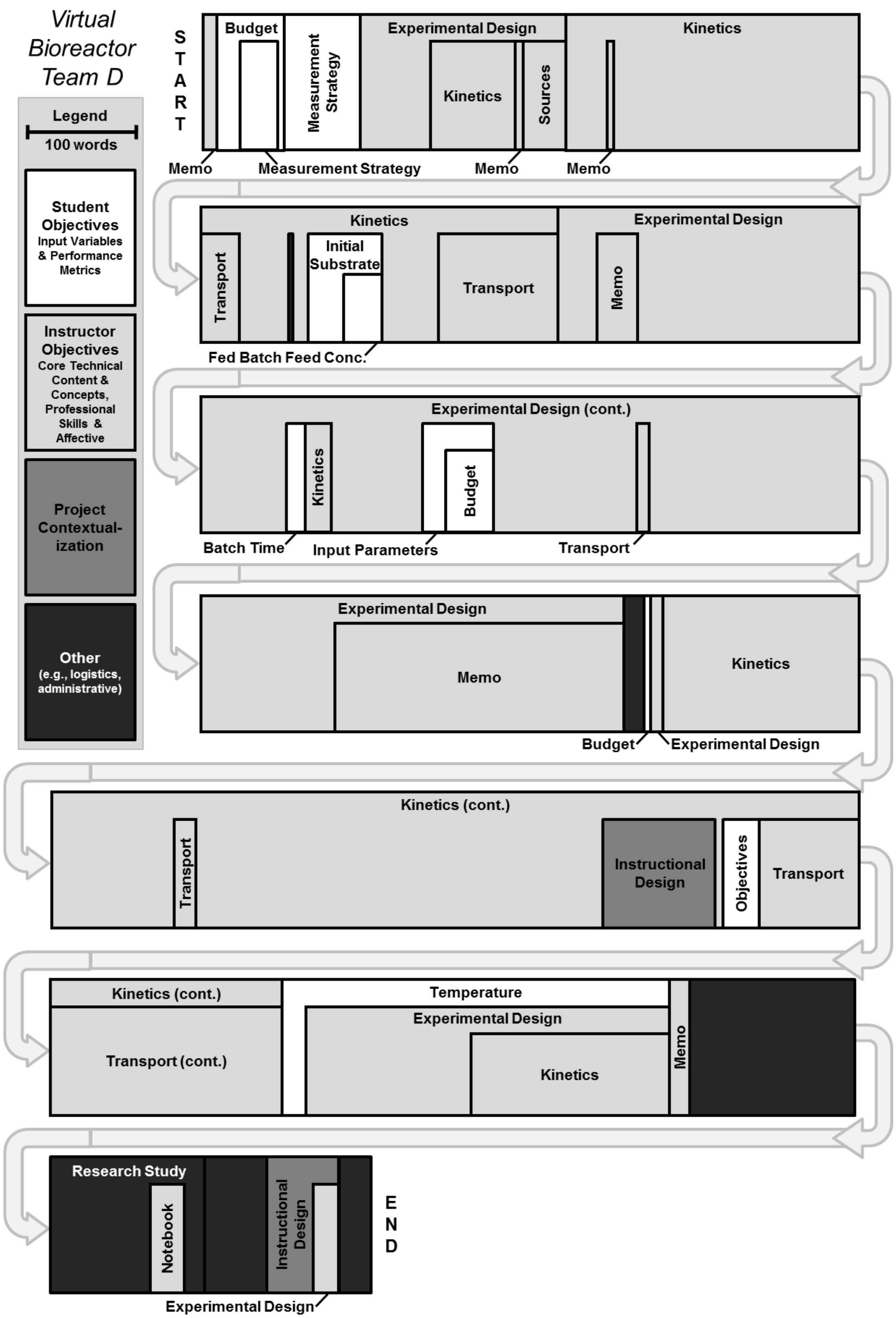


Figure 11 - Chronological Representation of DMM Episodes for Team D

These nesting diagrams provide an introduction to the composition and flow of the DMM for each team. To further investigate the Tier I discourse analysis categories, the proportion of words dedicated to each theme during the DMM is shown for each team in Figure 12. In agreement with the results from the nesting diagrams, Team B and Team D show a higher proportion of words on Instructor Objectives and a lower proportion of words on Student Engineering Objectives than the other two teams. Meanwhile, Team C has more Project Contextualization. This analysis shows that the themes of the DMM are different for each team, which means that discussion between the instructor and the student teams is unique in each case.

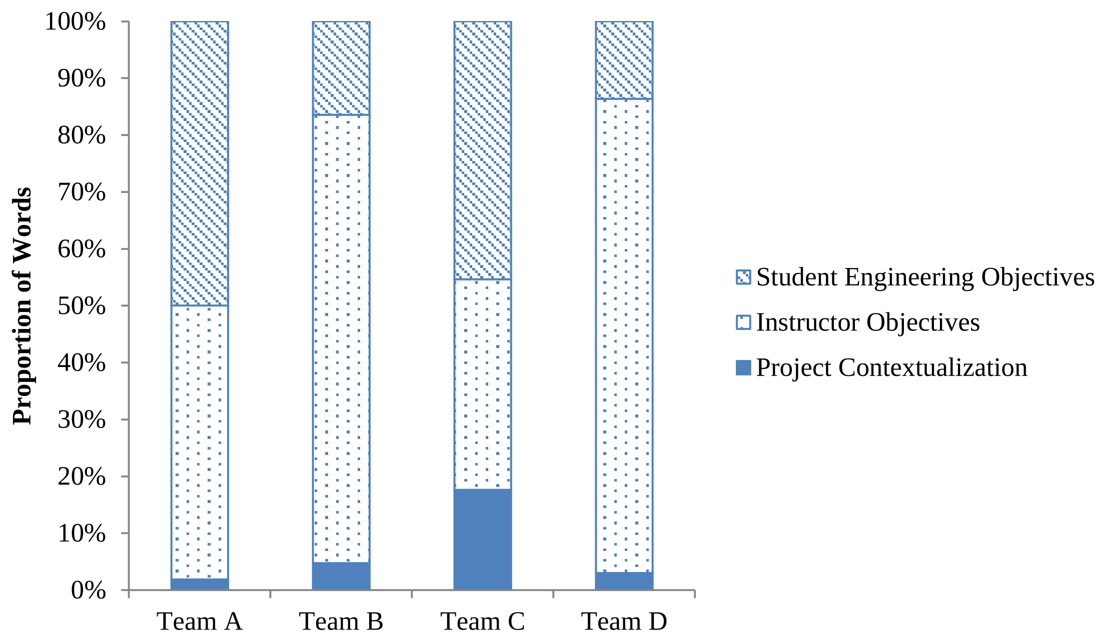


Figure 12 - Tier I themes by team

To further explore these similarities and differences, Tier II themes are displayed by team in Figure 13. Theme names have been abbreviated as follows: Input Parameters (IP), Performance Metrics/Objectives (PM/O), Core Technical Content & Concepts (CTC&C), Professional Skills (PS), Affective (A), Situate (S), and Instructional Design (ID). Recall that IP and PM/O are associated with Student Engineering Objectives, CTC&C, PS, and A are associated with Instructor Objectives, and S and ID are associated with Project Contextualization.

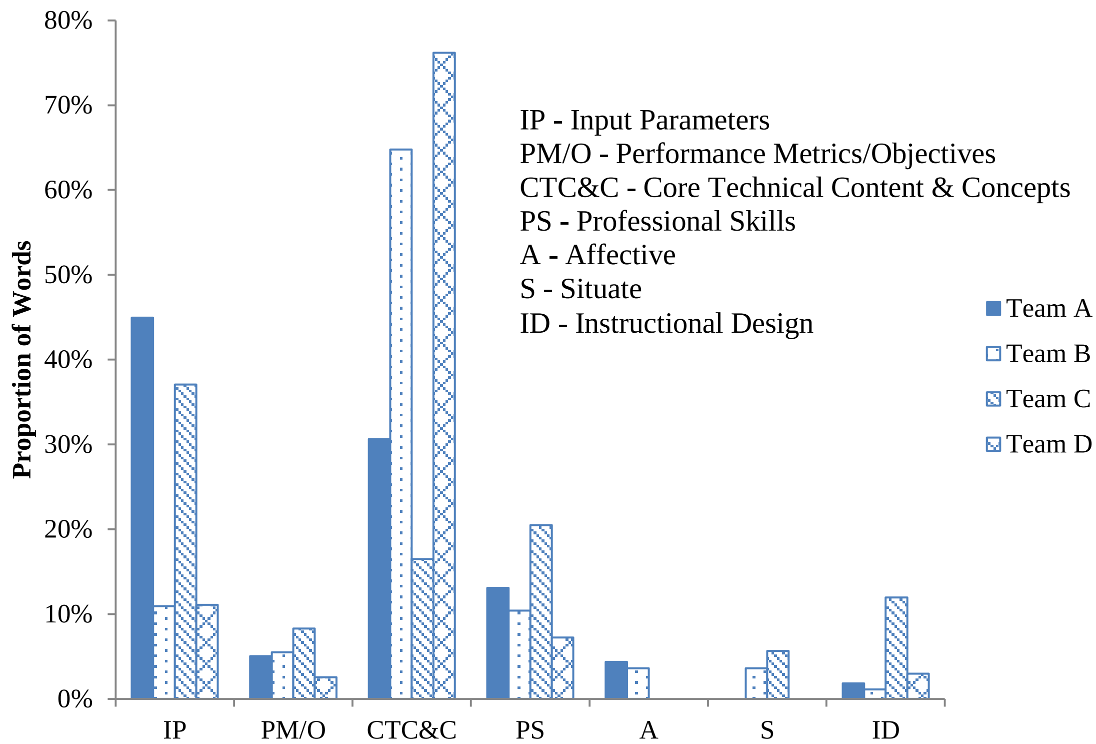


Figure 13 - Tier II themes by team

It can be seen that the greater proportion of words for Instructor Objectives previously noted for Team B and Team D are due to a very small proportion of words for Input Parameters and a very large proportion of words for Core Technical Content & Concepts. Team A and Team C show the opposite trend, with a larger proportion of words for Input Parameters and a smaller proportion of words for Core Technical Content & Concepts. Based on the following text from the DMM transcripts, it is evident that the Team B students had acceptable input parameters included in their memo but they did not communicate a coherent strategy:

> Instructor: “So this is, okay, so here’s, when I read the whole thing, here’s my big picture: these are very reasonable, right, your first guess parameters. Your strategy doesn’t really come out at me. Like so far I don’t really know what you’re doing, except you will hold everything constant and move one of them and then hold everything constant and then move another. That’s kinda what it says. Is that what is says?”
>
> Student B1: “That’s like preliminary worst case scenario.”

> Instructor: “Yeah and that is REALLY worse case ‘cause you know that these things interact and you know how... in some cases you know how they interact.”
>
> Team B: Agreeing

Team D also had acceptable input parameters and also included some wording about strategy, but the instructor encouraged the students to develop their strategy even further.

Team A and Team C did not communicate a clear experimental design, but the instructor noticed potentially more problematic issues to discuss first. For example, Team A and Team C both included measurement strategies in their memos but with plans to take excessive measurements. This strategy is problematic because it unnecessarily increases the budget. Measurement Strategy is a Tier IV category associated with Input Parameters, which largely explains why these two teams have a higher proportion of words associated with Input Parameters and Student Engineering Objectives. Following is a portion of the primary Measurement Strategy episode for Team A that highlights the instructor’s concern with the team’s current plans:

> Instructor: “…amount of info gained, right, versus number of samples, right? And so, certainly if you have one sample and you get two, you get a lot more information, if you have three you get a lot more information, if you have four and at some point though increasing the number of samples doesn’t get you any more information, really. And so you guys know what a batch curve looks like, it’s gonna look something like this [drawing] and it can look anywhere in there right.”
>
> Team A: Agreeing
>
> Instructor: “So, does it take 30 samples to describe this curve? Probably not…but if you take, like 30 samples is kinda, like how many samples do you need to describe pretty much this curve do you think, would you guess?
>
> Student A1: “Well I think, I think the only reason we, we chose that was because like all three of us are ChemE’s we have really no clue how a batch reactor is gonna run, like so if you…”
>
> Instructor: “Right, but I’m saying like, let’s say this was a chemical reaction.”
>
> Student A1: “Yeah.”

> Instructor: “Right. Let’s say this was, uh your little sister’s growth, uh, right. How many, like could you describe this in like two samples?
>
> Team A: “No”
>
> Instructor: “Could you describe it in 3? Almost, right? But certainly you wouldn’t want to just do 3. Could you describe this in 5, no matter what it really looked at, could you describe this in 5 equally spaced samples?”
>
> Student A1: “Probably.”
>
> Instructor: “Pretty, ya know, I’m not saying go with 5, but I’m saying 30 seems excessive.”

Because the DMM is scheduled for a fixed amount of time (20 or 30 minutes), some topics are not addressed in as much detail for some teams, partially due to a lack of time. These teams need adaptive feedback that allows them to advance along their unique solution paths. Different teams struggle and excel with different aspects of the VBioR Laboratory Project and they also move through the project at different speeds and along different solution paths. It is possible for teams to come to the same final process recipes using different approaches. For Team B and Team D, these differences mean that the DMM focuses more on Core Technical Content & Concepts, including Experimental Design, Kinetics, and Transport. Meanwhile, Team A and Team C both have substantial Measurement Strategy episodes and focus less on Core Technical Content and Concepts. Figure 14 illustrates the similarities and differences between teams for these four themes of interest. These results provide an example of the adaptive nature of the feedback provided during the information gathering and problem formulation process for the VBioR Laboratory Project.

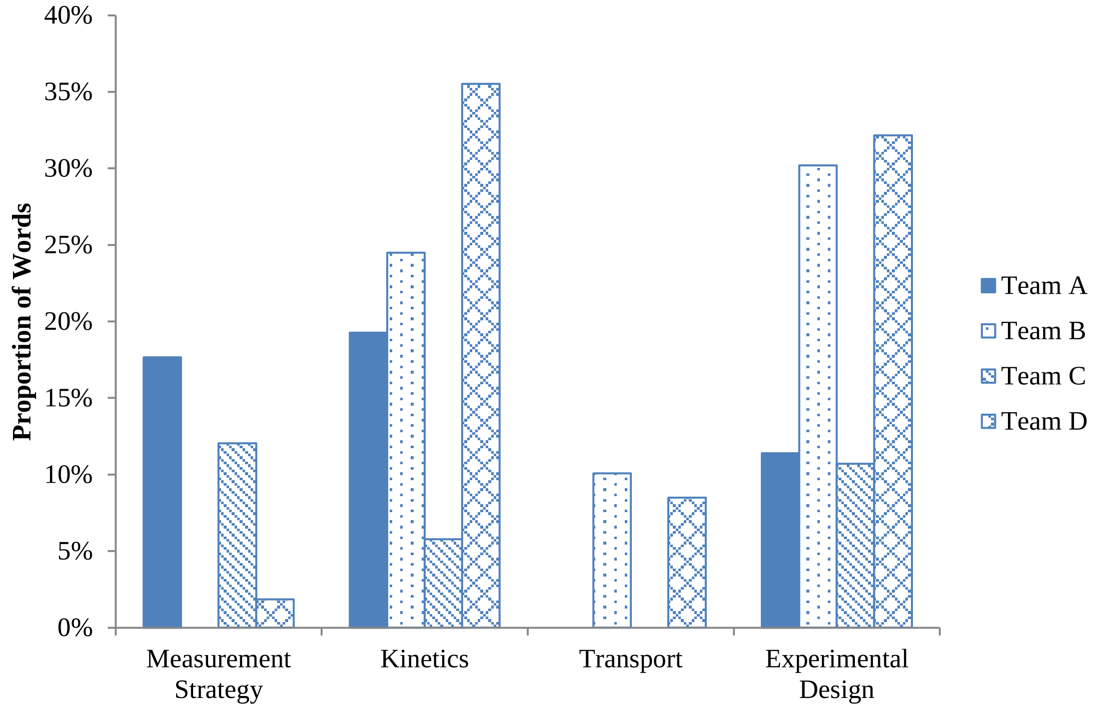


Figure 14 - Example themes by team

Next, Figure 15 shows the proportion of words for Input Parameter Tier IV themes. In addition to the differences in Measurement Strategy, the Input Parameter Tier IV themes differ in other ways. For Team A and Team D, the Input Parameters are covered in a more disjointed manner during the meeting. For both Team B and Team C, the input parameters tend to be discussed more collectively, as sub-episodes within two larger episodes directly coded as Input Parameters. The differences in the Input Parameters discussed further highlight the adaptive nature of the feedback provided during the DMM.

