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Gender and Participation in an Engineering Problem-Based Learning Environment

Laura Hirshfield (University of Michigan) and Milo D. Koretsky (Oregon State University)

Abstract

The use of problem-based learning (PBL) is gaining attention in the engineering classroom as a way to help students synthesize foundational knowledge and to better prepare students for practice. In this work, we study the discourse interactions between 27 student teams and two instructors in an engineering PBL environment to analyze how participation is distributed among team members, paying particular attention to the differences between male and female students. There were no statistically significant differences between the amount that male and female students spoke; however, stereotypical gender roles and traditional gendered behavior did manifest in the discussion. Also, regardless of the gender composition of the team, the amount of time that each member talked was usually unbalanced. Our findings lead to recommendations to instructors interacting with student teams and contribute to knowledge about team and gender interactions in PBL environments.

Keywords: discourse analysis, engineering, gender, team interactions

Introduction

Problem-based learning (PBL) is drawing increased attention from engineering educators as a means to better prepare students for professional practice and to aid in the development of discipline-specific knowledge and nontechnical professional skills (Beddoes, Jesiek, & Borrego, 2010; Woods, 1994). PBL activities mimic the structure of authentic engineering work to form a "learner-centered approach that empowers learners to conduct research, integrate theory and practice, and apply knowledge and skills to develop a viable solution to a defined problem" (Savery, 2006, p. 9). While the pedagogical benefits of PBL are well-established, research is needed to identify effective practices for implementation (Conway & Little, 2001), particularly in an engineering context (Jolly, Brodie, & Jolly, 2011).

While teamwork forms a cornerstone of engineering practice, engineering students often resist participating in teams. They can resist simply because they are used to working independently. Or, more subtly, potential status judgments can adversely affect team functioning (Horn, 2012). When status comes into play, the valuation of a student's contribution is based more on who says it rather than what is being said. Thus, students with different status have different opportunities to participate in the team: high status students can dominate while low status students can withdraw and be marginalized (Horn, 2012). In engineering, status may be often assigned based on gender: women have long been the minority in engineering programs (Hill, Corbett, & St. Rose, 2010; National Science Foundation & National Center for Science and Engineering Statistics, 2015). Stereotype threat and implicit biases can lead to women being assigned to a lower status in their teams, and this lower status can lead to dissatisfaction, lowered participation, or negative attitudes. These issues of status may be amplified in the complex social and technical environment of PBL in the engineering classroom.

In this article, we characterize the interactions between students and instructors in an engineering PBL environment. Specifically, we analyze the talk time between engineering student team members and the course instructor while they are participating in an "industrially situated" design meeting. We examine how the discourse progresses throughout the meeting, considering both the team's general conversation and the influence of gender roles. We ask: is the conversation balanced between each team member? Does the

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gender make-up of the teams influence the discourse or division of talk time? Do students of different genders interact differently with one another or with the instructor? Through this analysis, we seek a better understanding of how student teams converse in PBL scenarios, and more specifically, of the relation between gender and the team interactions in an engineering PBL context.

Ultimately, this understanding can lead to transferrable knowledge on the ways that all engineering students engage in PBL settings, and the resultant knowledge can allow instructors to more effectively implement PBL within their engineering classrooms. This study also contributes understanding as to how gender can influence participation in PBL settings. Greater awareness of gendered interactions can not only allow instructors to better manage gender dynamics within their own PBL classrooms, but also better prepare engineering students to effectively engage in team problem-solving environments in practice.

Background

Problem-Based Learning in Engineering

PBL has historical origins in medical education, but has more recently drawn attention in engineering education for many reasons, most broadly, as a way to better prepare students for practice (Mills & Treagust, 2003). Students must integrate knowledge from across the curriculum to define the problem and design a solution, while considering many possible solution paths with no single right answer. There are many potential advantages to using PBL in engineering courses: PBL can motivate and engage students with authentic engineering work; improve metacognition; and aid in the development of problem-solving, critical thinking, and professional skills (Azer, 2001; Schmidt, 1983; Woods, 1994). The open-ended nature of PBL activities also encourages students to become self-directed learners, learning how to teach one another and teach themselves, as they will in professional practice.

PBL is team based, and good problems are "group-worthy" in that they are complex, ill structured and open ended, and thus difficult for students to complete individually (Lotan, 2003). To succeed in group-worthy projects, team members need to be able to contribute their own ideas but also be able to encourage the participation of other team members and incorporate their ideas (Horn, 2005). This type of successful teamwork has been found to improve achievement, knowledge retention, and student satisfaction (Johnson, Maruyama, Johnson, & Nelson, 1981). Working in teams also further reinforces the authentic nature of PBL in engineering, as it reflects the social structure of engineering work in practice. Therefore, teamwork in PBL not only introduces students to a more authentic work environment, but also can improve many industry-relevant skills, such as communication, conflict management, and social skills, and can lead to higher performance and better learning outcomes (Finelli, Bergom, & Mesa, 2010; Johnson, Johnson, & Smith, 1991; Prince, 2004; Terenzini, Cabrera, Colbeck, Parente, & Bjorklund, 2001).

However, the very aspects of PBL that allow for a productive educational experience make it challenging to implement in the classroom. A previous study has identified that the main difficulties in implementing and participating in PBL include the nontraditional instructor role, the atypical and challenging project structure, and potentially challenging team interactions (Aarnio, Lindblom-Ylänne, Nieminen, & Pyörälä, 2014; Jones, Epler, Mokri, Bryant, & Paretti, 2013). Instructors may be uncomfortable with their altered, less authoritative role in the educational experience in which they have less direct control of the learning environment. Students can also experience a "culture shock" when transitioning from passive roles in the traditional lecture-based classrooms to leaders of their own self-directed learning experiences (Henry, Tawfik, Jonassen, Winholtz, & Khanna, 2012; Hmelo-Silver, 2004; Mitchell, Smith, & Kenyon, 2005; Vardi & Ciccarelli, 2008). Students may also struggle while attempting to think critically to solve these group-worthy problems.

Management and assessment of student team interactions is critical to the effective implementation of PBL (Azer & Azer, 2014). Students may have difficulties working in teams if much of their prior school experiences were individual and not collaborative. Back to the pioneering work at McMaster University (Woods, 1983, 1994), instructional designers have worked to establish productive team behaviors. Student team interactions in PBL environments have been studied in other contexts (Azer & Azer, 2014; Imafuku, Kataoka, Mayahara, Suzuki, & Saiki, 2014; Woodward-Kron & Remedios, 2007), but research on team dynamics in engineering PBL contexts is sparse.

Gender Status and Team Interactions in Engineering

Poor team interactions in engineering projects can decrease students' enjoyment and motivation and lead to unproductive performance with unequal participation and opportunities to learn (Meadows & Sekaquaptewa, 2013). Team issues may arise due to clashing personalities or work ethics or due to individual students' status judgments. Status, or the "perception of students' academic capability and social desirability" (Horn, 2012, p. 21) impacts how students participate in team discussions. High status students are comfortable speaking up and asking questions and are generally trusted by their peers. Low status students are ignored or disregarded and may be less likely to participate in team activities or discussion. Status can be influenced by previous academic performance, but also by stereotypes based on race, nationality, class, or gender (Horn, 2012); for example, the belief that women are bad at math and science (Rudman, Moss-Racusin, Phelan, & Nauts, 2012).

