AN ABSTRACT OF THE DISSERTATION OF

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The Virtual Chemical Vapor Deposition (CVD) Process Development Project provides the context for the two areas of the research presented in this dissertation. The first area, generally referred to as feedback in this dissertation, focuses on student learning and the interactions of students and instructors that take place in the project, specifically focused on characterizing feedback and determining the influence of feedback as student teams progress towards completing the project. The characteristics of feedback found in this project are presented within a situative perspective using the analytical framework of episodes. The characteristics include: a list and categorization of episode themes, the structure and flow of episodes during the coaching session, the sub-structure present within individual episodes, and the types of feedback present. This dissertation shows how these characteristics frame participation in a community of practice and can be used as tools to scaffold instructor feedback in project-based learning. Episodes analysis is also used to investigate how feedback on professional skills can help to enculturate students into a community of practice and influence their fluency with professional skills and engagement in more technical activities. The second area examines the spread of this innovative project from its home institution to

other institutions. In this area an analysis of the spread of the Virtual CVD Process Development Project in the high school setting is presented. The project was found to provide versatility for instructors and afford student learning in the areas of motivation, cognition, and epistemological beliefs.

These two areas inform each other. As the project is assessed at different institutions, it is continually improved and the sensitivity of different aspects of the project is explored, e.g., the aspects of the project that are crucial to maintain effectiveness are identified. One of these aspects is the feedback that takes place in the project. As the project is further examined at the home institution in depth, more can be learned about the best ways it can be delivered. This information informs scaffolding that then can be provided to faculty at other institutions such that they can attend to crucial aspects of the project in the most efficient, effective manner, improving not only the probability of successful adaptation, but also the likelihood that the project will further diffuse to other institutions.

Industrially-Situated Project-Based Learning: A Study of Feedback and Diffusion

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

Debra M. Gilbuena, Author

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Industrially-Situated Project-Based Learning: A Study of Feedback and Diffusion

1. General Introduction

The Virtual Chemical Vapor Deposition (CVD) Process Development Project provides the context for two areas of the research presented here. The first focuses on the learning of students during the student-faculty interactions that take place in the project. Specifically, this research focused on characterizing feedback and determining the influence of feedback as student teams progress towards completing the project. This area will generally be referred to as feedback in this dissertation. The second deals with the spread of this innovative project from its home institution to other institutions. This process has been described in a few different ways: scale-up, diffusion, and implementation, and in this thesis will generally be referred to as diffusion. These two areas inform each other. As the project is examined at the home institution in depth, information is gained about the best ways it can be delivered. This information informs scaffolding that then can be provided to faculty at other institutions such that they can attend to crucial aspects of the project in the most efficient, effective manner, improving not only the probability of successful adaptation, but also the likelihood that the project will further diffuse to other institutions. As the project is assessed at different institutions, it is continually improved and the sensitivity of different aspects of the project is explored, e.g., the aspects of the project that are crucial to maintain effectiveness are identified. One of these aspects is the crucial role that feedback plays in the project.

In the area of feedback, this dissertation includes two proposed journal articles (Chapter 2 and Chapter 3) and three conference papers (Chapter 6, Appendices A-C). The articles in Chapter 2 and Chapter 3 use a situative perspective and the framework of episodes to analyze the discourse in student-faculty interactions, including feedback, in this project. The article in Chapter 2 presents the characteristics of feedback in this project, and suggests that these characteristics can provide a useful tool for other project-based learning environments. The article in Chapter 3 uses episodes to investigate the feedback on professional skills, how that feedback influences students' use of professional skills and learning in the project. Appendix A presents the original introduction of the episodes framework, which was presented at the annual conference and exposition for the American Society for Engineering Education in 2011. Appendix B presents the use of episodes to investigate the structure of episodes in a coaching session and the interplay between student and coach objectives. Appendix B was presented at the Research in Engineering Education Symposium in 2011. Appendix C presents the use of episodes to investigate the influence of feedback on modeling, presented at the Frontiers in Education Conference in 2012. This work has also been presented at workshops and in various other settings.

In the area of diffusion, this dissertation includes one journal article (Chapter 4) and one conference paper (Chapter 6, Appendix D). Chapter 4 presents a detailed investigation of the implementation of this project in the high school setting. Appendix D presents a broad overview of the sources of project effectiveness and the implementation of this project in high schools, community colleges and universities.

2. Characteristics of Feedback in Project-Based Learning

Debra M. Gilbuena, Ben U. Sherrett, Edith S. Gummer, Audrey B. Champagne, Milo D. Koretsky

2.1 Abstract

Project-based learning has been described as beneficial for students because it focuses on learning by doing in the context of real-world problems. It has been to shown to increase student motivation and learning. Because of its advantages, project-based learning has been used to engage students in science and engineering at all levels of education. While this approach can be advantageous, it requires careful and intentional instructional design and implementation. We argue that providing students with feedback is critical for the implementation of project-based learning. Feedback is one of the most influential ways educators can help students close the gap from novice to expert. We use the framework of episodes, defined as thematic units of discourse with a central theme, a relatively clear beginning and end, and a substructure of four stages: surveying, probing, guiding and confirmation. We present four characteristics to help instructors scaffold feedback: a list and categorization of episode themes, the structure and flow of episodes during the coaching session, the stages sub-structure present within individual episodes, and the types of feedback present. We show how each of these characteristics provides a useful tool for analysis and to scaffold interaction in project-based learning.