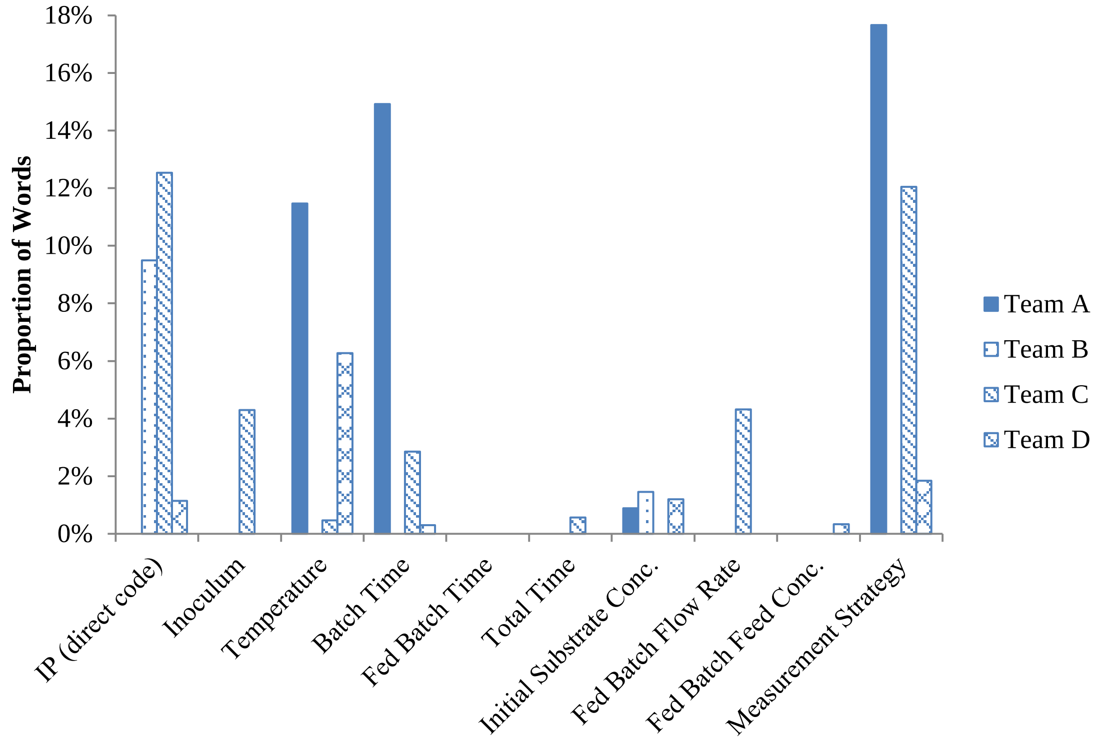


Figure 15 - Tier IV IP themes by team

Without discussing every single parameter, a few aspects of Figure 15 are worth elaborating on. Team A has 11 percent of words coded as Temperature and 15 percent of words coded as Batch Time, accounting for over one quarter of all words in the DMM. Team A and Team D both discuss Temperature as it relates to Experimental Design. Temperature is the input parameter with the highest proportion of words for Team D. The episode begins with Temperature as an input parameter, but the discussion quickly transitions to sub-episodes of Experimental Design and Kinetics. Team D's Temperature episode is provided below.

> Instructor: "I wanted to ask you one more thing, here, okay, so you're looking at temperature, but here you only have two temperatures investigated. So…let's say your optimum temperature is, I don't know, 35, right. So this is your highest growth rate, and this is 35. And you're going to…you're doing 20 and 25. Your optimum temperature could be 35… [drawing a graph of temperature versus growth rate]
>
> Student D2: "Right."
>
> Instructor: "It's hard to say much."

Student D2: “[I] see it, the trend.”

Instructor: “Right….but do you see where it's hard to say if you've just got two valuations.”

Student D2: “Right.”

Instructor: “…What’s your thought on temperature?”

Student D1: “Well, I know that there’s two different temperatures that we would kind of want, except that we can't change the temperature throughout the process….You want a higher temperature when you're growing the cells because they like that, but then also you want a lower temperature when product is being produced…”

Instructor: “Yeah, okay, right. But you can’t do that.”

Student D1: “No.”

Instructor: “Right…so you know temperature affects things in different ways.”

Student D2: “Right.”

Instructor: “Because…you've got to think about growth…which is fine, that's what you want to do first.”

Student D2: “Right.”

Instructor: “At some point, you've got to shift your attention to product, which is not in your model. There's product production in your model, but not other things that can happen to product, right. So then you've got to shift your attention to product…optimum growth might, or might not, give you optimum product. So at some point that's a strategy that you have to realize you're going to undertake. But it's perfectly appropriate to look at growth first, because you have to have some cells to get some product.”

Student D1: “Yeah.”

According to their Design Strategy Memo, the students of Team D are proposing to investigate two temperatures in order to optimize that input parameter. The instructor uses a drawing to help illustrate a trend that the students may encounter. Student D1 then articulates understanding of the conflicting relationship between biomass and temperature (positive relationship) and product and temperature (negative relationship). The instructor concludes the episode with feedback verifying the team’s plan to focus on growth first, but also elaborating that the optimal temperature for growth will not necessarily be the optimal temperature for product. The students should consider this tradeoff as part of their strategy.

For Team C, episodes with Inoculum and Fed Batch Flow Rate themes have the greatest proportion of words. The Fed Batch Flow Rate episode is immediately followed by an Inoculum episode. In the discourse below, the instructor helps Team C think carefully about these input parameters.

> [Beginning of Fed Batch Flow Rate episode]
>
> Student C3: “Fed batch flow rate we didn’t know again and we just kind of chose one liter per hour.”
>
> Instructor: “So you start with 2000 liters and you are going to go for 24 hours, and you are going to end with?”
>
> Student C1: “2024 liters. So we get out a lot more. We just found that out”
>
> Instructor: “It seems like that whole fed-batch is, yeah so you just found out.”
>
> Student C1: “So it is going to increase a lot.”
>
> Instructor: “I would say use that.”
>
> Student C2: “Can we try going to 5000 by the end?”
>
> Student C1: “Say you wanted 20 percent of that space left.”
>
> Instructor: “I said working volume is 5000. So working means that is the liquid volume and there is headspace in there.”
>
> Student C1: “Okay, so we don’t have to worry about that.”
>
> Instructor: “Okay so that’s good.”
>
> Student C3: “So we just kind of, because all the fed-batch stuff we couldn’t find any references on it.”
>
> Student C1: “So we decided to keep it because that is what we chose for our initial batch flow plus concentration.”
>
> Instructor: “Okay.”

[Beginning of Inoculum episode]

Student C1: “And we found this in a reference about 15 grams per liter inoculation.”

Instructor: “Really? Okay…”

Student C1: “10 or 15. That’s what we found.”

Instructor: “So to me that is pretty high and you would see when you try to put in 15, the [VBioR Laboratory] will say no.”

Student C3: “Is 10 too high?”

Instructor: “Yeah so the thing is, what kind of thing are you expecting at the end? Did you find any information on what kind of cell density you might be expecting at the end? Okay that is something to think about because I am not going to let you fill a bioreactor with something that has already grown up because that would mean you had another bioreactor that is not really accounted for in the productivity. Right? So I would let you fill something with what might be reasonable in the seed train. Right? But that’s not a variable that you are going to have to mess with that much because as soon as you try you will understand.”

In these episodes, the instructor addresses misunderstandings related to two input parameters. For Fed Batch Flow Rate, the team set the rate at one liter per hour and for Inoculum the team set the cell density at 15 grams per liter. Both of these values are the wrong order of magnitude, albeit in opposite directions. The instructor feedback attempts to clarify each of these input parameters for Team C. The working volume of the bioreactor is also explained.

Referring back to Figure 13, it can be seen that Team C has a higher proportion of words dedicated to Performance Metrics/Objectives than the other two teams. Although the overall proportion of words for PM/O is small relative to some of the other themes, there are important differences to highlight. Figure 16 shows the PM/O sub-themes; note that it is also possible for ‘Performance Metrics’ or ‘Objectives’ to be directly coded when being discussed more generally than Productivity or Budget would indicate. The following sample of discourse provides an example of a sub-episode coded as ‘Objectives’ toward the end of the DMM for Team C; it is within a larger episode on Experimental Design.

> Instructor: “And then the other thing is I am trying to remember , I don’t see in here, this kind of goes with the strategy: *what are you looking for*?, how do you know when you’ve got something good because you’ll want to tell from that 1st run is it something good? You probably won’t be able to tell from the first run but how will you tell from your 1st to your 2nd run is something good or...”
>
> Student C2: “And it can be for whatever time?”
>
> Instructor: “Not exactly, that’s one component of your *objective*. So strategy and *objective*, that goes into strategy. So compare run 1 and run 2, how will you know what are you going to do to check if run 1 or run 2 is better. Right? So I am going to send you back but don’t think that is bad or anything. You’d be happier that you did this first before jumping into a run.”

This discourse demonstrates that Team C has not yet determined what measure to use for the project’s objectives. On the other hand, Team A proposes an inappropriate objectives measure. For Team A, the memo states “In order to achieve the highest *production rate* while minimizing process development costs, optimal bioreactor operating conditions will be determined.” The instructor provides the following feedback for Team A regarding this issue:

> Instructor: “Okay so, you just want to keep in mind that um production rate is something that’s certainly significant, right. But that’s not exactly what you’re optimizing right? So…I’m gonna write that down. Not exactly. It’s very, you know, it’s very much related to product.

It can be seen in the Design Strategy Memo that Team B has already defined the measurement they will use to evaluate objectives given the following plans: “the *volumetric productivity* for both batch and fed-batch will be calculated for straightforward comparisons between all trials.” Team D also includes an appropriate measurement as follows: “The optimization of bioreactor operating conditions for recombinant protein production to *maximize profit* is being investigated…maximal product production rate is desired.” In this case, Team D communicates their understanding that, while product production rate is important, profit is what they will optimize. For Team B and Team D, the DMM discussion on objectives is brief and limited to instructor clarification of the calculation methods the students will use.

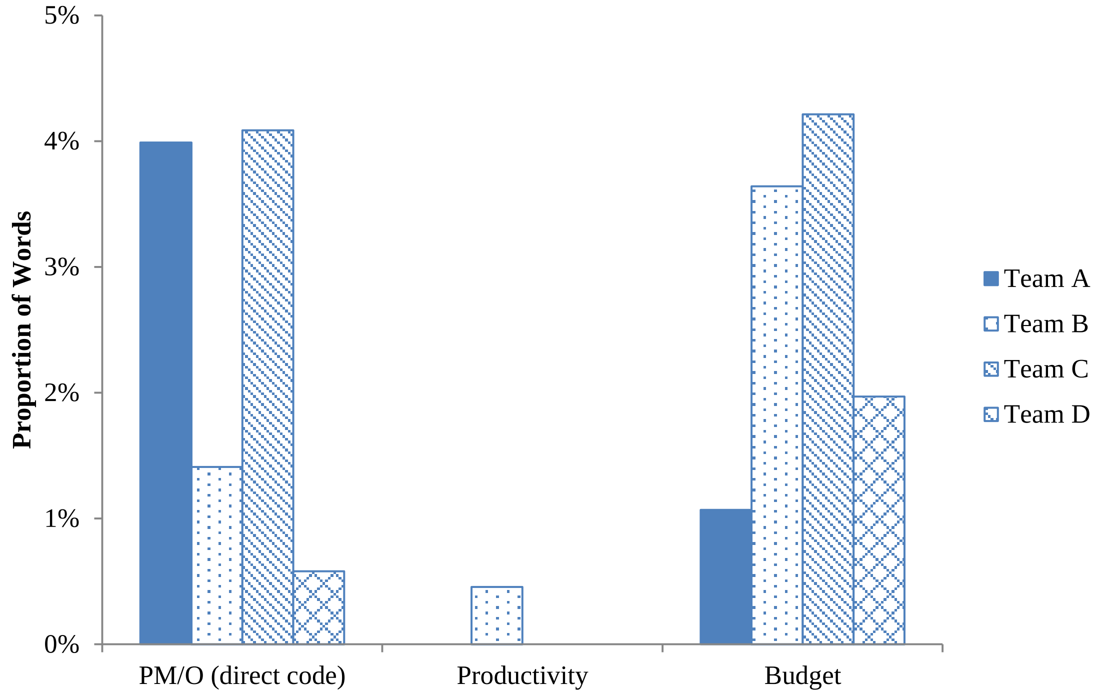


Figure 16 - PM/O themes by team

There are also some differences in the Budget theme proportion of words, with Team A having much less focus on Budget. The Team C students did not include a budget in their Design Strategy Memo, the feedback focuses on the need for developing a budget for the project.

> Instructor: "…you should come up with your estimate of a budget for the whole project. How much you might think, like a reasonable amount to get a good set of optimum input parameters. <u>So it is an estimate but it is an exercise for you to do budgeting because you'll certainly have to do that when you are working. You know what I mean.</u> So budget estimate for the entire…"
>
> Student C1: "And this should go in our memo."
>
> Instructor: "Exactly, all of these things go in memo."
>
> Student C1: "Okay."
>
> Instructor: "So budget estimate for entire project."

The other three teams proposed a budget in their memo. Team A's budget is approximately 50 percent higher than the budget of Team B and Team D. During the DMM, the instructor does not recommend any budget changes for Team A but explicitly requests a budget reduction from Team B and Team D. This difference is related to an increased emphasis on the budget aspect of the project from the first cohort to the later cohorts. The feedback guidelines document developed between these two years includes a range of acceptable budget figures. The following text is Team B's Budget episode:

> Instructor: "So the budget... A little bit high. I have a range that I have *from previous time's expectation* and this is another thing. So we ask you to prepare a budget because it is something that you would typically have to do. Right, think about, gosh, right and you can't know that. How many experiments is this going to take to optimize. But you came up with a pretty good guess here really. But I would say that you are always going to get some kick back. Someone is going to say, either 'you don't have enough money to do this job' or they're gonna say, 'yeah it would be great if we could spend that much but we can't'…and so I'm saying that, that we can't really spend that much. I would reduce it twenty percent or so, okay?"
>
> Student B2: "Which if we are accounting for multiple things then we shouldn't have to…"
>
> Instructor: "Right because of the plan here. Lower the budget."