Women have long been underrepresented in engineering, and the difficulties that women face in the engineering classroom are well established (Hill et al., 2010; National Science Foundation & National Center for Science and Engineering Statistics, 2015). In this work, we focus on the difficulties that female students face a team-based problem-based learning environment. Women, in particular, often find teamwork in engineering courses to be frustrating and ineffective (Wolfe, Powell, Schlisserman, & Kirshon, 2016). Engineering is a male-dominated field, both in terms of the gender majority and in terms of what tasks are valued in engineering work and how they are framed. Engineering projects emphasize many so-called "male" or "masculine" tasks, which are nonpersonal, goal-oriented, and involve hands-on activity, tinkering, and problem solving (Dasgupta & Stout, 2014; Meadows & Sekaquaptewa, 2013). Men have long been considered to be better at math and science, and this outdated stereotype still continues to have an impact today (Dasgupta & Stout, 2014; Smyth & Nosek, 2015). This "stereotype threat" can impact the behavior and judgments of both men and women in engineering (Bell, Spencer, Iserman, & Logel, 2003; Hill et al., 2010); however, women in engineering have also been found to hold more of these implicit biases (Smeding, 2012). Assimilation of these stereotypes or stigmas can determine how a woman forms her identity (Nosek, Banaji, & Greenwald, 2002), performs (Galdi, Cadinu, & Tomasetto, 2014), or gains confidence to persist in a STEM-related field (Cadaret, Hartung, Subich, & Weigold, 2017). Women may also be assigned a lower status than their male counterparts due to these perpetuating stereotypes or biases (Rudman et al., 2012). For example, science faculty have been found to rate male applicants as more competent when evaluating an identical application that was randomly assigned a male or female name (Moss-Racusin, Dovidio, Brescoll, Graham, & Handelsman, 2012). Even in gender-balanced groups, it has been found that women are more likely to assume nontechnical, traditional female roles—organizers, secretaries, writers, project managers—while men tend towards the more technical roles (Meadows & Sekaquaptewa, 2013), although both types of roles are important for engineering practice. These issues may be even more pronounced in student teams, as gender status is more likely to emerge among undergraduates than among older people or people who are not as familiar with one another (Meadows & Sekaquaptewa, 2013).

Also, gender status can easily manifest in PBL environments. Women working on student engineering projects often find themselves in mixed-gender teams. In these teams, gender status issues may emerge, as men tend to dominate more when in the presence of women (Wolfe et al., 2016). Men are more likely than women to become leaders in group discussions, to talk more and longer, to interrupt, to talk over others, and to control the topic of conversation (Meadows & Sekaquaptewa, 2013; Zimmermann & West, 1996). Men are also typically more assertive in their speech, whereas women are more affiliative; men more commonly assert dominance or leadership in discussion, while women are more likely to positively affirm others (Leaper & Ayres, 2007). Women who do act or speak assertively tend to be less liked or perceived to be incompetent (Rudman et al., 2012; Williams & Tiedens, 2016). When men interrupt women, in particular, it can be perceived as trivializing the women's comments or changing or ending the women's statement topics (Coates, 2015; Zimmermann & West, 1996). Women have been found to use language that displays a lack of confidence, through the use of "tag" questions—"do you agree?" "don't you think?"—qualifying statements, and deferential comments (Coates, 2015).

Previous studies on PBL in an engineering context have focused on the role of the tutor or coach (Masek, 2016) or the influence of PBL on their learning (Guerra & Holgaard, 2016; Purzer, 2011; Zhou, Kolmos, & Nielsen, 2012). There have also been studies focusing on analyzing the division of discourse between team members or between students in different gender groups (Donath et al., 2005; Meadows & Sekaquaptewa, 2013), but not in a PBL environment. For example, Meadows and Sekaquaptewa studied the division of talk time of first-year students during formal presentations of an engineering project (Meadows & Sekaquaptewa, 2013). They found that men disproportionately presented the technical content, spoke more often, and answered more questions than women, while women completed more of the written final report because, as one student noted, "engineers are not good writers," exemplifying that some women may be assigned nontechnical tasks because of the lower status assigned by their peers (Meadows & Sekaquaptewa, 2013, p. 11). There is a need to understand how gender status and gender roles manifest within the context of engineering PBL environments in order to form deliberate strategies to address differences in status and ensure that all students have equal learning opportunities.

In this article, we specifically examine how discourse proceeds between students while in a coaching session with their instructor, paying particular attention to the gender divisions in participation and the opportunity to learn. This research project is unique in that it applies qualitative research methods to a relatively large sample of students compared to other PBL studies that either use quantitative instruments or qualitatively study a smaller subset of students (Gilkison, 2003; Papinczak, Tunny, & Young, 2009). Our study focuses on a different context: the less scripted interactions during a project design meeting in a senior course. We chose this context because the teams must justify their approach to the instructor, and also because there is a significant emphasis on making meaning and connecting to the foundational knowledge of the discipline. This setting also differs from Meadows and Sekaquaptewa's study in that all student participants are seniors, as opposed to first-years, and thus may have more established engineering identities (Matusovich, Streveler, & Miller, 2010). Therefore, it is a rich setting to investigate the influence of gender status on the opportunity to learn in a PBL environment. We hypothesize that many of the same patterns reported by Meadows and Sekaquaptewa will emerge: men will talk more and be more likely to answer questions and discuss technical issues, while women will talk less about technical issues and talk more about nontechnical topics.

Research Questions

This study investigates the coaching sessions of a cohort of student teams working on the Industrially Situated Virtual Laboratory Project. We characterize how the discourse proceeds among the students and the instructor with the goal of developing recommendations on delivering feedback that addresses gender status. To achieve this goal, we considered the following research questions.

1. How is talk time distributed among the students in the teams?
2. How do male and female students compare in terms of talk time and topic of discourse?
3. Do any talk time patterns depend on the gender makeup of the team?
4. How does the posing and answering of questions compare between male and female students?
5. What types of strategies do coaches use to attempt to balance the talk time between students?

Methods

To investigate gendered participation, we conducted a mixed-methods study using video-recorded interaction data between students and instructors during a targeted project meeting.

Problem-Based Learning Environment

The context for this study is the Industrially Situated Virtual Laboratory Project (ISVLP), a problem-based learning environment designed to motivate and challenge students while they complete a "real-world" task (Koretsky, Amatore, Barnes, & Kimura, 2008). The industrially situated task allows students to practice engineering professional skills, complete an open-ended problem, and experience an authentic engineering process in a "safe" space without the consequences that come with an actual industrial project. Past studies have found the ISVLP to be rated by students as the more effective learning medium than physical laboratories in a senior laboratory class (Koretsky, Kelly, & Gummer, 2011), with higher self-reported levels of engagement and knowledge transfer (Nolen, Hirshfield, & Koretsky, 2014).