The underlined sections of text above provide good examples of Project Contextualization sub-episodes occurring within a larger Budget episode. For Team C, the two sentences underlined are coded as Situate. For Team B, the first four underlined sentences are coded as Instructional Design and the final two underlined sentences are coded as Situate. Figure 17 presents the proportion of words coded as Situate or Instructional Design for each team, which are the Tier II themes for Project Contextualization. These results show a potential difference by cohort. Team B and Team C (second cohort) have a higher proportion of words and more instances of situating in comparison to Team A and Team D, which have no situating.

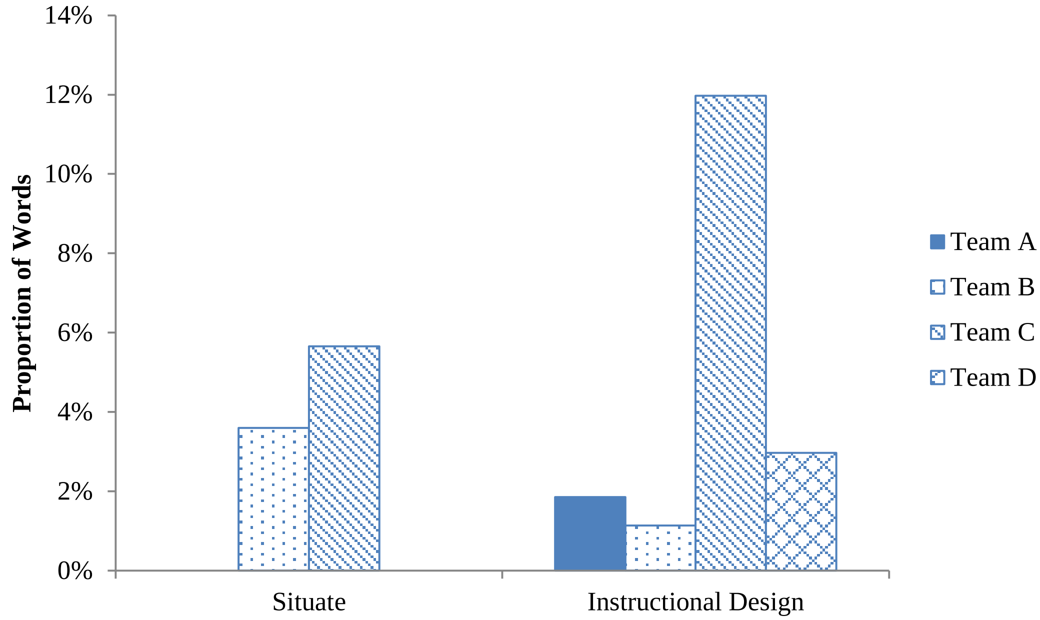


Figure 17 - Tier II Project Contextualization themes by team

Team C has 18% of words coded as Project Contextualization. This emphasis is largely due to a 466-word Instructional Design episode in which the instructor clarifies details of the assignment, how the students operate the VBioR, and how many runs the students can do between the DMM and TUM. Below is an excerpt from this episode.

> Student C1: "Do we just do one run for this lab and then write another memo?"
>
> Instructor: "No, no, no. Once I give you your code you can do as many runs as you want till the next week. I mean you're going to give me a budget, I wouldn't go 85 times that budget so when I give you your code you are working on it all week, and then you will tell me at the beginning of next week where you are. Some people do a few runs and then they are still thinking while some people do a lot of runs so people approach it differently."
>
> Student C2: "And can we only do it on Mondays at this time?"
>
> Instructor: "You can do runs whenever you want. You do runs from your house, its web."
>
> Student C3: "And about how long does one run take?"

> Instructor: “About…so you’ll log in, you’ll set those seven parameters and then you’ll say I want to take 10 samples or 50 samples, whatever it is. Once you set that a new window comes up that tells you the times. You know run hour, zero, one, two, three. You don’t have to write in which time you want for those number of samples and what you want taken, you will check boxes. And then once you push that enter it is about 30 seconds.
>
> Student C2: “Oh okay.”
>
> Instructor: “And then the data will just come at you in a table, it will echo what was ran. The run was run with these conditions and you will have that data. You can go back to options and export to excel if you want or you could just look at it, whatever you want to do.”
>
> Student C2: “Okay.”
>
> Instructor: “Yeah, if it was for a real bioreactor it would take longer.”
>
> Student C2: “You know, it’s 60 hours.”
>
> Instructor: “That’s right.”

Figure 18 shows the Tier III codes of Professional Skills by team. Team A and Team C both have a similar proportion of words for discussion of Sources, while Team B and Team D have a very small proportion of words for that theme. Reviewing the Design Strategy Memos from each of these teams reveals that Team A and Team C did not cite any sources and Team B and Team D cited multiple sources. This finding supports the differences noted in the DMM discourse. Also, Team C has the greatest proportion of words for the Memo theme, and the initial Design Strategy Memo was not in memo format and only included a list of input parameters and a measurement strategy table, without any rationale. The other three teams used an acceptable memo format, including input parameters, measurement strategy, experimental design, and budget information. In terms of Notebook, the instructor typically just verifies that the students are keeping notes in their laboratory notebook. In the case of Team A, this episode did not occur, possibly due to an oversight on the part of the instructor or lack of time. Improving this type of consistency from team to team is one reason the feedback guidelines were created.

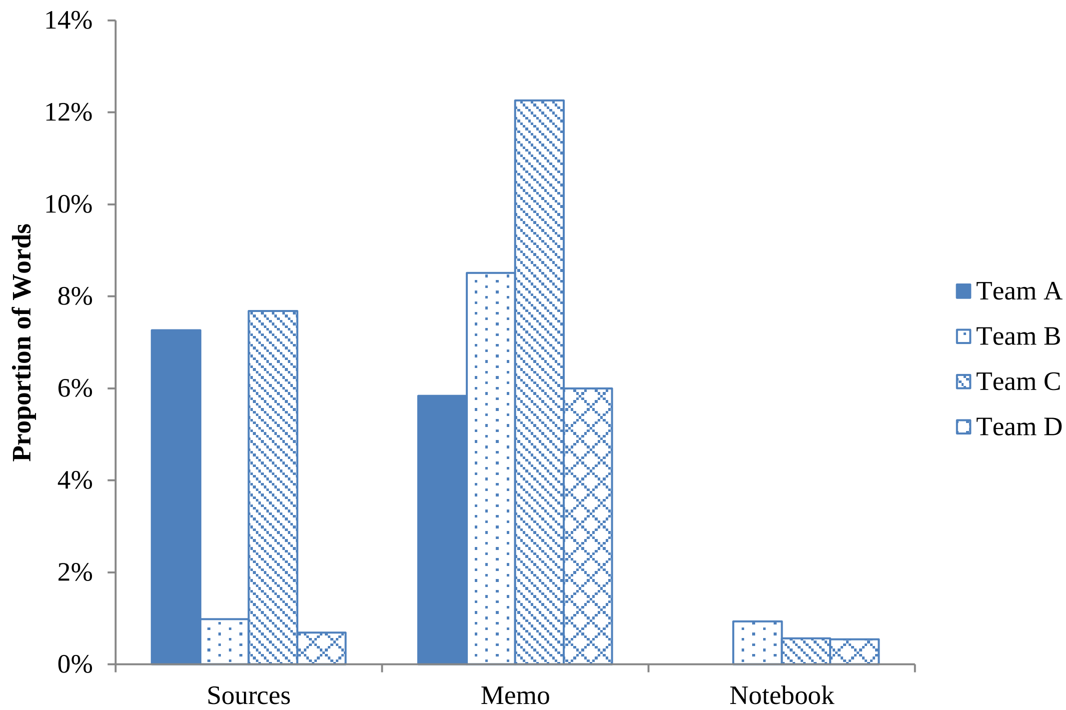


Figure 18 - Tier III Professional Skills themes by team

This detailed characterization of episode themes from four different team's DMMs show that feedback is adaptive to address the unique solution paths of each team. This finding is supported by pedagogical theories that recommend student-centered instruction (Felder & Brent, 1996) and individualized instruction (Chung et al., 2007). However, there are certain elements of feedback that can have increased consistency through the use of a feedback guidelines document. The instructor must carefully balance the need for adaptive feedback to address unique solution paths and consistent feedback to address project constraints (e.g., financial constraints) and deliverables (e.g., design notebook review).

5.2 Feedback Stages

In addition to coding episode themes, another way to characterize feedback in the context of the VBioR Laboratory Project Design Memo Meetings (DMMs) is coding the Feedback Stages of the discourse. The previously presented Feedback Stages Framework (see Figure 5) can be used to code the entirety of the DMM discourse. This framework provides insight into which Stages of Feedback are present during the DMM and in what proportions, as displayed in Figure 19. This view shows a couple of high-level differences between teams. Team A and Team D have about twice as much Probing as Team B and Team C. Also, Team B has about twice as much Confirmation as the other three teams. Team C has the most Guiding.

All teams show minimal Surveying, with Team D having the highest proportion (8%). Review of the DMM discourse suggests that the instructor surveys through reviewing the Design Strategy Memo. Once familiar with the team's approach, potential misconceptions, and limits to understanding, the instructor moves directly into the probing stage. So the surveying stage is still technically present even though it is not captured through the discourse analysis methods used. The surveying stage is more prominent in the VCVD Laboratory Project DMM discourse, which was used to develop the Feedback Stages Framework. Analysis of four VCVD team's Material Balance episodes showed the proportion of words dedicated to surveying ranging from approximately 10 to 40 percent (Gilbuena et al., 2011[a]). Rather than reading the memo silently, the instructor reads the memo aloud. This evidence highlights a difference between instructors because VCVD and VBioR teams meet with different instructors by project type.

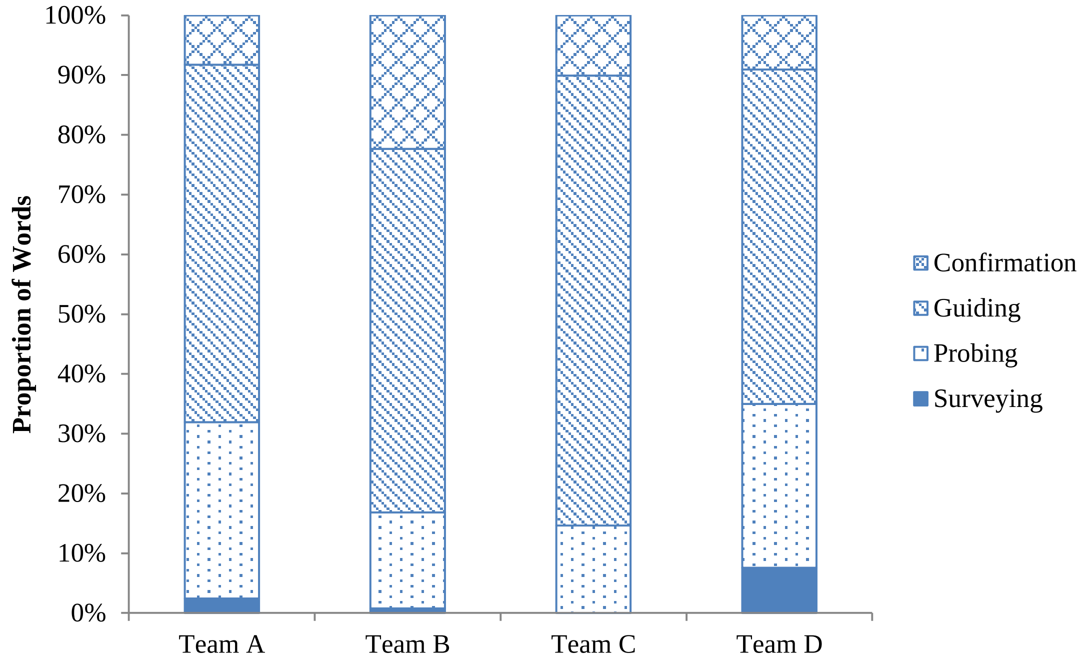


Figure 19 - Feedback Stages by team

Not all episodes neatly cycle through Feedback Stages as presented in Figure 5. In some instances, particularly when sub-episodes are present, probing can be followed by several sets of guiding and confirmation feedback. Confirmation can also occur without following the guiding stage, such as instructor confirmation of the appropriateness of Design Strategy Memo content without the use of probing or guiding. Regardless, Feedback Stages is a meaningful framework for characterization, particularly for comparable episodes across teams. For the teams analyzed, there are four episodes that allow comparison between two or more teams.

A comparison of the word count and proportion of words for the Measurement Strategy episode for three teams is shown in Figure 20. Regarding the Measurement Strategy episode, Team A and Team C have a similar discussion with the instructor, while the episode for Team D is different and much shorter. The episode for Team D mainly consists of Probing and Confirmation. Team A has more Guiding while Team C has more Probing. Team A states in the memo that "...cell density, substrate concentration and product concentration samples will be taken at increments of one hour for a total of 30 hours." The memo goes on to describe how the team will analyze the data by plotting a growth curve. The instructor has underlined “one hour” on the memo and the Measurement Strategy episode focuses on whether 30 hourly samples are really necessary. The conclusion is that the sampling plan seems excessive.

Team C includes a table to communicate the proposed measurement strategy, but does not provide any rationale. Over the course of the student’s proposed 44 hour run time, they plan to take a cell density sample every two hours, a substrate concentration sample every six hours, and a product concentration sample every 10 hours. The beginning of their Measurement Strategy episode includes a Kinetics sub-episode that involves instructor probing to understand how the students arrived at their sampling plan and how they planned to analyze the data. The guiding portion of the episode is similar in content to that of Team A, only briefer. It seems that the main reason for the additional Probing and Confirmation with Team C is related to the lack of rationale provided in their memo.

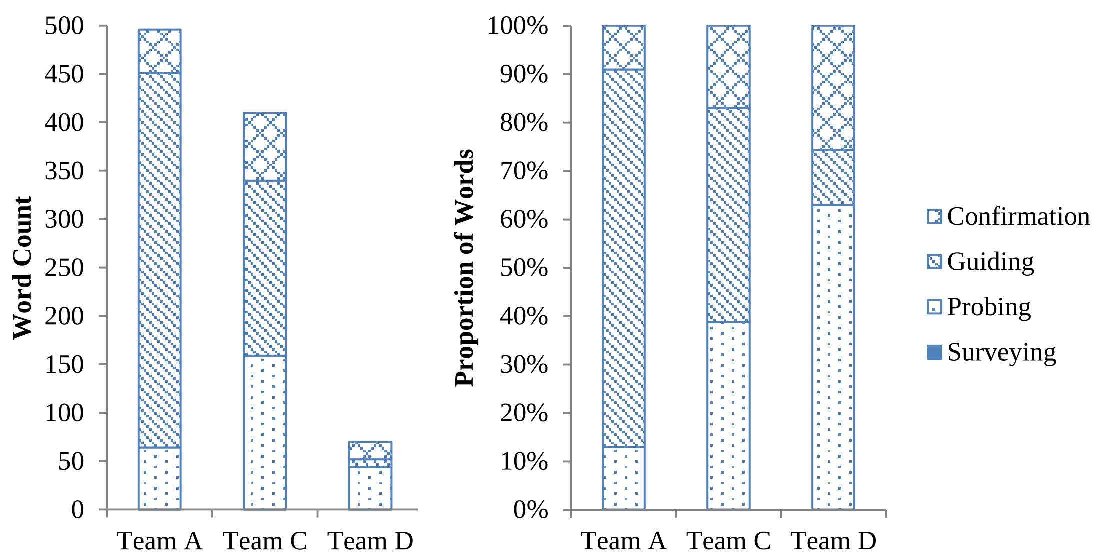


Figure 20 - Measurement Strategy episodes by Feedback Stages by team

Similar data of the Feedback Stages coding for Budget episodes of Team B and C are shown in Figure 21. Team B has twice as many words dedicated to Guiding compared to Team C. Also, Team C has more Confirmation. As previously mentioned, DMM feedback guidelines were developed between the cohorts of these two teams, leading the instructor to place more emphasis on budgeting for Team B and Team C. For Team B the instructor explains the reason that the instructional design includes a mandatory budget and asks the students to reduce their budget by relating the VBioR Laboratory Project to an industrial setting. On the other hand, Team C did not include a budget in the Design Strategy Memo. The Budget episode for these students is focused on clarifying this requirement.

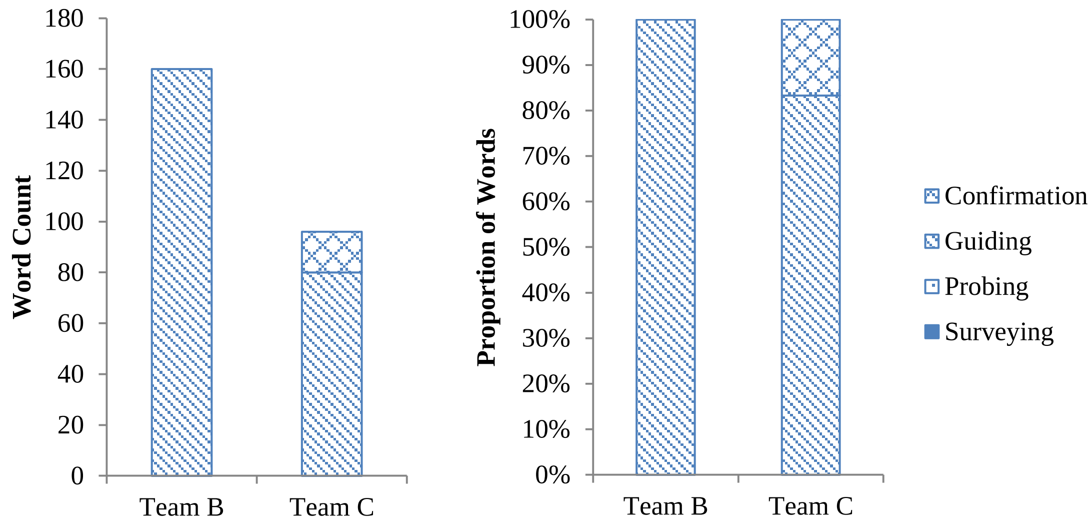


Figure 21 - Budget episodes by Feedback Stages by team

Next, a comparison of Memo episodes for all four teams is provided in Figure 22. The composition of the feedback with respect to the Feedback Stages coding varies significantly from team to team. Team A has the most Surveying and the most Confirmation. In this case, the Memo episode is near the beginning of the DMM and the discourse primarily consists of the instructor reading through the memo and providing confirming comments. Team B has the most Probing. For this team, the instructor reads the memo silently at the start of the episode. This particular difference in Surveying technique appears to be a temporal difference, considering that the Memo episodes for Team C and Team D begin similarly with the instructor reading the memo silently. Team D's Memo episode consists mainly of the instructor reviewing recommended changes to the memo and the students confirming the recommendations.

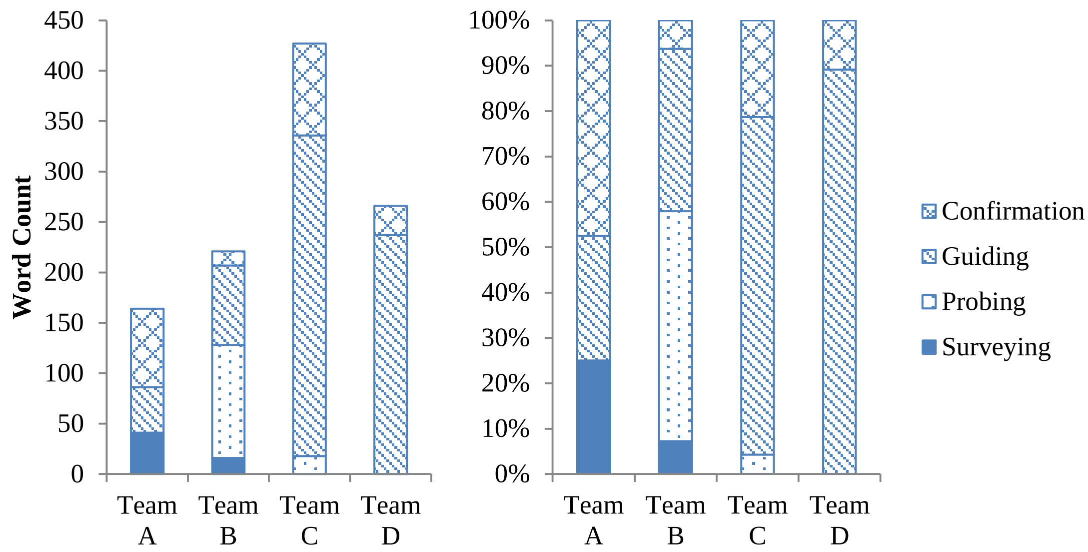


Figure 22 - Memo episodes by Feedback Stages by team

Team C has no Surveying and a lot of Guiding. This team's memo only includes a list of input parameter values and a measurement strategy table. Memo format is not used and no justifications are provided. The following discourse is the first three-quarters of the Memo episode. The last portion that is not included is a Budget sub-episode that has already been presented. The Guiding aspect of this Memo episode includes four points of feedback from the instructor regarding Team C's memo: 1) link citations to information they are used for, 2) use a memo format, 3) note the type of project, and 4) include the budget in the memo.

> Instructor: "So a memo, right, is more like a letter, right? So yeah when someone says memo or memorandum it is more like a letter to me. Right?
>
> Student C1: Do we have to write it like [another instructor] did?
>
> Student C2: "Oh, okay."
>
> Instructor: "Do you know what I am saying?
>
> Student C2: "Like to, from?"
>
> Instructor: "Yeah, something sort of like that. So if your boss said to you, "could you write a memo to so-and-so," you wouldn't like just start off with a list right. You would introduce it and say this was about."
>
> Student C2: "Like purpose or..."

> Instructor: “Yeah like this is the subject you want [your boss] talking to you about. Yeah so let’s…”
>
> Student C1: “Should we rewrite this?”
>
> Instructor: “Yeah I think I will have you do that, but you can just put minimal [writing something]. Okay, so you specified everything that’s, good, your measurements, so you are going to take all of these. Okay, you opted to save some money there.”
>
> Student C1: “We are spending a lot of money.”
>
> Instructor: “Oh, see would you be telling me?”
>
> Student C1: “Yeah it’s at the bottom. It’s because we are running for 60 hours.”
>
> Instructor: “Okay so, let me get this [reading silently]. Okay, the main thing, okay so you have some references here but you don’t say what they were used for. Right? So I am going to write a couple of comments here. Like if you’re writing a letter and this was going to your boss or something you might want to say, one, like note what information the references gave you, right?”
>
> Student C1: “On this list or in the memo?”
>
> Instructor: “Note in the memo. Like, you know…”
>
> Student C1: “… from blah blah blah?”
>
> Instructor: “Right because I don’t know how these helped you get what information. Because you probably got some information to help you make some decisions right? So you know what info from what reference. And I would, two, say a memo format. Oh and you guys are doing I guess is it the production one or the waste one?”
>
> Student C1: “Production.”
>
> Instructor: “Memo format, and three, production. Just note it.”

Finally, all four teams analyzed have distinct Experimental Design episodes, coded by feedback stages in Figure 23. Team A and Team C have much shorter Experimental Design episodes than Team B and Team D. Team B’s episode largely consists of Guiding and Confirmation, with a small amount of Probing. The instructor attempts to clarify the team’s experimental design by asking probing questions, providing feedback to address student concerns and misunderstandings, and then the instructor confirms the strategy that the team is articulating. Team D is similar but with more Surveying and Probing and less Confirmation. Team A and Team C both have shorter Experimental Design episodes consisting almost entirely of Guiding. For Team A, the instructor is doing almost all of the talking, explaining to the students that it is important for them to come up with a strategy that incorporates their understanding of how the VBioR system functions. There is a brief confirming statement at the end of the episode. Near the end of the DMM, Team C's Experimental Design episode is entirely Guiding. It is similar in nature to that of Team A, but lacking a confirming statement.

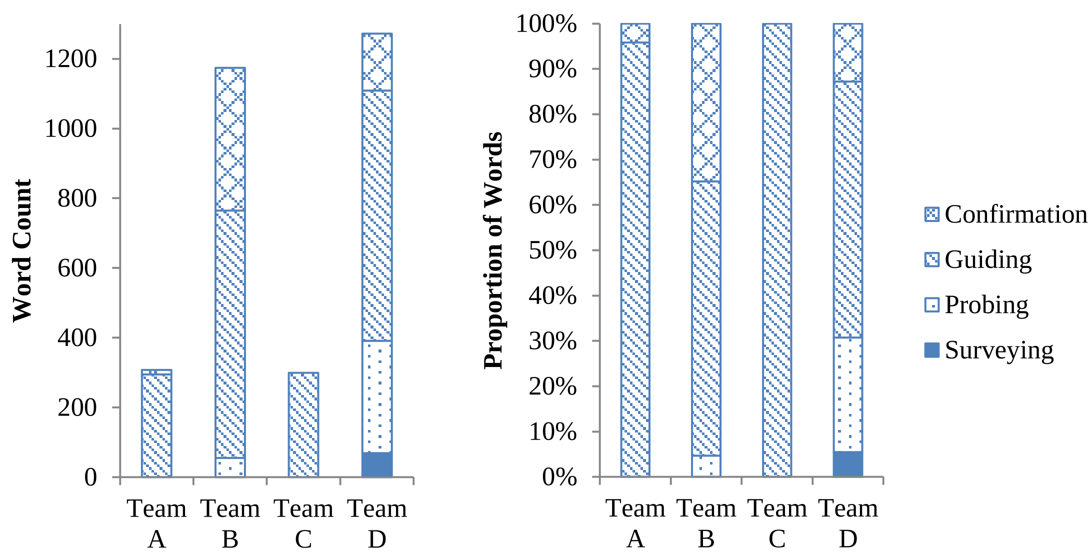


Figure 23 - Experimental Design episodes by Feedback Stages by team

It appears that the instructor attends to misconceptions and lack of understanding in some order of priority. In terms of Experimental Design, Team A and Team C simply did not have time available to discuss this theme in as much depth as Team B and Team D; more problematic concerns were identified by the instructor (e.g., excessive measurements, inappropriate magnitude for input parameters). This finding reiterates the different conditions the student teams are in when they come to the DMM. The instructor surveys the teams verbally and by reading the memo to direct the discourse themes of the meeting. For Teams B, C, and D, the feedback guidelines document also helped shape the discussion. The results of the theme-based coding and feedback stages coding have similar conclusions even though the coding methods are different. The instructor balances the adaptability and the consistency of the feedback provided.

5.3 Influence of Feedback

The influence of feedback can be considered temporally, by reviewing discourse before, during, and after the DMM. Other sources of data include post-DMM surveys, student work products throughout the project, and post-project interview questions (when available). This investigation focuses on some specific changes in student solution paths that take place following the DMM. In this section, two examples are presented to contrast the influence of instructor feedback for fundamental concepts versus advanced concepts. These two examples are illustrative of the breadth of teams engaged in the VBioR Laboratory Project.

Example 1: The Influence of Feedback on Fundamental Concepts

The process that Team C goes through to determine the input value for Fed Batch Flow Rate is a basic example of the influence of feedback on fundamental concepts during the information gathering and problem formulation process. Before the DMM, the team struggles to determine what value to use for flow rate. The following discourse is provided below to highlight the student's uncertainty in determining this input parameter:

> Student C3: "So we need fed batch flow rate and fed batch feed concentration."
>
> Student C1: "I don't know what the flow rate is. Because there's…is that the flow rate of the feed coming in?"
>
> Student C3: "Yeah and there's something, it's the flow rate of the feed coming in."
>
> Student C1: "But there was something, you know how she was talking about stirring?"
>
> Student C2: "Does it fill up the thing?"
>
> Student C3: "I think stirring is all the time."
>
> Student C1: "Yeah, so we need to have room for feeding."
>
> Student C3: "But we don't pick the volume. So they must kind of just figure that out."
>
> Student C1: "The cells?"

Student C2: “The cells do.”

[The students discuss other themes for about 25 minutes.]

Student C2: “But we don't know how fast our flow rate is... so it doesn't really help us.”

Student C3: “No, it’s just the…”

Student C2: “Oh yeah we do.”

Student C3: “We choose how much per liter we want to make. But, do we choose the rate as how many liters per hour?”

Student C2: “Yeah we do.”

Student C3: “So how much do we want to feed them, I guess, per hour?”

[The students discuss other themes for about 15 minutes.]

Student C2: “What else do we need?”

Student C3: “We decided on one liter per hour?”

Student C2: “That's fine, unless anybody came up with something.”

The first version of Team C’s memo reflects this decision to set the Fed Batch Flow Rate. Ultimately, the students guess a value of one liter per hour, which is extremely low given the other constraints of the reactor, especially with the Fed Batch Time set to 24 hours. During a Flow Rate themed episode in the DMM, which was previously presented to describe Input Parameter Tier IV themes, the instructor provides feedback to the students regarding these input parameters as follows:

Student C3: “Fed batch flow rate we didn’t know again and we just kind of chose one liter per hour.”

Instructor: “So you start with 2000 liters and you are going to go for 24 hours, and you are going to end with?”

Student C1: “2024 liters. So we get out a lot more. We just found that out”

Instructor: “It seems like that whole fed-batch is, yeah so you just found out.”

Student C1: “So it is going to increase a lot.”

Instructor: “I would say use that.”

Student C2: “Can we try going to 5000 by the end?”

Student C1: “Say you wanted 20 percent of that space left.”

Instructor: “I said working volume is 5000. So working means that is the liquid volume and there is headspace in there.”

Student C1: “Okay, so we don’t have to worry about that.”

Instructor: “Okay so that’s good.”

In this case the discourse of this episode illustrates the instructor addressing the addressing the uncertainty the students had about the fed batch flow rate value and the working volume of their bioreactor. Once the instructor guides the students through the use of a probing question, they immediately recognize that they can calculate the flow rate value. After the DMM, the Team C students meet to address the instructor’s feedback, and fed batch flow rate is one of the input parameters they change. They calculate the maximum possible flow rate that will not overflow the bioreactor by dividing the available reactor volume by the fed batch time.

Student C1: “So the initial batch volume is 2000 and she said that we could go to 500, and we’re running for 24 hours. So it's...”

Student C2: “5000?”

Student C1: “3000 divided by 24?”

Student C2: “125.”

Student C1: “125 per hour?”

Student C2: “Yep. That's for the fed batch, right?”

Student C1: “Yeah.”

Student C2: “Okay.”

[The students discuss other themes for about 3 minutes.]

Student C3: “We just need to increase the rate, like a lot more than one liter per hour.”

Student C2: “Yeah. We just, made it go up to 5000.”

Student C3: “We could do a ton.”

Student C2: “So it's 125.”

Student C3: “So we have at least 3000.”

Student C1: “Is that 100.5 or 125?”

Student C2: “125.”

Student C1: “Okay.”