The ISVLP tasks students with optimizing a complex, authentic engineering process, while considering budgetary constraints and real-world implications. Experiments are performed virtually and would otherwise not be available at the university level due to cost, time, and space constraints. The students are situated as process development engineers working in industry, while instructors are situated as coaches or bosses. The students are tasked with developing a process "recipe" for high-volume manufacturing. The structure of the project also incorporates a considerable feedback component, in which the coach and student teams meet to discuss the team's strategy and progress. Students are also required to deliver industry-relevant work products like memoranda, written reports, and oral presentations to their coach.

The student projects investigated in this article are based on two different reactor systems. In project A, a recipe for an industrial-scale virtual chemical vapor deposition reactor is needed in the context of a computer chip manufacturing company. The reactor grows silicon nitride thin films from dichlorosilane and ammonia gases at low pressure and high temperature. Student teams are tasked with achieving maximum thickness uniformity, minimum dichlorosilane utilization, and minimum process time by adjusting operating parameters including gas feed rates, temperatures of five reactor zones, system pressure, and duration of operation. In project B, an industrial stirred-tank fed-batch bioreactor is used in either batch or fed-batch mode. Students aim to achieve maximum volumetric productivity by varying input parameters including temperature, substrate concentrations, cultivation times, and feed flow rates. The class studied here was divided between two different application contexts, the production of a recombinant protein or the degradation of waste. Problem assignments for the chemical vapor deposition project and the bioreactor project are provided in appendices A and B, respectively.

The ISVLP took place over three weeks in a senior laboratory course in a chemical, biological, and environmental engineering program. The project timeline with key milestones is summarized below in Table 1. The students first received an introductory lecture, which presented the project task. After that, the teams worked together during laboratory time and on their own time. A typical team spent 20–30 hours working on the project. They received feedback from the coach during half-hour meetings at the end of week 1 and at the end of week 2, and presented their final design in the end of week 3.

Table 1. Overview of the ISVLP project structure with feedback opportunities.

Timeline	Key Project Milestones	Student-Coach Opportunity for Feedback
Project Begins	• Introductory seminar • Laboratory notebook is provided	The instructor delivers a presentation about the industry, relevant engineering background, the software interface, and project constraints, objectives, and deliverables. Feedback is limited to in-class questions, discussion, and interaction.
End of Week 1	• First-run parameter set • Budget estimate • Experimental strategy • Design Memo Meeting	In this first coaching session, called the Design Memo Meeting (DMM), feedback takes the form of a 30-minute meeting in which the coach and students discuss the team's design strategy memo. If the initial parameter values, budget, and strategy are defensible, the team is granted access to the ISVLP equipment.
End of Week 2	• Progress to date on reactor performance achieved, strategy and budget • Team Update Meeting	Another opportunity for feedback occurs during this second coaching session, called the Team Update Meeting, which has the same format but is typically a few minutes shorter than the first coaching session. The coach and students talk about progress the team has made thus far, addressing issues and discussing future plans.
End of Week 3	• Final parameter set is released to production • Final Written Report • Final Oral Report • Laboratory notebook submitted	Teams deliver a 10–15 min oral presentation (to the coach, two other instructors, and other students in their lab section) that is followed by a 10–15 minute question and answer session that allows additional feedback. Final project feedback consists of grades and written comments on final deliverables.

The study reported here focuses on the Design Memo Meeting (DMM) at the end of week 1 of the project (highlighted in Table 1). In the DMM, students presented their initial experimental strategy to their coach, detailed in a design memo work product. The coach could use this time to assess student understanding, discuss how the team selected their process parameters, and guide students to improve their strategy. If the memo and initial strategy were acceptable, the team then received their log-in information to access the ISVLP to begin doing experimental runs.

Participants

This study was conducted at a US land grant university with an enrollment of 30,000 that also holds the Carnegie Foundation's top designation for research institutions. About one-third of the undergraduate students are Pell eligible and one-quarter are first-generation students.

The participants in this study were drawn from a cohort enrolled in a senior-level laboratory class in a chemical, biological, and environmental engineering department where they self-selected into teams of two to three students. Of the 116 students enrolled, the 78 study participants were on teams where every student consented and signed informed consent forms which were approved by the Institutional Review Board. Fifty-two of the students identified as male and 26 as female.

The student teams opted to work on one of two projects. Both projects had the same instructional design but each project focused on a reactor from a different industry and was led by a different coach. Fourteen teams worked on a chemical vapor deposition project, which was led by coach A. Thirteen teams worked on a bioreactor project, which was led by coach B. Both coaches are long-term faculty members and content experts in the engineering processes in their projects. One coach is female and has over ten years of experience teaching. She regularly teaches the capstone design and laboratory courses and has developed several new courses during her tenure at two research universities. The other is male, with almost twenty years of university teaching experience, and actively pursues innovative curricular designs such as the one described in this paper. Both coaches are highly engaged in teaching and regularly attend disciplinary education conferences like ASEE. Their general approach to the coaching sessions was to reinforce the disciplinary nature of the project, emphasizing the roles of process development engineers (students) and mentors/supervisors (coaches) and the professional context of the work. At the time of the study, one coach (coach B) had formal training in addressing gender inequity through a 60-hour workshop focusing on issues of difference, power, and discrimination. The other coach did not have any formal training in this area.

The first author of this study was not involved with data collection for the cohort studied; however, she collected ethnographic data from a student team in another year which helped her conceive of examining gendered interactions. Her main role was to code and analyze data. She was not involved in the delivery of the course. The second author designed the learning system and leads a research program to understand student participation in this industrially situated task, including development of professional skills, use of models, novice-expert comparisons, feedback interactions, disciplinary engagement, and metacognitive regulation. As one of the coaches, he did not participate in coding the data. Both authors participated in writing.

Research Design

The study presented here was part of a larger research project, with an overarching goal of investigating student-instructor feedback interactions during the ISVLP. This mixed-methods study targeted the distribution of verbal participation among students and their gendered interactions. Some of the analysis included the coding and quantification of qualitative data, that is, the discourse in interview transcripts (Chi, 2012).

Data Collection

Data were collected by observing and video-recording consenting teams each time they met with the coach, including the DMM, the Team Update Meeting, and the final presentation. In addition, six students from the cohort were interviewed after the project was completed. The interview data were collected as part of a separate ethnographic study; however, since the interview addressed the students' project experience as a whole, it was suitable to triangulate analysis in this study as well.

Data Analysis

Transcribed data of recorded DMMs from 27 teams and two coaches were used for this study. The DMMs ranged from 20 to 35 minutes long, and on average were 28 minutes long. Using ATLAS.ti, the transcripts were analyzed using an episode framework, in which the discourse is separated into thematic units (van Dijk, 1982). The six post-project interviews were also analyzed.