Student C2: “Is that 125 times 24, is 3000?”

Student C1: “I think.”

Student C3: “So you could do 125 liters…”

This example shows that the instructor feedback prompted the students to realize they can calculate an appropriate input value for flow rate in this situation. The change from one liter per hour to 125 liters per hour for Fed Batch Flow Rate is reflected in Team C’s updated Design Strategy Memo. Other concerns that were raised by the instructor during the DMM that Team C addressed in their follow up Design Strategy Memo include inoculum, initial substrate concentration, and memo formatting. To discuss these changes, Team C has a second DMM with the instructor, to follow up on the feedback from the first DMM prior to receiving a username and password for the VBioR Laboratory. The characterization of the discourse from these two meetings can be compared to help understand the influence of feedback in this context. The following analysis, Figure 24 through Figure 27, compares the themes and feedback stages coding for Team C’s first and second DMM.

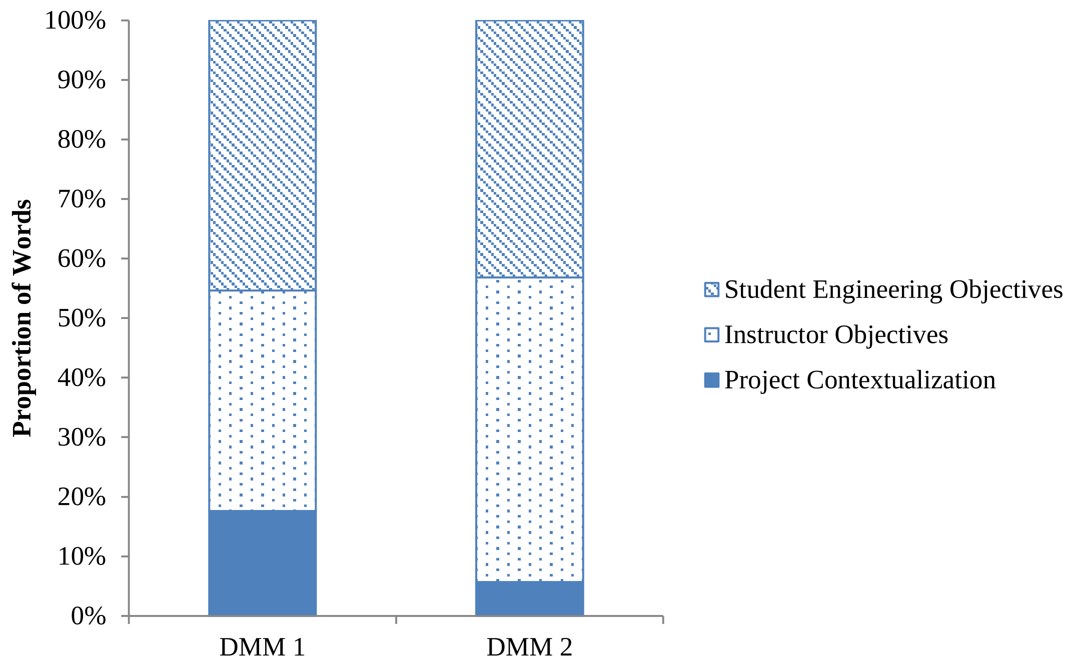


Figure 24 - Tier I themes by DMM for Team C

In Figure 24, the most noticeable differences from the first DMM to the second DMM are the increase in the proportion of words dedicated to Instructor Objectives and the decrease in Project Contextualization discourse. These differences are clarified in Figure 25. In terms of Project Contextualization, the proportion of words coded as Situate is the same but in the second DMM there is no discussion of Instructional Design. This change is probably because the Instructional Design episode in the first DMM is prompted by student questions about how they will interact with the VBioR Laboratory system. These questions are addressed by instructor feedback in the first DMM. It is also evident in Figure 25 that a much higher proportion of words are coded as Performance Metrics/Objectives and Core Technical Content and Concepts in the second DMM relative to the first DMM. The proportion of words coded as Input Parameters is much lower.

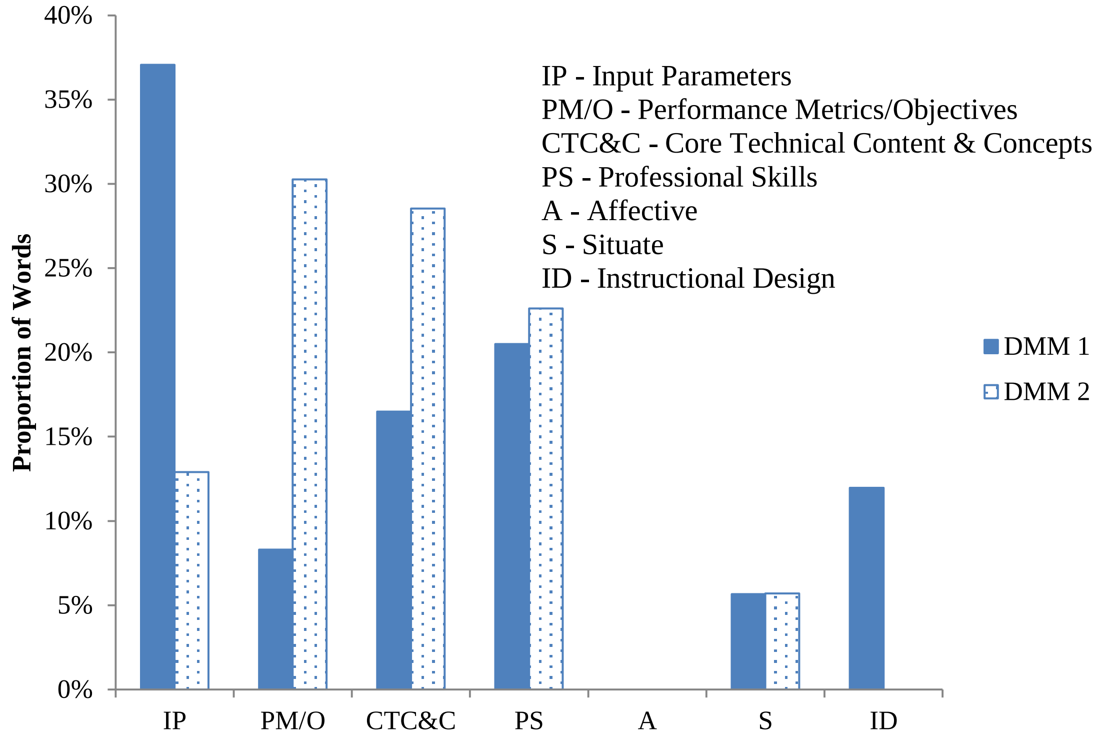


Figure 25 - Tier II themes by DMM for Team C

Recall that IP and PM/O are associated with Student Engineering Objectives, CTC&C, PS, and A are associated with Instructor Objectives, and S and ID are associated with Project Contextualization. Figure 26 shows the discussion of Productivity is causing the increased proportion of words for the PM/O Tier II theme. Similarly, the increased proportion of words for the CTC&C Tier II theme is due to discussion of Kinetics. Other differences from the first DMM to the second DMM include a relative reduction in the discussion of Budget and Experimental Design. Transport is not discussed in either DMM for Team C.

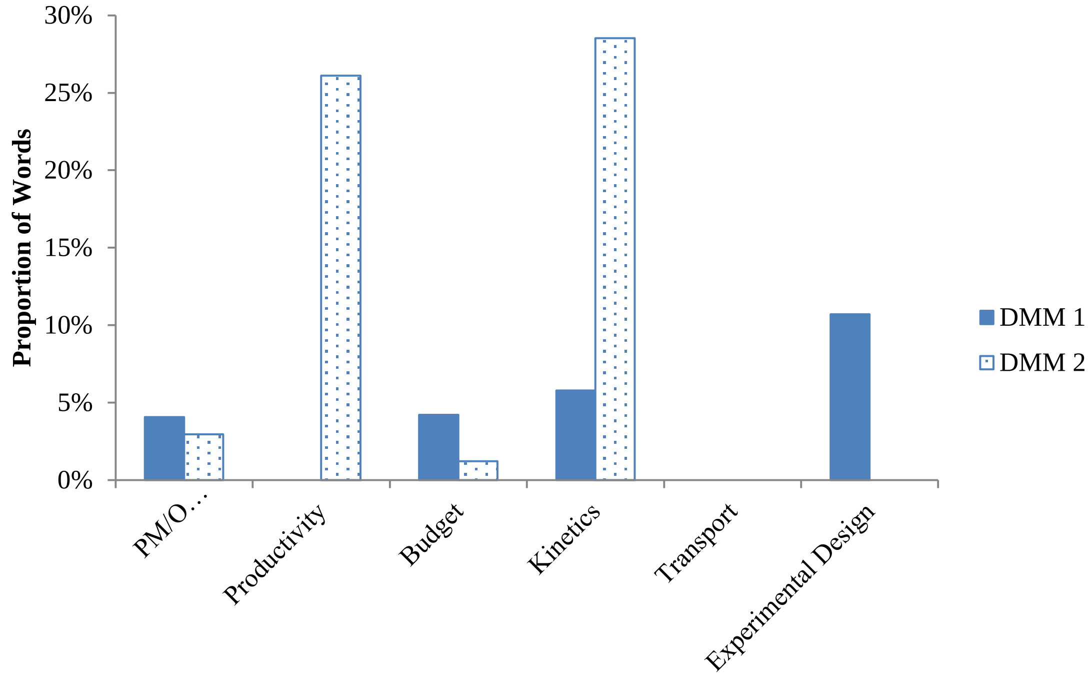


Figure 26 - PM/O & CTC&C themes by DMM for Team C

The discussion of Productivity is toward the end of the second DMM, once the instructor has already discussed Input Parameters and Kinetics with the students. It seems that this theme is the last one that the instructor wants to check with the students before providing them with their username and password for the VBioR Laboratory. In the following discourse the instructor provides feedback to make sure the students are comfortable calculating an appropriate performance metric:

> Instructor: "…and volumetric productivity, you're looking, you're calculating volumetric productivity of biomass production. Right. What do we want the volumetric productivity of?
>
> Student C1: "Of the product?"
>
> Instructor: "Right, yeah."
>
> Student C3: "So we want the protein."
>
> Instructor: "Yeah. So what would the equation for that be?"
>
> Student C1: "Is it just this?"
>
> Student C3: "Grams of protein over batch time, or total time. And volume of the reactor."

> Instructor: “And volume of the reactor, good. And time, what does this time consist of?”
>
> Student C3: “It's the batch cultivation time...”
>
> Student C2: “The filling time.”
>
> Instructor: “Yeah, right, so it's batch, plus fed batch, plus five, right, and so…”
>
> Student C2: “That makes sense.”
>
> Instructor: “Right. And so that is the productivity that you guys want to find.”
>
> Student C2: “We were struggling trying to figure this out.”
>
> Instructor: “So it's good that you started to think about that.”

This episode follows the Feedback Stages framework of surveying, probing, guiding, and confirmation. The instructor surveys by reading the team’s memo, asks a probing question about volumetric productivity, provides some guidance while the students clarify how they plan to calculate productivity, and provides confirmation at the end of the episode that the students have an appropriate approach.

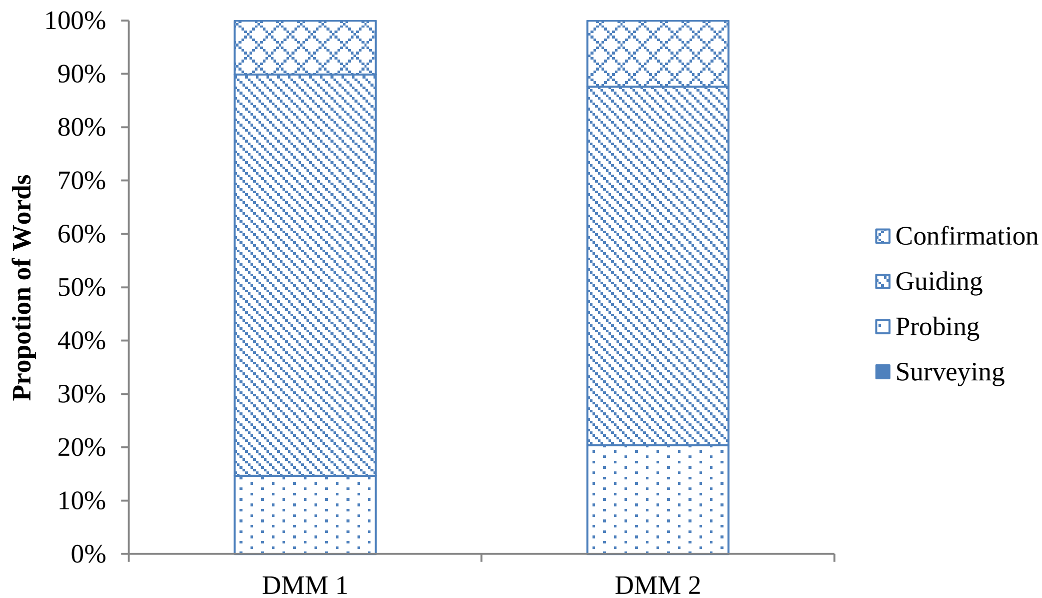


Figure 27 - Feedback Stages by DMM for Team C

The two DMMs for Team C can be compared overall by considering Feedback Stages coding. Figure 27 displays the results of this analysis. The composition of the stages of feedback is fairly similar between the first and second DMM. The main difference is a slight increase in Probing and Confirmation, and a slight decrease in Guiding. These changes are probably because the discourse includes Probing and Confirmation related to the changes the students made to their memo.

Example 2: The Influence of Feedback on Advanced Concepts

Another aspect to assess is the influence of feedback on more advanced concepts. Team D used extensive modeling in their solution path for the VBioR Laboratory Project and is used as an example to highlight the influence of feedback on modeling. Prior to the DMM, the Team D students conduct a thorough literature review to determine an initial set of input parameters. In their Design Strategy Memo they explain their experimental design plans to adjust input parameters as needed based on the outputs of each run. During the DMM the instructor discusses additional details of the experimental design as follows:

> Instructor: "So you've got a matrix here, of your, all of your approaches, right."
>
> Student D1: "Yeah."
>
> Instructor: "You know what I don't see here, is anything from bioreactors [class]. Who's in bioreactors?"
>
> Team D: "We all are."
>
> Instructor: "I almost see nothing, right, there's not a single word. Well, batch. But what about the stuff you learned in bioreactors. Are you going to use that to help you, and how would you?"
>
> Student D1: "So we made equations for the batch, fed batch, and then during fed batch…"
>
> [The students and instructor discuss other things for about 5 minutes]
>
> Instructor: "Equations, you did [use] equations."
>
> Student D1: "Yes."

> Instructor: “But you didn’t put them in here.”
>
> Student D1: “No, we didn't know if that would be important for you to be able to see, or just know what our plan was.”
>
> Instructor: “Yeah, okay, so give me your plan in words…”
>
> Student D1: “So, what we want to do actually, kind of the idea is to put these into MATLAB with maybe what we are considering to be from these values [in the memo].”