Episode framework

Previous research involved developing the coding protocol to characterize the feedback given in these sessions in terms of feedback stage (Gilbuena, Sherrett, Gummer, & Koretsky, 2011; Gilbuena, Sherrett, & Koretsky, 2011) and theme (or topic). Episodes can be characterized in one of three overarching Tier I themes, as shown in Table 2 (see next page): Student Engineering Objectives, Coaching Objectives, and Project Contextualization. Student Engineering Objectives involve themes that relate to project deliverables that will be used to assess the team's work, such as process parameters selection or the performance metrics. Coaching Objectives comprise themes that relate to the instructional goals of the project: reinforcing fundamental engineering concepts like material balances, transport, kinetics, or professional skills like communication or teamwork. Project Contextualization themes refer to ways that the project is situated, either in terms of the students' prior coursework or in the engineering industry. Episodes can be coded further to Tier II levels, which are types of topics within the Tier I themes (such as Input Parameters within Student Engineering Objectives).

The coding protocol was then refined between two researchers. They reconciled differences after one round of coding then completed a second round to calculate Cohen's Kappa to represent interrater reliability (IRR). Cohen's Kappa for the coding of the themes was 0.80 overall (0.87 for Student Engineering Objectives, 0.93 for Coaching Objectives, and 1.0 for Project Contextualization) and is reported in more detail elsewhere (Hirshfield, Whinnery, Gilbuena, & Koretsky, 2014).

Question analysis

We also quantified and analyzed the questions that the coach posed during each meeting to determine if there were differences between the types that male and female students answered. The questions were also categorized in two ways. First, questions were determined to be direct if they were posed to a specific student, or indirect if they were posed to the group as a whole. Second, a question was labeled a technical question if it was coded within a Student Engineering Objectives or Core Technical Content and Concepts episode; it was labeled a nontechnical question if it was coded within a Professional Skills episode.

Talk time analysis

Each speaker is labeled "S1," S2," and "S3," according to the number of words they spoke, where student S1 spoke the most within the meeting and student S3 spoke the least. While the gender of each student was identified, it is not included in the labels in this article. After coding was complete, the qualitative analysis was "quantified" (Chi, 2012) to compare the talk time in each coach's meetings and between

Table 2. Episode coding themes with descriptions.

Tier I	Tier II	Description	Example
Student Engineering Objectives	Input Parameters	Measurement strategy and reactor-specific control variables (e.g., temperature, flow rate, time, pressure, substrate concentration)	"For the first set we want to keep that 700 degrees Celsius constant and find a, flow rate for DCS and ammonia gas to obtain that 1000 Angstroms."
	Performance Metrics & Project Objectives	Budget and reactor-specific indicators (e.g., utilization, uniformity, productivity, process efficiency)	"There's also concern that we may be running a reaction rate that's too fast. So the reaction on the outer edge of the wafer is occurring too quickly. So you get bad uniformity across the wafer."
Coaching Objectives	Core Technical Content & Concepts	Kinetics, transport, material balance, modeling, experimental design, and strategy	"Because the reaction rate is so much higher that the diffusion is going to be what's holding back the process."
	Professional Skills	Communication, experimental documentation, teamwork, economic impact of engineering solutions, and project management	"Just get it all in that lab notebook. Just so that it's documented. There's actually good reasons for that. So if you figure something out about the process and want to go back, then that documentation becomes part of evidence of when you came up with that."
Project Contextualization	Situate	Relating the project to industry and engineering practice	C: "Okay. So from your supervisor, do you want to tell me that your objective is to get complete utilization?" S: "No." C: "No. What's a better word for that?" S: "Maximum." C: "Yeah, you can say maximum. That's risky too but that's better."
	Instructional Design	How the project is structured and why and comparison to traditional homework	"In her [reactors] class, she says A+B goes to C+D. And the she does math around how fast that happens."

male and female students. One-way ANOVA was used to determine if there were significant differences in the number of words spoken by participants or a significant difference in the words devoted to various episode themes. Groupings were made based on the coach in the DMM and based on the overall gender makeup of the team (all male, all female, one male and two female students, or one female and two male students). Statistical analysis included a Pearson's correlation test to determine correlations between performance factors (oral presentation grade, final report grade, overall project grade) and both participation (the number of words spoken by students, the number of words devoted to each theme) and demographic (the gender make-up of the team) factors. An alpha value of 0.05 was used to determine significance.

Results and Discussion

How is Talk Time Distributed Among the Students in the Teams and How Does This Relate to Other Aspects of the Team Experience?

Before considering how gender dynamics manifest in PBL teams, we first analyzed if discourse is balanced among team members at all, regardless of gender composition. Table 3 shows the

Table 3. Percentage of words spoken by students, relative standard deviation (RSD), and total words spoken by students and by the coach.

Project A	Project B	S1	S2	S3	RSD	Total Words (Coach)	Total Words (Students)
	B1	36.9%	34.4%	28.7%	0.127	2672	861
	B2	38.9%	35.2%	26.0%	0.199	2975	1907
A1		57.1%	42.9%		0.199	1465	1276
A2		39.2%	37.3%	23.5%	0.256	1729	1339
A3		42.9%	35.5%	21.6%	0.324	2691	2412
A4		47.1%	32.1%	20.8%	0.395	3021	2218
A5		43.4%	38.9%	17.6%	0.414	3416	1248
	B3	49.1%	27.8%	23.1%	0.415	3145	1502
	B4	42.7%	41.9%	15.4%	0.467	1988	917
	B5	52.2%	29.6%	18.3%	0.518	3092	1461
	B6	50.2%	37.4%	12.3%	0.579	3025	1419
	B7	55.7%	23.9%	20.5%	0.582	2944	1583
A6		56.7%	22.7%	20.6%	0.608	1929	1589
	B8	58.5%	26.7%	14.8%	0.678	3370	600
	B9	50.1%	42.3%	7.6%	0.679	2465	1327
A7		56.7%	31.8%	11.5%	0.680	2364	1248
A8		50.7%	42.6%	6.7%	0.703	3095	2954
	B10	52.2%	42.1%	5.7%	0.735	2899	1202
A9		61.7%	24.4%	14.0%	0.753	2482	1555
A10		65.9%	17.3%	16.9%	0.845	2051	1429
	B11	54.6%	45.4%	0.0%	0.877	3365	652
	B12	67.6%	26.5%	5.9%	0.943	2268	392
A11		85.0%	15.0%		0.990	1344	1320
A12		69.5%	26.9%	3.6%	1.002	1955	1252
A13		87.6%	12.4%		1.064	1979	1339
	B13	74.4%	18.1%	7.4%	1.080	4004	1572
A14		91.0%	5.5%	3.5%	1.498	2051	1599

Table 4. Significant correlations found between factors.