This discourse shows that the students had thought about modeling the system for the VBioR Laboratory Project, but did not include this aspect of their experimental design in their memo. One plausible explanation is that the team had not yet fully formulated the extent to which they would incorporate modeling into their solution path. The instructor guides them to think about how to use modeling for this project in the following discourse:

> Instructor: “So then you use [the] parameters that you got from the experiments… to model. Then what do you use that for?”
>
> Student D1: “Then we can use that model to go back to our experimental plan, and see like...”
>
> Student D2: “…and determine where we want to make changes.”
>
> Student D1: “Yeah. So like for batch, we'll be able to know, well, maybe this was run too long, because all of a sudden we're jumping into stationary phase and maybe now we're even declining off, so we could see where should we...”
>
> Instructor: “Right, but you could see that from the experiment.”
>
> Student D1: “That’s true.”
>
> Instructor: “So how does the model help you? You… you're looking at them.”
>
> Student D3: “Well if we make a model…”
>
> Instructor: “I’m not saying that it doesn’t…”
>
> Student D3: “If we make a model with what our ideal numbers would be, and not necessarily the numbers from the first experiment, and then look

> at the numbers from the first experiment, we can see how to get to our ideal situation better.”
>
> Instructor: “Okay, how to get by changing what?”
>
> Student D3: “By changing the input values.”
>
> Instructor: “Right, okay. So here you're going to look at the effect of the input values, right. You can do that in experiment, but expensive!”
>
> Student D1: “It would cost, yeah, it would cost a lot of money.”
>
> Instructor: “Right, you can model for free, right?”
>
> Student D2: “Yeah.”
>
> Instructor: “So that's an excellent use of a model, right. So what's the effect of input variables…”

During this feedback process, the students begin by focusing on using a model to help predict input parameters. However, with additional probing from the instructor, the students also articulate how modeling can help them develop an optimal solution at a potentially lower cost. The differences between modeling and experimentation are clarified through instructor feedback. The context of the VBioR Laboratory Project affords the opportunity for students to more fully appreciate the value of using modeling in their solution path. In other classes modeling is often compulsory. For example, homework assignments often require students to demonstrate modeling. However, in this project the use of modeling is optional; the students decide how much they use models to optimize the bioreactor system. During the DMM, the instructor also guides the students to discuss further differences between modeling and experimentation results in the following discourse:

> Instructor: “So now, are you, is your model going to match whatever you get from your experiment exactly?”
>
> Student D1: “Probably not.”
>
> Student D2: “No.”
>
> Instructor: “Why?”

> Student D3: “Because our experiment is going to change every time, a little bit. Even if the input values are the same.”
>
> Student D1: “Variation.”
>
> Instructor: “Right, variation. But why else? A bigger reason.”
>
> Student D2: “The model is going to be idealized…”
>
> Instructor: “Right. In your model, you're incorporating… some major behaviors. But you might not be incorporating all of the behaviors that actually happen.”
>
> Student D1: “Yeah.”
>
> Instructor: “That’s the biggest reason a model doesn’t match the data.”
>
> Student D2: “It’s more of a generalization.”
>
> Instructor: “Yeah, it’s more…I’m trying to capture the main behaviors with math.”
>
> Student D2: “Right.”

First, the students recognize that modeling results are typically more consistent than experimental results because of process variation. But the instructor guides the students further, to distinguish models as an idealized representation of the system. The instructor provides feedback about reasons a model might not match experimental data exactly. This feedback could increase the students’ confidence in dealing with modeling results throughout the project because they are anticipating inconsistencies. Finally, the instructor and the students discuss the usefulness of a model for helping develop understanding of the system. Using mathematical modeling requires the students to think about behaviors occurring in the bioreactor. Following the DMM, the students complete Design Meeting Process Engineer’s Reflections (post-DMM surveys). In these reflections, all three students indicate aspects of modeling they are taking away from the DMM. For example, in response to the question “What are the top three things you are taking away from this meeting?” the students’ responses are as follows:

> Student D1: “Using modeling not just to optimize but to understand a system/process.”

> Student D2: “Building a model based on experiments determined parameters allows for preliminary testing of input variables.”

> Student D3: “Making a mathematical model to show how your experimental plan will change is important in a memo.”

After completing their reflections, the students meet to revise their Design Strategy Memo. During this post-DMM meeting they work on developing a MATLAB model of the bioreactor system. Their revised memo includes a set of bioreactor model equations and a preliminary MATLAB model using these equations. The revised memo is sufficient for the team to obtain authorization to run the VBioR Laboratory.

Once the students from Team D have access to the VBioR Laboratory, they begin running experiments. After each run they consult their models in order to decide how to adjust the input parameters for the next run. While the modeling and experimental results are similar, they are not exactly the same. However, for the final report and presentation the students are able to include results that highlight their use of modeling throughout the project to guide them to a highly profitable solution. During post-project interviews with the students (interviews are conducted with students individually), Student D1 and Student D2 both discuss how the instructor’s feedback influenced their use of modeling. First, in response to the question “What was your strategy and how did it change?” both of these students talk about how they incorporated modeling into their strategy for the project.

> Student D1: “Going into it we thought more of just…using our intuition…like if we ran it at one temperature, recognizing that cells weren’t growing, okay, maybe we need to increase the temperature and see if cells grow more and then hopefully with more cells we’d get more product. I think it…that’s how it started out, but then *we realized pretty quickly the importance of having a model, even if it didn’t predict perfectly what was going on, that we would have some idea of what would happen in the bioreactor so that we wouldn’t be wasting a whole bunch of money*. So I think that was kind of a change, it actually happened early on, but was something that definitely helped.”

> Student D2: “We didn’t have a specific strategy starting out…*a lot of that changed during our meetings with [the instructor]*, developing the idea that, well we want to look at maybe temperature first, because…for some reason the model wasn’t incorporating that parameter, so we were thinking if we can optimize temperature then *we can try and model what’s going on. So that was one big change, just switching to looking at a model in general*.”

The students recall that they incorporated modeling early in the project, although not at the very beginning. Student D1 highlights the idealized aspect of modeling and how it can be useful for saving money. Student D2 attributes changes in the team’s strategy to the feedback sessions with the instructor. These responses support the other data sources considered in this analysis. Another question asked during the interviews was “What do you remember about the Design Memo Meeting?” This question is broad, but both Student D1 and Student D2 discuss modeling within their response.

> Student D1: “One of the biggest things I remember actually is *talking about a model and developing a model not just to be able to try to predict what’s going to happen, but to actually understand what is happening.* So, obviously it’s helpful to be able to save money and just throw numbers into a computer and have it spit something out to you, but also to understand the system that you’re working with… one of the big things was talking about oxygen limitation and having such a high concentration of glucose in there that it would become too viscous for oxygen to be able to get to the cells, and thinking of if we’d be able to incorporate that into our model, which is something that we didn’t do, and it’s probably a big reason for why our model differed, but, *just being able to develop a model that explains the system that you’re working with so that, not only does it help predict, but so that you understand.*”

> Student D2: “A lot of ‘oh’ moments. [The instructor] would bring up a concept that we hadn’t really thought about yet, you know what, we really should look at having more than just two temperatures that we are testing or…*looking at how we were going to model the system, looking at what was actually going on in within the reactor instead of just approaching it from a… oh we’ll put these in and look at the numbers we get out.* I feel like those two meetings were probably some of the most helpful points that we had apart from being able to just kind of bounce ideas back and forth among the team.”

Student D1 explains that modeling can help make predictions, but it can also help with understanding. This finding is directly related to the discussion observed in the

DMM. Student D2 elaborates on the change in strategy that the team experienced during the project, from a more experimental approach to a more modeling-based approach. When asked "Did you feel better or worse about the project after the DMM?" Student D1 responded with even further description about how the instructor's feedback influenced the team's use of modeling.

> Student D1: "I felt better, because when we came out we had kind of a better understanding of what our system was going to be. *I think [the instructor] helped us a bit with that, by getting us to think about it a little bit more, and it also made us focus a bit more on developing a model to predict the outcomes of the bioreactor*… and also it I think it made us feel a bit more confident with what we had chosen going into the meeting, rather than having [the instructor] say that 'oh these values are way off' or anything…. there wasn't like a huge approval saying 'these values are great' because obviously we are looking for the optimal parameters and we need to find those on our own but it was a good feeling coming out because we felt that at least we were in a good range to start with."

In addition to the influence of feedback on modeling, this student says the instructor's feedback about their input parameters helped them feel more confident. Based on this analysis of Team D, it appears that the instructor's feedback helped the students develop their use of modeling in four main ways. First, the student's should communicate modeling as part of their experimental design if they plan to use models. Second, modeling can provide potential cost savings by testing input parameter variations in between experimental runs. Third, modeling has limitations; it can be useful as a tool, but because it is idealized the students cannot expect predictions to be perfect. Fourth, using modeling can help students understand the system better. By opting to use modeling for this project, the students could be more likely to incorporate modeling in other projects in the future.

<u>Influence of Feedback Conclusion</u>

Overall, the examples in this section show that feedback in this context can both support and influence the different solution paths student teams take. These examples are considered representative of many other cases of instructor feedback for students engaged in the VBioR Laboratory Project. The instructor feedback is thought to be effective at identifying misconceptions and increasing understanding because the feedback is adaptable to different students and varied solution paths. The instructor feedback is also able to increase the students' confidence in their own solution path in some cases. At the same time, the instructor uses a feedback guidelines document to maintain consistency for certain elements of feedback, including the enforcement of financial constraints and checking of project deliverables. Also, the feedback timing focuses on guiding the students through the information gathering and problem formulation stages. The timing of the DMM, before students gain access to the VBioR Laboratory, provides opportunities for the students to gain greater understanding of the project and further develop their experimental design prior to completing any experimental runs.

5.4 Student Perceptions of Feedback

With constructivism as the theory of learning for this study, student perspectives on the feedback process are a necessary component of this analysis. This assessment of student perceptions of feedback comes from responses from students asked to reflect on the feedback they experienced during the Design Memo Meeting (DMM). Using the themes developed for episode discourse analysis, the most frequently cited themes by question are shown in Table 5. The threshold frequency for inclusion in the table is five. Figure 28 also displays this data by question for the overall top five themes. It can be seen that overall Kinetics is the most common theme for all of the questions, with a total frequency of 85. Experimental Design (65), Transport (33), Budget (25), and Measurement Strategy (16) are also frequently cited. This data translates to 69 percent of the themes coded as Instructor Objectives, 30 percent of the themes coded as Student Engineering Objectives, and one percent of the themes coded as Project Contextualization. This analysis means, for the most part, students say they are taking away ideas that are aligned with Instructor Objectives.

Table 5 - Most frequent themes in student reflection responses by question

Question	Most Frequent Themes (frequency)
Q1: What are the top three things you are taking away from this meeting?	Kinetics (28), Experimental Design (29), Budget (18), Measurement Strategy (11), Transport (10)
Q2: What interaction with the professor do you remember most and why?	Kinetics (22), Experimental Design (17), Transport (9)
Q3a: Is there anything that happened during the meeting that especially helped you understand something?	Kinetics (27), Transport (13), Experimental Design (15)
Q3b: Is there anything that happened during the meeting that was especially confusing and you wanted to discuss more?	Kinetics (8)

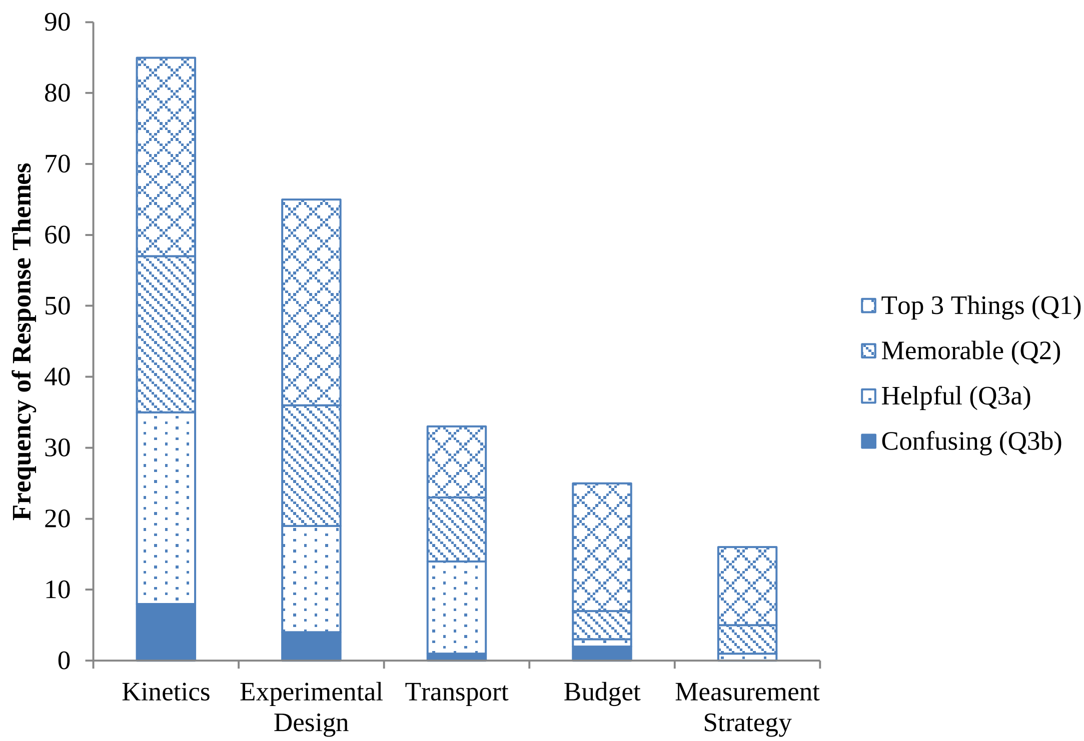


Figure 28 - Overall most frequent themes in student reflection responses

In most cases, the team members' responses to the first question tend to be similar, while responses to the other questions are more varied. In the second and third questions, the students noted several instructor techniques that they found helpful for increasing their understanding. These instructor techniques include situating in engineering practice, drawing graphs, doing calculations, advising on literature/research, relating the project to known concepts, and asking questions. These techniques relate to the information gathering and problem formulation modeling stages.

Even though a small number of students made Project Contextualization themed comments, it is still interesting to consider further. One team had two out of three team members with situating responses. One team member, in response to Question 2, wrote that the most memorable interaction with the professor was the following: "understanding the perspective of the lab worker". Another member of the same team, in response to Question 3, explained something the instructor did that was especially helpful – "[The instructor] had stated if you were to ask the lab technician to take 100 samples they would be very upset. This made me think about the lab more in terms of a real life experiment versus a virtual lab." According to these two students, the instructor's situating of the project with respect to engineering practice was both memorable and helpful.

A large portion of the students remarked that drawing graphs with the instructor helped them understand bioreactor principles. Below are three students that recount drawing during the DMM in response to Question 2. "What interaction with the professor do you remember most and why?"

> "The instructor had me draw the curves for cell and substrate concentration that we would expect to see in batch and fed batch reactors and then used this graph to help us think about the necessary sampling time. This interaction made me realize the type of approach we need to have to be successful with this project."
>
> "drawing graphs – it's a good way to help us understand relationships and math behind behavior"
>
> "having to draw graphs of X, S, & P and relate those to input parameters"
>
> "graphing general predictions of the batch curves helped me to understand changes taking place"

Additionally, many students drew graphs as part of their responses to the questions on the survey. Many students also wrote that reviewing relevant mathematical models (or calculations) with the instructor was memorable. The following comments are also in response to Question 2, “what interaction with the professor do you remember most and why?”

> “- when [the instructor] made us write out [the specific growth rate equation] and integrate. It made me realize that μ will not be hard to determine. [drawing of a graph of ln(X) vs. t with μ as the slope of the line]”

> “How the math and what’s actually going on are related”

> “…figuring out how to use the math to see substrate inhibition [specific growth rate equation]”

Eight students commented on a literature search in response at least one question. The following are some of the student responses to the different questions as indicated:

> Question 1 (top three things): “What I should look for in articles as far as graphs, values of rate kinetics, etc.”

> Question 2 (most memorable): “Discussing research and literature - confirming appropriateness of boundaries”

> Question 3 (especially helpful): “The instructor's explanation of how we could estimate certain parameters from literature values to give us a good idea of the trends we should expect.”

> Question 4 (wanted to discuss more): “setting up initial parameters, i.e., do we run multiple runs & adjust, are the values supposed to be straight from literature?”

Information gathering is a major stage in the modeling process. It appears that the students appreciate instructor feedback on research and literature. However, in some cases students listed this topic as something that was confusing and they wanted to discuss more.

Another common response from students is about relating previously learned concepts and information to the VBioR Laboratory Project. In the responses below, students explain that instructor feedback in the DMM helped them connect the VBioR system to other ideas they already know. The students describe that their learning is based on prior knowledge, which aligns with the theory of cognitive constructivism (Glaserfeld, 1996).

> Question 1 (top three things): “apply physics and biology to understand changes in the system”

> Question 2 (most memorable): “The instructor's relation of chemical reaction concepts to bioreactor concepts because it helped me make connections with the bioreactor to my knowledge of chemical reactors.”

> Question 2 (most memorable): “The comparison of something you know and something you're learning. When you know one change will give a particular result you can get the output you want, you know how to manipulate the output. When learning something you have to think critically about everything before you do it and then try to understand the outputs if they're different than expected.”

The final common response identified is about the instructor asking the students open-ended questions and not just giving them answers. These comments probably refer to facilitative feedback that the instructor uses to engage students in the feedback process. The following comments illustrate this response type:

> Question 2 (most memorable): “Leading us to the answers instead of just giving us the answers helps with understanding.”

> Question 2 (most memorable): “The instructor asked a couple of questions about the calculation approaches that made us think more about our approach. The instructor was very helpful in helping us understand exactly how we would determine µ.”

> Question 3 (especially helpful): “Asking open-ended questions”

In summary, the six common instructor techniques highlighted by student comments include (1) situating, (2) drawing, (3) calculating, (4) literature/research, (5) relating, and (6) asking. These techniques align with the Feedback Theory associated with this study. Nearly all of the student responses point to feedback that is specific to the task at hand – the VBioR Laboratory Project. The asking technique is related to using facilitative feedback. Several students noted a preference for more facilitative feedback in response to open-ended questions regarding what about the DMM was memorable and especially helpful.

6 Conclusion

The goal of this research was to characterize the feedback between the instructor and student teams engaged in the VBioR Laboratory Project. Within this context, the research questions asked (1) what role the instructor feedback has in the information gathering and problem formulation stages in the modeling process, (2) what similarities and differences can be identified for different teams, and (3) how an instructor's feedback changes with time. This research has implications both methodologically and pedagogically. In terms of methodology, using an ethnographic approach allowed a detailed characterization of instructor feedback for student teams in the information gathering and problem formulation stages of the modeling process. Also, the use of episodes analysis allowed consideration of the relative emphasis of different themes present during the DMMs. In terms of instructional design, this study highlights the potential effectiveness of timely and adaptable instructor feedback, which aligns with student-centered instruction (Felder & Brent, 1996) and individualized instruction (Chung et al., 2007).

Student surveys were analyzed to understand student perspectives of the instructor feedback that occurred during the DMMs. The questions were open-ended and asked students to comment on what they were taking away from the DMM, what interaction with the instructor was memorable, and if anything happened during the meeting that was especially helpful and/or confusing. Theme coding revealed the most common themes for student responses included kinetics, experimental design, transport, budget and measurement strategy. Based on the student reflection responses, interactions with the instructor during the DMM are supporting themes associated with Instructor Objectives. Additionally, six instructor techniques were highlighted by the students. These techniques included situating to engineering practice, drawing graphs, doing calculations, advising on literature/research, relating the project to known concepts, and asking questions. The instructor techniques of situating to engineering practice and relating the project to known concepts align with objectives of PBL, particularly the concept of transfer (Engle, Nguyen, & Mendelson, 2011, p. 603).

The results of this thesis suggest that the instruction techniques concur with existing recommendations for promoting student learning and providing effective feedback. The recommendations include providing verification and elaboration (Shute, 2008) through the use of adaptive but consistent feedback. Techniques for verification and elaboration noted by student reflections specify feedback that includes drawing graphs and doing calculations as memorable and helpful. Also recommended is the use of facilitative feedback approaches (Black & Wiliam, 1998). Examples in the DMM discourse show that facilitative feedback in the form of probing and guiding questions can be effective. Also, students stated that it was helpful when the instructor asked questions rather than providing answers.

The analysis presented in this thesis illustrated the adaptive nature of the instructor feedback in the given context, but also that feedback consistency can be important for certain aspects. Differences in the instructor's technique were noted between an earlier cohort and later cohorts. The instructor developed a feedback guidelines document to help structure the DMM. The feedback guidelines document could help increase the consistency of instructor feedback from team to team. This research illustrated that teams were able to adjust misunderstandings based on instructor feedback they received during the DMM The instructor feedback was also useful for developing the use of modeling for the VBioR Laboratory experimental design. Student teams discussed how modeling can be useful for the VBioR Laboratory Project optimization process through potential cost savings and increased understanding of the system. Furthermore, students felt more confident about their chosen solution paths after the DMM in some cases.

There was an aspect of timing to the instructor feedback. The instructor tended to address more problematic issues first, such as concerns about order of magnitude and unacceptable communication. Addressing these issues before the students could complete experimental runs allowed them time to adjust their experimental design and communicate changes before spending money from their budget. The results of this study support research that indicates the timing of feedback is an important factor for feedback effectiveness (Hattie & Timperley, 2007; Shute, 2008).

In conclusion, this thesis describes the feedback between an instructor and student teams engaged in the VBioR Laboratory Project. The instructor plays a valuable role by providing timely and specific feedback that is positively perceived by the students as being memorable and helpful in many ways. Student teams observed were able to incorporate instructor feedback during the information gathering and problem formulation phases of the process. This influence of feedback is at least in part due to the structure of the project, because students are cannot access the VBioR Laboratory prior to instructor approval of their Design Strategy Memo. The ethnographic approach was necessary for a detailed analysis of teams. Observing a team throughout the project provided a very detailed account of the student's solution path in relation to the instructor feedback they received. The most critical pieces of information were the Design Strategy Memo, the Design Memo Meeting discourse, final reports and presentations, post-feedback surveys, and post-project interviews.

7 Recommendations for Future Research

The data sources analyzed in this thesis are extremely rich and detailed and therefore provide the opportunity for additional analysis. First, related to the influence of feedback on modeling, Model Maps have been developed to illustrate the student use of modeling during the Virtual Laboratory Projects. While it is beyond the scope of this thesis to provide detailed analysis of these model maps, figures are provided in the Appendix for Team A, Team B, and Team C for reference. Please refer to Seniow (2010) for more information on these analyses. More research could be done to compare the episodes analysis themes and feedback stages to the model maps for each team to further investigate the influence of feedback on modeling.

Another possibility for future research is a more detailed comparison of the VBioR and VCVD Virtual Laboratories through the use of episodes analysis. The same thematic hierarchy has been found to be applicable for both learning systems, with discipline specific differences in Tier IV of the hierarchy presented in Table 3. Also, preliminary feedback stages analysis has shown some differences between the two systems/instructors, such as a different proportion of words dedicated to the Surveying stage. It could be useful to further understand similarities and differences between these two projects. Further research could also be done to investigate differences between instructors for the same project and for different projects to further develop best practices for instructor feedback.

Also, each team has a unique interpersonal dynamic. In this thesis, Team B and Team D were shown to be relatively similar in terms of their solution paths and DMM themes. However, outside of the analysis for this thesis, the teamwork and communication styles of these two teams were perceived as being significantly different. This difference is partially evident in Figure 7, but additional evidence is available through meeting transcripts and post-project interviews. In summary, Team D demonstrated a more constructive team interaction than Team B, but it is not yet clear how this difference may have influenced instructor feedback or the teams' solution paths. More research on this aspect could be particularly useful for understanding potential effects of differing team dynamics.

In addition to Team D, two other teams in the same cohort used extensive modeling in their solution paths. Video recordings of DMMs, TUMs, and final presentations are available for all three teams, along with post-DMM surveys and student work products. Analysis of these three teams could provide a useful comparison of the influence of feedback on modeling. If possible, students from the other two teams could also be interviewed regarding the project, and specifically their recollection of the DMM.

Finally, some evidence was presented to indicate that students felt more confident about their solution paths after the DMM. It could be useful to better understand what aspects of instructor feedback contribute to student confidence and for which aspects of the project. Also, more research regarding the effect of student confidence on the use of modeling during the project could provide additional understanding of the influence of feedback on modeling, via student confidence. This investigation could be accomplished through additional analysis of pre-DMM and post-DMM discourse, targeted student surveys, student interviews, and student work products.

8 References

Atman, C. J., R.S. Adams, M. E. Cardella, J. Turns, S. Mosborg, & J. Saleem. (2007). Engineering design processes: A comparison of students and expert practitioners. *Journal of Engineering Education*, *96*(4), 359-379.

Black, P., & Wiliam, D. (1998). Assessment and classroom learning. *Assessment in education*, *5*(1), 7-74.

Bordogna, J., E. Fromm, & E. Ernst. (1993). Engineering education: Innovation through integration. *Journal of Engineering Education, 82*(1), 3-8.

Bransford, J. (2000) *How people learn: Brain, mind, experience, and school*. National Academies Press.

Buckley, B. C., Gobert, J. D., Horwitz, P., & O'Dwyer, L. M. (2010). Looking inside the black box: assessing model-based learning and inquiry in BioLogicaTM. *International Journal of Learning Technology, 5*(2), 166–190.

Burbules, N. C. (2000). Moving beyond the impasse. In Phillips, D. C. (Ed.), *Constructivism in education: Opinions and second opinions on controversial issues* (308-330). Chicago, IL: University of Chicago Press.

Chi, M. (1997). Quantifying qualitative analyses of verbal data: A practical guide. *The Journal of the Learning Sciences*, *6*(3), 271-315.

Chung, G. K., Delacruz, G. C., Dionne, G. B., Baker, E. L., Lee, J., & Osmundson, E. (2007). Towards Individualized Instruction with Technology-Enabled Tools and Methods. *Online Submission.*

Cobb, P. (1994). Where is the mind? Constructivist and sociocultural perspectives on mathematical development. *Educational Researcher, 23*(7), 13-20.

Engle, R. A., P. D. Nguyen, & A. Mendelson. (2011). The influence of framing on transfer: Initial evidence from a tutoring experiment. *Instructional Science*, *39*(5), 603-628.

Felder, R. M., & Brent, R. (1996). Navigating the bumpy road to student-centered instruction. *College Teaching*, *44*(2), 43-47.

Gilbuena, D. M., B. U. Sherrett, E. Gummer, & M. D. Koretsky. (2011[a]). Episodes as a discourse analysis framework to examine feedback in an industrially situated virtual laboratory project. Proceedings of the 2011 *American Society for Engineering Education Annual Conference & Exposition*.

Gilbuena, D. (Presenter), B. Sherrett, E. Gummer, M. Koretsky, (2011[b]). Understanding feedback in an authentic, ill-structured project through discourse analysis: Interaction between student and instructor objectives. In W. Hernandez (Ed.), 2011 Research in Engineering Education Symposium: Book of Proceedings (p. 680-688), Madrid, Spain: Universidad Politécnica de Madrid. ISBN 978-84-695-2615-6.

Glasersfeld, E. V. (1996). *Radical constructivism: A way of learning* (Vol. 6). Routledge.

Hattie, J. & H. Timperley. (2007). The power of feedback. *Review of Educational Research, 77*(1), 81-112.

Howe, K. R. & J. Berv. (2000). Constructing constructivism, epistemological and pedagogical. In Phillips, D. C. (Ed.), *Constructivism in education: Opinions and second opinions on controversial issues* (19-40). Chicago, IL: University of Chicago Press.

Jonassen, D., J. Strobel, & C. Beng Lee. (2006). Everyday problem solving in engineering: Lessons for engineering educators. *Journal of Engineering Education, 95*(2), 139-151.

Koretsky, M.D., C. Kelly, & E. Gummer. (2011). Student perceptions of learning in the laboratory: Comparison of industrially situated virtual laboratories to capstone physical laboratories. *Journal of Engineering Education, 100*(3), 540-573.

National Research Council. (2011). *Assessing 21st Century Skills: Summary of a Workshop.* Washington, DC: The National Academies Press.

National Science Foundation (NSF). (2008). S&E Degrees: 1966-2008, field of degree: Engineering. Retrieved from http://www.nsf.gov/statistics/nsf11316/content.cfm?pub_id=4062&id=2.

Phillips, D. C. (2000). An opinionated account of the constructivist landscape. In Phillips, D. C. (Ed.), *Constructivism in education: Opinions and second opinions on controversial issues* (1-18). Chicago, IL: University of Chicago Press.

Prince, M. J. & R. M. Felder. (2006). Inductive teaching and learning methods: Definitions, comparisons, and research bases. *Journal of Engineering Education, 95*(2), 123-138.

Seniow, K. R. (2010). *Engineers as learners, engineers as teachers: Representing student model development in the Virtual Bioreactor Laboratory and application to international development projects.* (International degree thesis). Oregon State University, Corvallis.

Sherrett, B.U., E.J. Nefcy, E.S. Gummer, and M.D. Koretsky. (2012) Characterization of an expert solution to inform assessment in a computer simulated and industrially situated experimental design project. *Journal of Engineering Education.* In review.

Shute, V. J. (2008). Focus on formative feedback. *Review of Educational Research, 78*(1), 153-189.

van de Sande, C. C. & Greeno, J. (2012). Achieving alignment of perspectival framings in problem-solving discourse. *The Journal of Learning Sciences, 21*(1), 1-44.

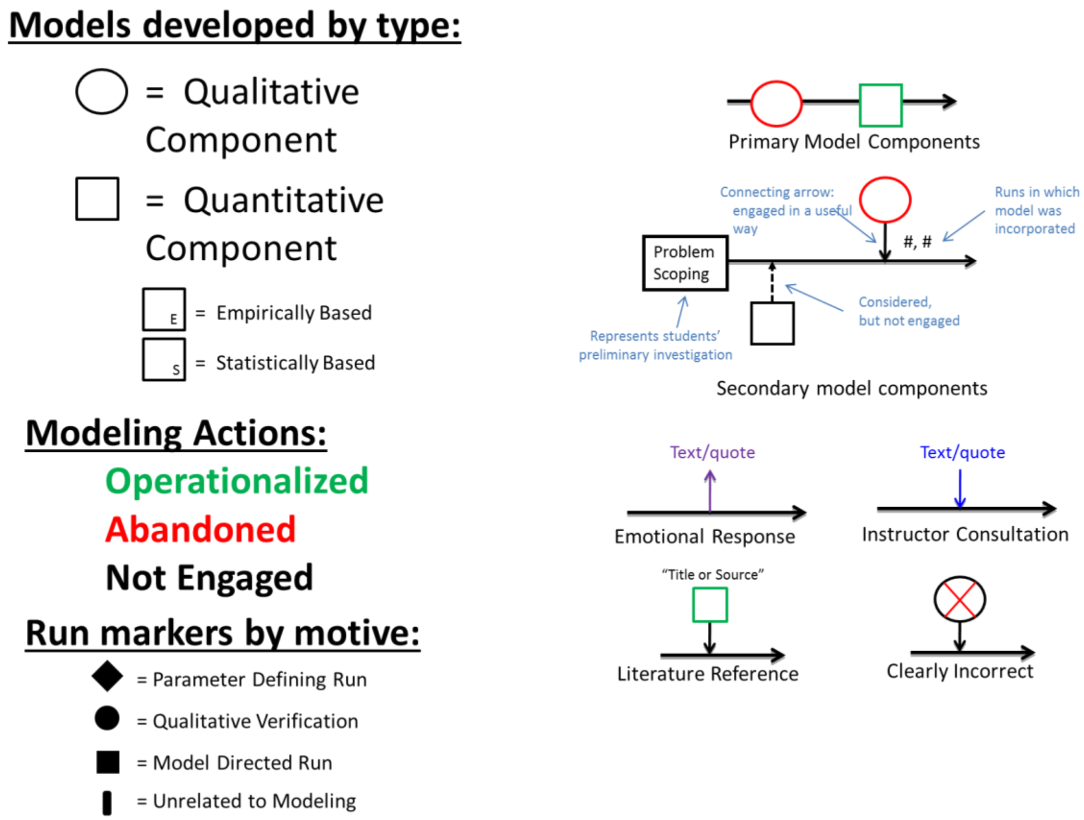
van Dijk, T. A. (1981). Episodes as units of discourse analysis. Published in Deborah Tannen (Ed.), Analyzing discourse: Text and talk. Georgetown: Georgetown University Press, 1981, 177-195.