Performance Factors	Participation and Demographic Factors	Pearson's Correlation Coefficient	*P*-Value
Final Report Grade	Number of words spoken by student S3	0.545	0.003
	Number of male students	0.423	0.028
Oral Presentation Grade	Core Technical Content & Concepts	0.396	0.041
Overall Grade	Number of words spoken by student S3	0.462	0.015
	Number of male students	0.436	0.023

division of talk time among the students for each team, where S1 pertains to the student who spoke the most in the DMM and S3 is the student that spoke the least. Teams labeled with "A" worked with coach A while teams labeled with "B" worked with coach B. The teams are ordered from having the most balanced talk time among members to the least balanced. Balance in teams was determined by the relative standard deviation (RSD), which is the standard deviation in the number of words between each team member divided by the average number of words spoken by the team; teams with the most balance have the lowest RSD and teams with the least balance have the highest RSD. All teams have three student members, except for teams A1, A11, and A13, which had two members each. As Table 3 illustrates, there can be a wide variation in students' participation within a team. For 19 of the 27 three-member teams, student S1 delivers over half of the student dialogue, and for 8 out of these 27 teams, there is at least one student who speaks less than 10% of the time.

Table 3 highlights that the number of words spoken by the coaches always exceeds the cumulative number of words spoken by the students as a whole; it ranged from team A11, where the talk was almost evenly divided, to team B12, where the coach speaks almost six times the number of words that students do. The high proportion of instruction discourse may seem unusual considering that PBL is, by nature, a student-centered pedagogy, in which the instructor should take a facilitative role rather than lecturing or dominating conversation. However, it is important to consider the context of the meeting in this project. A team works on the project on average 20–30 hours, but only has approximately 1.5 hours of formal feedback interactions with the coach, as specified in Table 1. This instructional design shifts the emphasis of these meetings to where the coach needs to identify previous student thinking and use that prior work as a catalyst for discussion and learning.

Table 4 shows all significant correlations between performance factors and participation and demographic factors found, doing a Pearson's correlation test. The number of words spoken by student S3, which is the student who had the smallest proportion of talk time, correlates significantly and positively to the final report grade ($p = 0.003$) and overall grade ($p = 0.015$), which can suggest that teams with more equal participation perform better. A greater focus on technical content correlated to oral presentation grade ($p = 0.041$). Finally, the number of male students correlated to the final report grade ($p = 0.028$) and overall grade ($p = 0.023$), which will be discussed in the following section.

How Do Male and Female Students Compare in Terms of Talk Time and Topic of Discourse?

The results shown in Table 3 demonstrate that students spoke far less than the coaches, and that the discourse division among team members was not always balanced among the students. After determining this finding, we considered how gender composition may influence this imbalance, by relabeling each student according to their gender and analyzing the divisions according to gender group or gender makeup of the team.

Table 5 (see next page) shows the average number of words spoken for male and female students, organized by the gender makeup for each team. Overall, male students spoke an average of 514 words and female students spoke 457 words, which is not a statistically significant difference. Both male and female students spoke less overall in meetings with coach B than with coach A. There was a female student present in a meeting with coach B who did not speak at all, but all male team members spoke at least once in every meeting.

Do Any Talk Time Patterns Depend on Gender Makeup of the Team?

The one-way ANOVA test demonstrated that there was no significant difference on the themes that students covered regardless of number of female or male students on each team. In other words, the gender makeup of the teams did not affect the content of the discourse. However, as shown in Table 4, the number of

Table 5. Average number of words spoken by male and female students.

Makeup of Team	Number of Teams	Female Students				Male Students				Coaches			
		Avg.	SD	Min.	Max.	Avg.	SD	Min.	Max.	Avg.	SD	Min.	Max.
All M	10					576	438	56	1499	2212	606	1344	3095
1 F, 2 M	12	446	327	0*	1034	431	318	23	1170	2890	627	1955	4004
2 F, 1 M	3	448	174	296	741	472	213	247	671	2459	650	1729	2975
All F	2	490	244	109	737					2805	481	2465	3145
In Meetings with Coach A	14	596	287	315	1034	581	422	45	1499	2255	619	1344	3416
In Meetings with Coach B	13	400	243	0*	741	396	284	23	1170	2939	519	1988	4004
Overall	27	457	266	0*	1034	514	380	23	1499	2585	661	1344	4004

*Note that there was one female student in a 1 F, 2 M team meeting with Coach B who did not speak at all, hence the minimum requirement of 0 words.

male students on the team positively correlated to both the final report grade ($p = 0.028$) and the overall project grade ($p = 0.023$). This latter result is consistent with research on gender-mixed design teams in which teams with fewer women performed better (Okudan & Bilén, 2003; Okudan, Horner, Bogue, & Devon, 2002). While interpretation of this result is speculative, we believe it is important to consider sociocultural explanations. For example, female students may have more difficulties in mixed-gender teams, due to lower status, stereotype threat, or differing behavioral norms between male and female students. If some of the teams with women face challenges with team interactions, even if they are minor, it may result in a "social friction" that leads to lowered productivity and poorer work product performance.

There was also no statistically significant difference between the number of words spoken by male or female students in mixed or in homogenous teams. Although female students spoke more on all-female teams than on mixed teams (as shown in Table 5, an average of 490 words compared to 447 words) and male students spoke more on all-male teams than on mixed teams (576 compared to 435), no differences were significant.

We examined the transcripts to identify particularly assertive or unassertive language and found noticeable differences between male and female students, particularly in mixed-gender teams. Prior work has reported that women used unassertive or unconfident language, overused phrases such as "like" or "kind of," posed answers as questions as opposed to statements, and trailed off in volume (Meadows & Sekaquaptewa, 2013). This type of language was noticed consistently in the female students studied here; for example, in team A2, there is a stark contrast between how female student S1 answers the coach compared to male student S2:

> Coach A: Alright. So you have temperature. What flow rates do you have?
>
> S1 (female): We want to kind of do, we're leaning toward the maximum, and we want a high flow rate because we want to feed the reactants in excess, because we haven't actually found one . . .
>
> S2 (male): In the patent they suggest another range for the flow rates, and we're following that.

The female student above uses indecisive qualifiers and phrases: "kind of," "leaning toward," and "actually." She seems too nervous to answer the question definitively; she does not use complete sentences, pieces together incomplete phrases, and trails off. Comparatively, the male student is direct and sure and uses confident language and phrasing. Similar patterns were observed in many of the other mixed-gender teams.

How Does the Posing and Answering of Questions Compare Between Male and Female Students?

Table 6 shows the average number of questions posed by coaches and answered by students throughout the DMMs. Most questions were related to technical themes (Core Technical Content & Concepts). However, coach A posed more questions per session than coach B and had a higher proportion of nontechnical questions.

Table 6. Average number of questions in a DMM.

			Technical Questions			Nontechnical Questions		
	Number of Teams	Total Number of Questions	Number of Questions	Answered by Female Students	Answered by Male Students	Number of Questions	Answered by Female Students	Answered by Male Students
In Meetings with Coach A	14	45	37	14	23	8	5	3
In Meetings with Coach B	13	27	26	10	15	1	1	1

Both coaches structured the meetings through questioning the students, keeping the conversation flowing by probing and guiding students as opposed to direct instruction. However, when investigating how the questions were actually posed to or answered by students, several differences emerged between the meetings with different coaches. As shown in Table 6, students answered significantly more questions in meetings with coach A than in meetings with coach B (an average of 45 compared to 27, $p = 0.012$). This difference was evident in the meeting transcripts when comparing the coaches' questioning strategies. Although coach B did pose questions to the students, they were often rhetorical and did not elicit a response beyond "right" or "okay" or they were answered immediately by the coach, as evidenced in the meeting with team B2:

> Coach B: How do you tell? Well you estimate the profit from this set versus this set. And so how you estimate the profit that of course includes everything. Right? To producing that product, because you're going to include that when you estimate profit. So those you look, that's the essentially, um, your objective function, right. Objective is optimized profit. And that's how you tell if one set is better than another set. And those are the numbers, the economic numbers from the slides.
>
> S1 (female): I see.
>
> S2 (male): Okay.
>
> Coach B: Okay.

Within meetings with both coaches, although men answered more technical questions than women on average, there were no significant differences. This finding differs from other work that found male first-year students more often answered technical questions (Meadows & Sekaquaptewa, 2013). There are several plausible explanations for these different findings. Female students could be answering more technical questions due to the fact that more confident female students persist farther in their engineering academic career (Seymour & Hewitt, 2000). It could also be due to male students viewing female students as more equal after working alongside them for four years. Or, it could simply be due to some aspect of the project environment that leads to female students being more comfortable and chiming in more.

In contrast, there was a significant difference in how nontechnical questions were answered: on average, five nontechnical questions were answered by female students compared to two by male students ($p = 0.022$). Therefore, while technical roles were divided more equally by female and male students, female students were still more likely to adopt the nontechnical roles, which are perceived as traditional female roles: project managers, schedulers, organizers, and so on. Another common traditionally female role is that of a "secretary," which involves taking notes in meetings and documenting the team's progress. Teams are required to document their progress during the DMMs, and thus there is a requirement to have a secretary; however, this role was filled equally by male and female students.

What Types of Interventions Do Coaches Use to Balance the Talk Time Between Students?

The degree that students are inclined to speak in meetings with the coach may be attributed to several factors. Some students are simply more outgoing, enthusiastic, or talkative, while some students may be more shy or reluctant to speak up. Students who have higher status may feel more comfortable contributing, while students with a perceived lower status may keep quiet. Just as talking more in meetings does not mean the student knows more than the other teammates, speaking less does not mean that the student is less engaged. However, if the discourse is dominated by one team member, it is difficult for the coach to gauge the other students' progress or understanding. Students who speak less also lose the benefit of talking through material aloud to others to reinforce the concepts and their understanding and to be able to meaningfully contribute to the team's co-construction of understanding (Koretsky, Nolen, Tierney, & Wetzstein, 2015). Lower participation in group discussions may also further reinforce a student's lower status.

Coach A had a straightforward approach to involving quieter students in the sessions. He would commonly direct questions to specific students. There were times where the called-upon student clearly preferred to stay quiet during the session and would answer the question then revert to sitting back. However, other times, the simple act of interacting with that one student would encourage more talking throughout the rest of the meeting. Once the student had a chance to speak up, he or she seemed far more comfortable interjecting throughout the rest of the meeting. For example, in team A4, a female student (student S3 in Table 3) remained relatively quiet through the beginning of the meeting; later on, the coach directed questions specifically at student S3 in a nonthreatening way, simply asking if she agreed with her teammates.

> Coach A: Yeah. So if you want to be reaction rate limited what do you need to pay attention to?
>
> S1 (male): Temperature.
>
> Coach A: Temperature should be lower or higher?
>
> S1 (male): If you want reaction rate limited, it should be higher.
>
> Coach A: So . . . do you agree with that, S3? It's alright not to agree.
>
> S3 (female): Well if we're reaction limited then wouldn't we want a slower reaction? So . . .
>
> S1 (male): It would depend on diffusion.
>
> S2 (male): Diffusion, yeah.
>
> S3 (female): So we'd want a lower temperature.

After this interaction, S3 contributed regularly to the conversation, which resulted in a fairly well-balanced discourse between the three teammates, as shown in Table 3.

As previously mentioned, we found no significant difference between the number of words spoken by male and female students; this result differs from other studies showing that in mixed-gender teams, female students speak far less than male students (Eagly & Karau, 1991; Meadows & Sekaquaptewa, 2013), but there are possible reasons for this incongruity.

In teams with one female student, like teams A5 and A12, coach A would often start the meeting by asking the female student "how are you?" The female student in team A5 (student S1) ended up talking the most in the session; of course, it cannot be determined whether this was because the student was a confident, outgoing team member, or if it was due to this coach's strategy of establishing rapport, but this is an easy strategy to ensure that the students in the gender minority are comfortable and acknowledged by the coach.

In the sessions led by coach B that involved female students (particularly those with all-female teams), the coach's dialogue was more conversational and informal. There are more examples in transcripts of coach B talking about unrelated topics, like the artwork in her office, with teams with more female members, whereas with other teams discourse more quickly reverted to the project task. Whether this approach was intentional or not, it appeared to create an environment that led to female students feeling far more comfortable to speak up. The average number of words spoken by a female student in all-female teams was 490 words, as opposed to 351 words in mixed-gender teams. Or, these female students could have been more comfortable speaking up since they were not in the gender minority.

More balanced discourse could also have come about due to students self-selecting their teams. Although students were cautioned against only working with their friends on the project, team A4 was comprised of three good friends (one female and two male students), and they ranked highly in terms of discourse balance. When asked in the end-of-project interview if their friendship contributed to positive team interactions, the female student mentioned:

> Yeah, we worked together a lot, so we knew what our strengths were, which is really important. That's something you don't necessarily know going into a team a lot of times, is like exactly what someone is really good at. But we all knew each other so well that it was like oh, well [one student is] good at this, [another is] good at this, I'm good at this, so let's do it that way. And . . . we all trusted each other really well. Because we all knew that we could do a really good job, so it was like if one person was gonna go write one section or go do this testing, it was like well, we trust you to do that.

Students who are more comfortable on their teams, whether it is because they knew each other previously or had otherwise established a rapport, may more easily have balanced discourse among the members. Although it is not necessarily advisable to always consider friendship when forming teams—as students can benefit from diversity, conflict, and working with new people—this balance, dynamic, and environment in team A4 is one that teams should strive for, even if the students do not know one another. The group above describes successful teaming behaviors such as positive interdependence, individual accountability, and teamwork skills (Johnson & Johnson, 1999; Smith & Sheppard, 2005). In this case, the positive team dynamics happened because the team had developed rapport and trust through other interactions, but the challenge for instructors is to help teams achieve that state more quickly. Their attitude or perspective is the type that leads students away from status-influenced behavior and towards valuing individual's contributions. Because this person respects everyone's different skills and abilities and is confident that they all contribute, each team member is seen as having more equal status, and thus status judgments would not affect the opportunities that each team member has in the project.