Wertsch, J. V. (1991). *Voices of the mind: Sociocultural approach to mediated action.* Harvard University Press.

9 Appendix

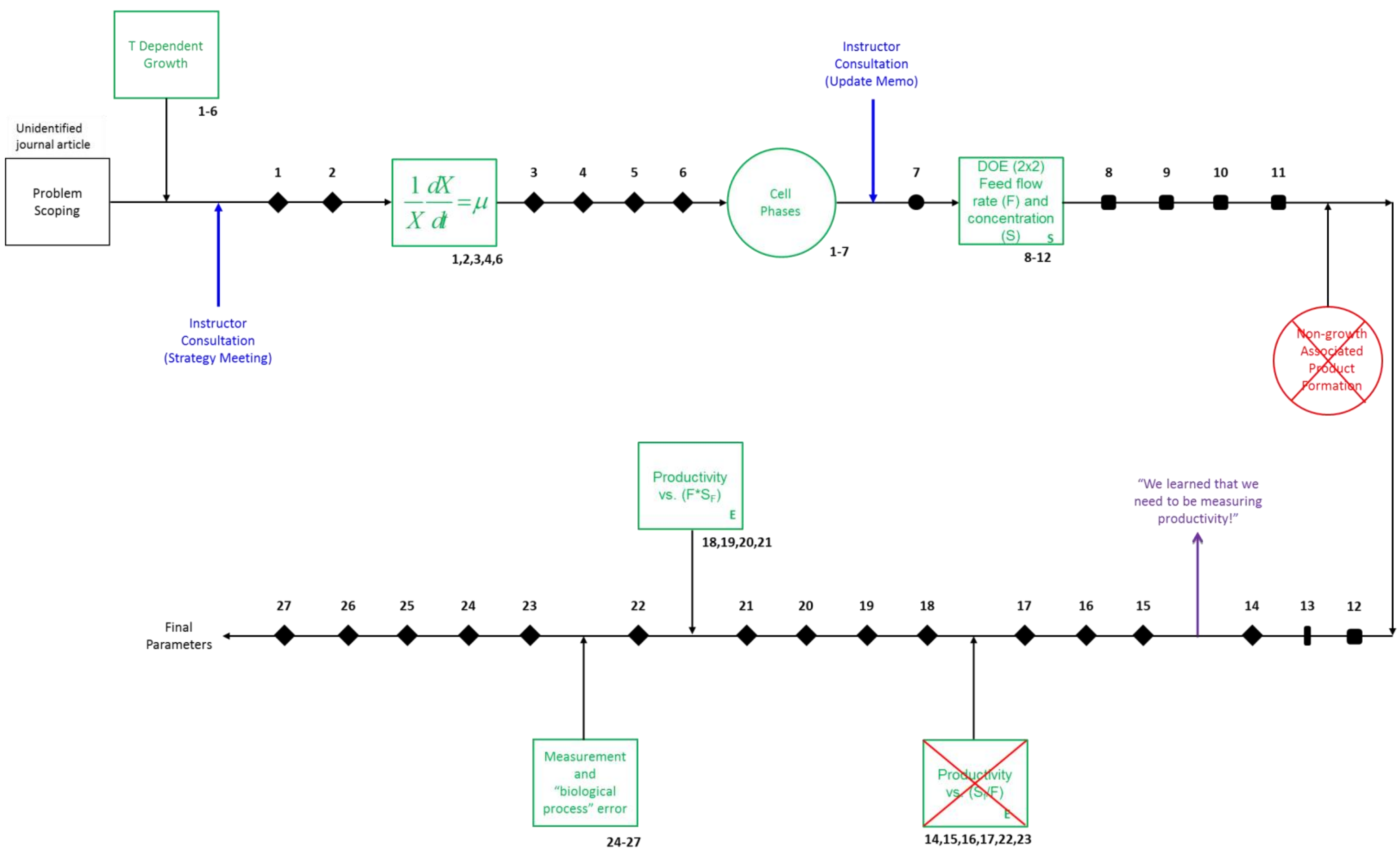
Sub-Theme Name	Description and/or Keywords
Inoculum	inoculum, inoculation
Temperature	temperature, degrees C
Batch Time	time, batch time, t, t[batch], how long, # hours
Fed Batch Time	time, fed-batch time, t, how long, # hours
Total Time	time, total time, t, how long, # hours
Initial Substrate Concentration	substrate, initial substrate, SI, S0, glucose, food, carbon, sugar
Fed Batch Flow Rate	fed batch flow rate, flow, reactor size
Fed Batch Feed Concentration	fed batch feed concentration, fed batch substrate
Measurement Strategy	samples, data, points, measurement, test, design of experiments, DOE
Productivity	productivity, product, protein, P
Budget	budget, cost, money, $, spend
Biomass Growth	biomass, bacteria, cells, X, organism, growth rate, µ max, Ks, yield, Y
Substrate Utilization	substrate, SI, S, S0, glucose, food, carbon, sugar, yield, Y, inhibition
Product Formation	products, P, product formation, productivity, production rate, protein
Temperature Dependence	temperature, degrees C
Oxygen Mass Transfer	mass transfer, oxygen, O2, viscosity
Substrate Limitation	substrate limitation, not enough substrate
Experimental Design	strategy, big picture, approach, plan, modeling
Sources	sources, literature review, research, papers, looked up, reference, search
Memo	memo, reading memo, discussing memo, letter, paragraph
Notebook	notebook, notes
Affective	ambiguity, stress, working in teams on the project
Situate	relating laboratory project to industry and engineering practice
Instructional Design	design of the project, how the project is structured and why
Administrative	logistics
Research Study	audio recording, research study

Model Development and Usage Representation (Model Representation)



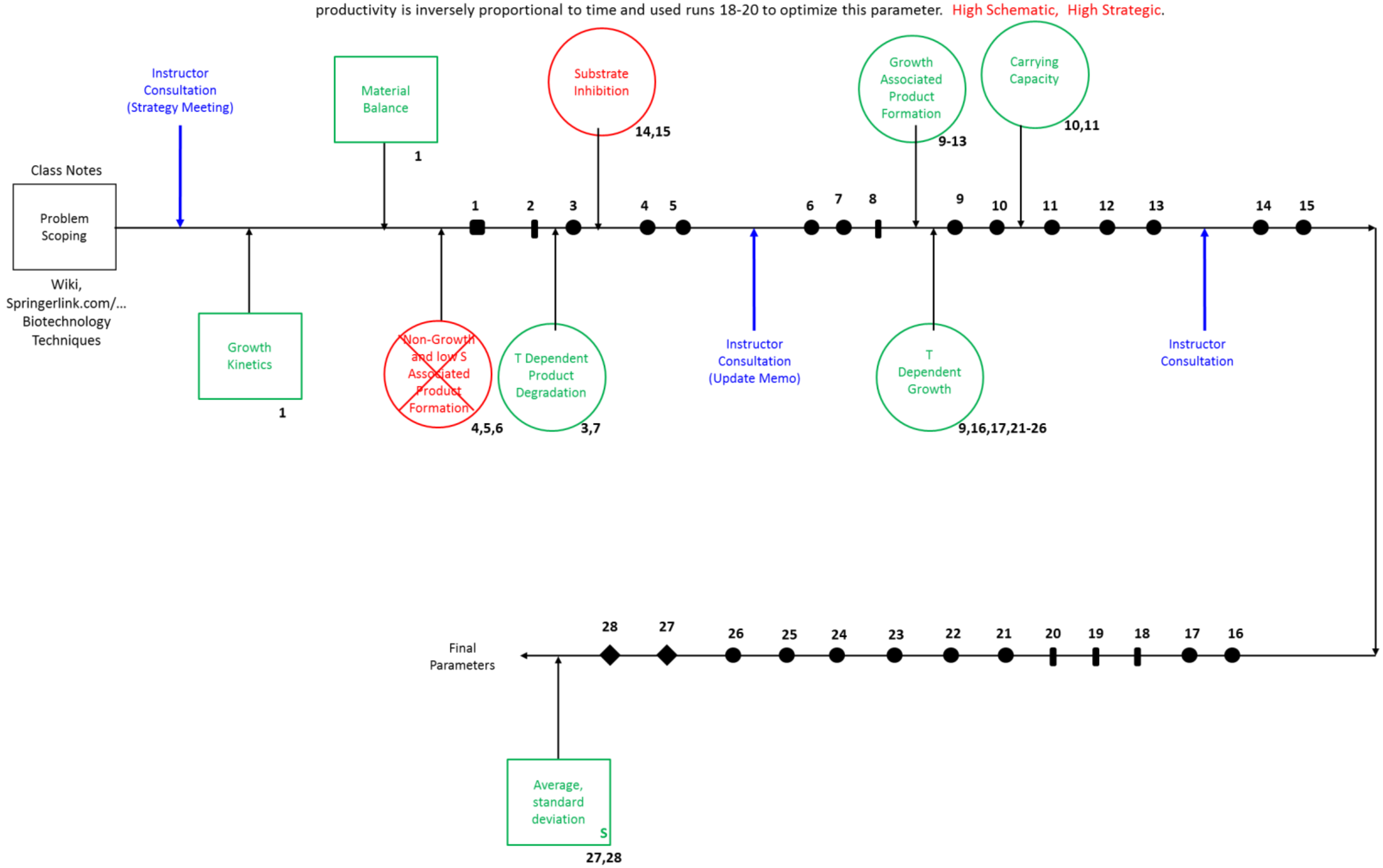
VBioR Team A

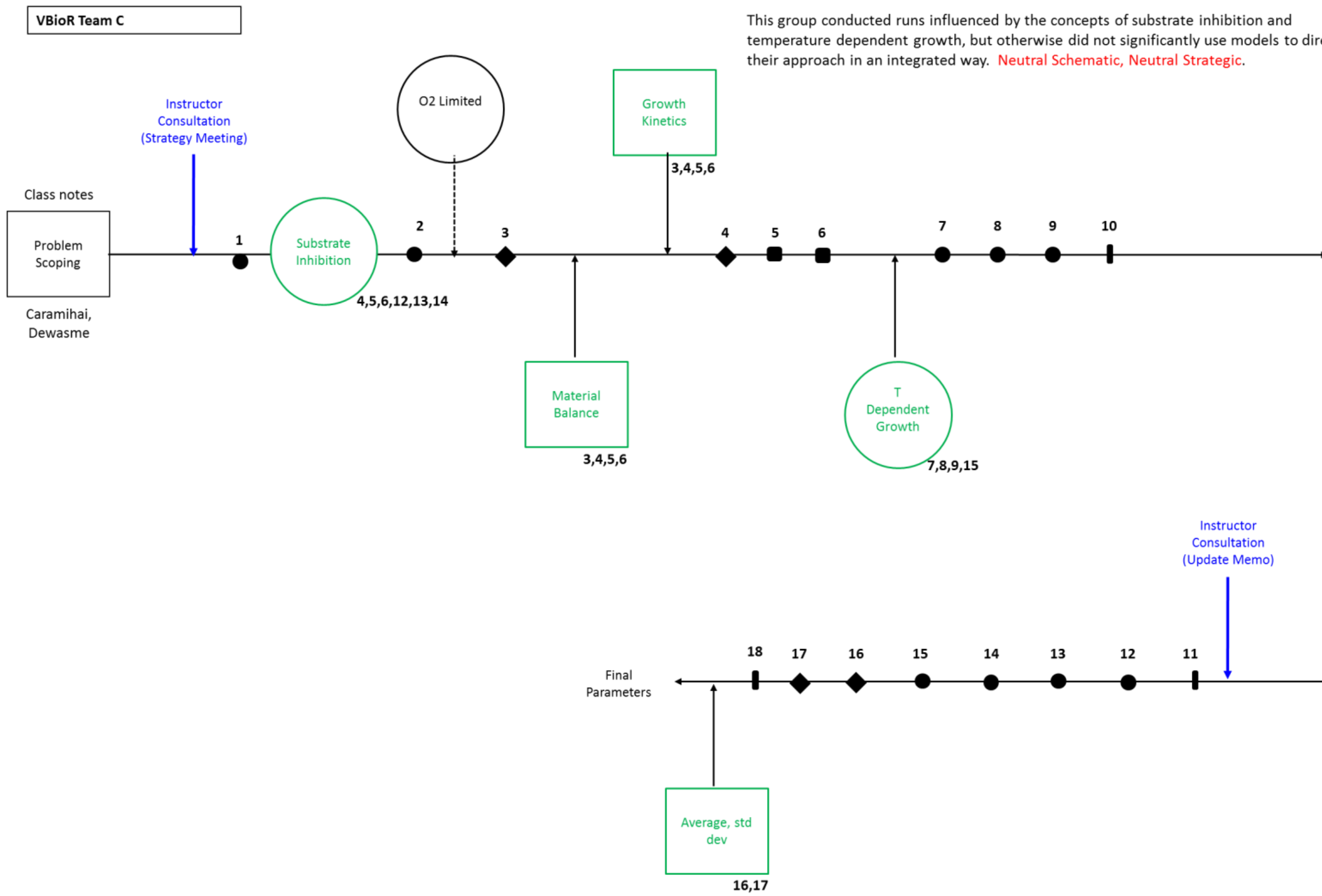
This group initially showed schematic knowledge in their search for the optimum initial substrate concentration and temperature (for which they used μ_{net}). Later, however, they just used a series of formal and informal DOEs in adjusting feed flow rate and concentration. Low schematic, low strategic.



VBioR Team B

This group systematically considered most of the important model components (material balance, growth kinetics, substrate inhibition, temperature dependent growth and product degradation, carrying capacity [due to oxygen limitation]) and other factors (inverse time dependence of productivity) governing the virtual bioreactor lab. Though strategic in selection of run parameters, this group could have been more efficient in overall run planning and order. They recognized that productivity is inversely proportional to time and used runs 18-20 to optimize this parameter. High Schematic, High Strategic.





This group conducted runs influenced by the concepts of substrate inhibition and temperature dependent growth, but otherwise did not significantly use models to direct their approach in an integrated way. Neutral Schematic, Neutral Strategic.