Conclusions

Implementing problem-based learning (PBL) can be challenging for instructors, due to the complex project structure, the altered role of the advisor, and the team experience. In engineering PBL environments, the team experience may be particularly difficult to manage due to engineering students' discomfort or unfamiliarity with team projects, team interactions, or gender status issues that manifest in engineering contexts. It is important to consider how student discourse proceeds in PBL situations to ensure that students all have equal opportunity to benefit from the PBL experience, in terms of accruing technical knowledge, developing professional skills, and gaining confidence as engineers. Women, in particular, are underrepresented in engineering courses and are generally perceived to have lower status than male students; many other studies suggest that women contribute less than men to technical content or to group discussions in team engineering projects (Laeser, Moskal, Knecht, & Lasich, 2003; Linder, Somerville, Eris, & Tatar, 2010; Meadows & Sekaquaptewa, 2013; Wolfe et al., 2016).

In this work, we studied the discourse that occurs among student teams working in an engineering PBL context, the Industrially Situated Virtual Laboratory Project. We compared the number of words spoken, themes covered, questions answered, and roles undertaken by each participant in PBL meetings, paying particular attention to gender status. We found that the majority of teams had a nonuniform division of talk time among the team members; however, our results suggest that these imbalances are not due to gender status. There was no significant difference in the number of words spoken between male or female students, regardless of the team makeup, and men and women both participate in technical and nontechnical themed episodes equally. This finding might imply that in this PBL context, team participation was not affected by gender status or team makeup. The only significant difference found between gender groups was that female students answered significantly more nontechnical questions than male students. This finding suggests that even if gender status may not be an overt issue in this context, women still may assume more stereotypical "feminine" roles such as notetaker, communicator, or planner. So while participation is not blatantly unbalanced, there is still a manifestation of socialized gender roles.

Of course, it is not certain that the significant differences in speech patterns were due solely to the students' status imbalances or gender divisions. The coaches studied in this work uses various strategies to be more inclusive and increase participation, including directing questions at specific students and intentionally building rapport. If PBL instructors are finding that team members are not participating equally, they can consider these strategies when managing discourse among team members, to encourage equal participation and discourage status issues in PBL teams.

The findings have other implications for the practice of PBL, both within engineering and in other PBL contexts. Most of the teams studied showed an imbalanced distribution of talking between the students, regardless of gender. Often teams had one student who did not participate substantially, and one team had a student who did not participate at all. Thus, it is imperative that PBL instructors notice interactions between all students—not solely between male and female students—and do their best to facilitate more balanced participation. Status differences can arise for many reasons beyond the gender division discussed in this paper—race, ethnicity, nationality, personality, perceived intelligence—and it is important for PBL facilitators to consider this when managing their student teams. Although we did not find any statistically significant differences between male and female students in terms of number of words spoken or topics discussed, other stereotypical behaviors were evident (i.e., women discussing more of the nontechnical topics). Thus, PBL instructors should attend to how gendered roles manifest, for example, how participation distributes across technical and nontechnical roles.

We believe it is useful to consider these gender dynamics in terms of the sociocultural currents in engineering school and the engineering workplace. Interaction norms are deeply ingrained within all actors in the environment. We do not suggest that a change in a single course experience can be the panacea for this important and deep-rooted problem. However, the interactions of PBL facilitators and student teams provide an opportunity to witness moments when actors express gender bias in situ. They can then become a useful place to confront issues and begin to shift norms. Of course, such responses have much greater influence if they align with other initiatives to make public issues of equity, inclusion, and social justice within the community.

In a broader sense, this study has implications for professional development for faculty who facilitate work in a setting in which a high proportion of work is done outside of the classroom. At the university level, engineering students work on team projects outside of class in many contexts besides PBL. Thus, the instructor is often put in the role of a facilitator, meeting only briefly with students but needing to assess and guide their understanding and also manage team interactions. In addition to gendered participation patterns, we observed differences between instructors in terms of the number of questions they posed and the degree that they included nontechnical professional skills. Differences of enactment of facilitation can be rooted in faculty conceptions of learning; those who embrace transmission model of learning will have more difficulty with facilitation than those with constructivist and sociocultural perspectives (Bednar, Cunningham, Duffy, & Perry, 1992; Cunningham & Duffy, 1996). We suggest professional development opportunities need to be developed to help engineering educators build more fruitful conceptions, and more diverse strategies and skills, so they can more effectively interact with teams in these contexts.

There are several limitations to this study that should be considered when interpreting the results. First, this study was performed at one university in one course in which the senior-level students had already been working together for multiple semesters. The coaches are experienced with this specific PBL environment, having assigned the ISVLP in prior offerings of the course, and thus their experience may not be representative of all PBL experiences, particularly for new tutors. Also, the coaches have different coaching strategies, and so the students that met with each coach had different experiences, which may have affected how their discourse proceeded. These findings should be verified in other settings, with other PBL problems, and with instructors of different levels of experience. Second, this analysis only focused on one 30-minute meeting within the context of the entire PBL setting in which students worked 20-30 hours; thus, it may not be representative of the student interactions when there is no coach present.

This work also reveals several future directions for research. In this context, it appears that overt gender status did not manifest. This finding leads to two questions. First, what are the conditions that lead to equal talk time? Is it based on the learning system, the instructors, or other elements of the context? Second, while males and female students divide talk equally, there are more subtle manifestations of gender-based cultural norms that are less obvious. How can an instructor identify these? What are ways to lessen them? Finally, while talk time is balanced between gender, talk time is imbalanced among students in most teams. Why is this occurring? What are further strategies to increase the participation of all students on a team? Equitable participation of all students in PBL teams would ensure that all students are able to benefit appropriately from the rich benefits of PBL experiences.

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Appendix A: Chemical Vapor Deposition Project Assignment

Objective

Develop an optimal "recipe" (i.e., choice process parameters) for four Low Pressure Chemical Vapor Deposition (LPCVD) reactors at as low a cost as possible. This recipe will be released into *high volume* manufacturing for the next-generation products at BeaverDam Chips.

Overview

Your team's task is to develop a "recipe" for high-volume manufacturing of silicon nitride (Si_3N_4) using Low Pressure Chemical Vapor Deposition (LPCVD). The growth and measurements will be made via computer simulation in our *VirtualCVD* laboratory. The furnaces have a capacity for batches of up to two hundred 300 mm (in diameter) wafers. The wafer spacing is 6.35 mm. They have 5 temperature zones that can be set individually. In addition, you can set the flow rates of ammonia (NH_3) and dichlorosilane (DCS, $SiCl_2H_2$) feed gases, the reactor pressure and the time. The flow rates are in units of sccm which is a "standard centimeter cubed per minute," which represents the volume rate that the gas would flow under standard conditions of 1 atm and 0 ^oC, the pressure is in mtorr and the time is in minutes. You will also have access to a (*Virtual*) ellipsometer, with which you can measure the film thicknesses at the points on any wafer that you select. You will be charged $5,000 for each run and $75 for each measurement (in *Virtual*$, of course). An equipment manual for the furnaces and ellipsometers is available.

You should develop a recipe that grows Si_3N_4 to a target thickness of 1000 Å uniformly within the wafer and from wafer to wafer. In addition your recipe should utilize as much of the reactant gases as possible, especially DCS. The manufacturing specification for uniformity is presently, 98%; however, this value was developed for 200 mm diameter wafers and the new process uses 300 mm wafers.

Deliverables

Five deliverables are required to be produced by each team:

A. Design Strategy Memo. Due Lab Session Week 8. Develop a strategy to explore the parameter space. Your group's design strategy must be explained in a memo and discussed with the CVD Project Supervisor. In your memo you are expected to have the first run and measurement set completely specified and explained, and ideas about the direction you think you will take. You should also provide a budget estimate for the project. The budget should include as separate items the experimental cost and the cost of your time as engineers working on the project. After your design strategy is approved, you will be given an access code for the *Virtual CVD* reactor. <u>The remaining time in the lab should be spent working on your project</u>. You can work in the Gleeson computer lab, Kelley computer lab, or the Gleeson first floor study areas.

B. Experiment Journal. Due at your team's final presentation. As you perform the virtual experiments, you need to keep track of <u>the run parameters, summary of output, data analysis, and an explanation of what you will do next</u>, i.e., what you infer from the analysis (similar to information you would track in "real" lab experiment). **Pay special attention to any unexpected results and any changes you make in your overall experimental strategy**. Your lab journal should be signed and dated by all group members after every session. You will be assessed on the completeness of your description and the soundness of your logic (so be clear!).

C. Intermediate Update Memo. Due Lab Week 9/10. During your lab session, your group will give the supervisor a status update on your progress. You should include the best uniformity that you have achieved, how much money you have spent with a budget revision if necessary and a discussion of how well your experimental strategy is working and what has changed (and why). Please have your journal with you for your supervisor to see. <u>The remaining time in the lab should be spent working on your project</u>. The Thursday and Friday lab sections should schedule an alternative time earlier in the week or the beginning of week 10.

D. Release to Production. Due at your team's final presentation. Submit your final process recipes for both furnaces for release to production (this must be done in the *virtual* fab). The recipes can be different for the different furnaces.

E. Final Oral and Written Reports. Due at your team's final presentation. The written report should follow the format described for Course xxxs. Both written and oral reports should include you final process recipe, your estimate of achieved uniformity, your estimate of DCS utilization, the final experimental and engineering costs, and your assessment comparing the performance of the four reactors.

For the Oral Report, prepare a 10-minute PowerPoint presentation that includes:

1. Brief background and overview
2. Design and measurement strategy
3. Data analysis methods
4. Final Process operating parameters
5. Expected uniformity and utilization in production
6. Final Cost
7. Lessons learned

Appendix B: Bioreactor Project Assignment

Objective

Develop optimal bioreactor operating conditions (i.e., choice process parameters) for a bioreactor cultivation. Each team will select from two types of bioreactor applications: (1) production of a recombinant protein in yeast or (2) degradation of a waste mixture by a consortium of bacteria acclimated to the specific waste mixture.

- *Production of recombinant protein*. The optimal conditions will result in the highest specific profit ($/gram product) for the production of recombinant protein.
- *Degradation of waste*. The specific waste mixture includes a significant fraction of sodium benzoate. The optimal conditions will result in the lowest specific cost ($/g) for treating the waste. The costs include bioreactor operation and treatment and fines associated with waste residue in the reactor at completion.

Overview

Your team's task is to develop optimal operating conditions for production or degradation in a yeast or bacterial bioreactor, respectively. The cell growth, production and degradation process, and measurements will be made via computer simulation in our *virtual* bioreactor. You should develop operating conditions that maximize specific profit (*Production of recombinant protein)* or minimize specific cost *(degradation of waste)*.

The pilot-scale bioreactor has a working liquid volume of 5000 L. The bioreactor is fully instrumented with temperature, pH, and dissolved oxygen sensing and control (except for oxygen). Oxygen is delivered at a constant rate using vigorous mixing and sparged air. The reactor will be operated in batch and fed-batch mode. The initial medium volume is 2000 L. The optimum pH set-point has already been determined. It is your team's objective to determine the medium concentrations, batch and fed-batch times, fed-batch flow rate, inoculum concentration, and the temperature that results in the highest volumetric productivity. You will be able to set these parameters for your virtual experiments.

You will also have access to a v*irtual* spectrophotometer to measure the cell density (mg/L), a *virtual* western blot apparatus to measure the recombinant protein concentration, and *virtual* HPLC to measure the substrate concentration (glucose in the case of production and the waste mixture for degradation). You can specify at what times you want samples to be taken and these parameters measured.

You will be charged $2,000 for each run plus $200/hr of run time. This includes reactor set-up (cleaning, sterilization, calibration, etc.) and medium costs. Consider set-up and harvest times in the volumetric productivity determination. Set-up and harvest will add 5 hours to each bioreactor run. Each cell density measurement will cost $25 and each substrate, product, or byproduct concentration measurement will cost $75 (in *Virtual*$, of course).

Deliverables

Five deliverables are required to be produced by each team:

A. Design Strategy Memo. Due Lab Session Week 8. Develop a strategy to explore the parameter space. Your group's design strategy must be explained in a memo and discussed with your supervisor during lab. In your memo you are expected to have the first run and measurement set completely specified and explained. You should also provide a budget estimate for the project and a general strategy of where you might direct your efforts after the first run(s). After your design strategy is approved, you will be given an access code for the *Virtual Bioreactor*. The remaining time in the lab should be spent working on your project. You can work in the Gleeson computer lab, Kelley computer lab, or the Gleeson first floor study areas.

B. Experiment Journal. Due during meetings and with final report (Week 10). As you perform the virtual experiments, you need to keep track of the run parameters, summary of output, data analysis, and an explanation of what you will do next, i.e., what you infer from the analysis (similar to information you would track in "real" lab experiment). Pay special attention to any unexpected results and any changes you make in your overall experimental strategy. Your lab journal should be signed and dated by all group members after every session. You will be assessed on the completeness of your description and the soundness of your logic (so be clear!).

C. Intermediate Update Memo. Due Lab Session Weeks 9/10. Thursday and Friday labs will meet with your supervisor on Mon., Tues. or Wed. due to Thanksgiving Holidays. At the meeting, your group will give the instructor a written status update on your progress. You should include the best productivity that you have achieved, how much money you have spent with a budget revision if necessary and a discussion of how your experimental strategy has changed (and why). Please have your journal with you for your supervisor to see. The remaining time in the lab should be spent working on your project.

D. Release to Production. Due Lab Session Week 10. Submit your final process recipe prior to your presentation for release to production (this must be done in the *virtual* bioreactor interface).

E. Final Oral and Written Reports. Due Lab Session Week 10. The written report should follow the format described for Course xxx. Both written and oral reports should include your final process recipe, the optimized specific profit or cost, your expected variation, and the final experimental cost (cost for the study) compared to the budget.

For the Oral Report, prepare a 6–8 minute PowerPoint presentation that includes:

1. Brief background and overview
2. Design and measurement strategy
3. Data analysis methods
4. Final process operating parameters
5. Specific profit or cost
6. Expected variation in production or degradation
7. Final cost of the study
8. Lessons learned