2.2 Introduction

Project-based learning has been described as beneficial for students because of its focus on learning by doing in the context of real-world problems (Krajcik, McNeill, & Reiser, 2007). This pedagogical approach has been to shown to have advantages such as increased student motivation and learning (Blumenfeld et al., 1991; Bradford, 2005; Hill & Smith, 1998; *How People Learn: Brain, Mind, Experience, and School*, 2000). Because of its advantages, project-based learning has been used to engage students in science and engineering at all levels of education from K-12 (Sadler, Coyle, & Schwartz, 2000) to undergraduate capstone engineering design courses (Dutson, Todd, Magleby, & Sorensen, 1997; Dym, Agogino, Eris, Frey, & Leifer, 2005). While this approach can be advantageous for student learning, it is also typically complex and requires scaffolded instructional design and careful, intentional implementation to help students engage and become more expert-like. Blumenfeld et. al. (1991) discuss the critical role that teachers play in project-based learning in “shaping opportunities for learning, guiding students’ thinking, and helping them construct new understandings” (p.393). To be able to do these things, Blumenfled et. al. (1991) emphasize that teachers will likely “need help with content, with new instructional forms, and with implementation and management of projects” (p.393). We argue that providing students with feedback is a critical aspect of the implementation of project-based learning. Feedback is one of the most influential ways educators can help students close the gap from novice to expert. However, research about how educators can provide students with rich feedback in project-based learning is limited. In this paper, we discuss a set of characteristics of interactions that can be used as a tool to investigate and scaffold feedback in project-based learning.

This paper reports findings from a study of feedback in the Virtual Chemical Vapor Deposition (CVD) Process Development Project. This industrially-situated project requires student teams to optimize an industrial process within economic constraints. It has been shown to engage student teams in iterative experimental design, data analysis and interpretation, and redesign(M. D. Koretsky, Amatore, Barnes, & Kimura, 2008). As part of this project, teams of students have opportunities to receive feedback during two structured meetings, referred to as coaching sessions, with a faculty member who acts as their supervisor and mentor, referred to as the coach. We take a situative perspective to examine the characteristics of the student-coach interaction in the first coaching session with a particular focus on the feedback given to student teams. We also investigate how this feedback helps students progress in the project and participate in a community of practice. We argue that the characteristics of feedback presented provide a potential scaffolding tool for instructors to give feedback in these types of project-based learning environments. We also discuss the potential applicability of our findings to other types of student-instructor interactions.

Specifically, we ask the following research questions:

1. What are the characteristics of feedback present in student-coach interactions?
2. How do these characteristics vary between teams and why?

3. How do these characteristics scaffold participation in a community of practice and facilitate negotiation of a joint enterprise?

2.3 Background and Theoretical Framework

We use situative learning as a framework with which to describe a model for scaffolding feedback in the student-instructor interactions of project-based learning environments. In this section we first introduce what we mean by situative learning, with specific attention to the how situated learning informs interactions. Within the interactions, our interest is feedback, so we next we provide a background of literature on feedback, with particular attention to different types of feedback we have used in our investigation. Finally, we provide a background on how our analysis of the discourse can be used to characterize student-instructor discourse and show how the combination of themes, types of feedback and structure in this study provide a tool that is useful for project-based learning.

2.3.1 Situative Learning

Situative learning provides a useful perspective with which to consider the interactions in project-based learning environments, especially to focus on the contextual aspects of discourse which help students become effective participants in the practices of science and engineering. This perspective has been described by many names, including situated cognition (Brown, Collins, & Duguid, 1989; Greeno, 1989), distributed cognition (Hutchins, 1995), and situated learning (Lave & Wenger, 1991). As eloquently stated by Nolen et al. (2012), “these frameworks share a focus on how activity changes over time through participation of members of some social group and how individual change is best understood in relation to this activity" (p. 6). In our case we are interested in how students' engagement changes over time as they participate in engineering activities and how that change relates particularly to the interactions students have with faculty. Similar to Sawyer and Greeno (2009), we adopt the term situative learning because we believe that all learning is situated in some context, i.e., there is no such thing as non-situated learning. We agree with Hutchins (1995) that knowledge can be acquired and can change within individuals. However, in this paper we employ a situative perspective similar to that of Lave and Wenger (1991) to shift our focus from the internal, cognitive mental structures of students to discuss how characteristics of interactions can facilitate students' participation in a community of practice. Lave and Wenger (1991) define a community of practice as "a set of relations among persons, activity, and world, over time and in relation with other tangential and overlapping communities of practice" (p. 98). Specifically, they describe three dimensions of communities of practice: mutual engagement by participants, a joint enterprise or goal with some form of mutual accountability, and a shared repertoire such as discourse, tools, concepts, and ways of doing things. We use the concept of communities of practice in a somewhat broad sense. This perspective affords the examination of the student-faculty interactions and how they contribute to students' engagement with the shared repertoire of a community of practice.

For example, in our study we consider three simultaneous communities of practice: first, the community of chemical engineering, which is disciplined-based; second, the semiconductor industry community which is industry specific; and third, the student community. While each of these communities can be defined separately, they may also overlap, e.g., chemical engineers can work in and participate in the semiconductor industry. The shared repertoire of a community is specific to each community. Discourse, a term used to describe written and verbal use of language in our study, is one of the aspects included in a community's shared repertoire. In this paper, we refer to discourse of chemical engineering (the discipline of our participants) as *disciplinary discourse* and discourse specific to the semiconductor industry (the specific industrial context for our engineering project) as *industry-specific discourse*.

Lave and Wenger (1991) refer to novices as legitimate peripheral participants, who engage in community activity at the periphery of the community initially. As novices engage in community activities over time, and become more familiar with the community, its social structure, power relations, and conditions for legitimacy, they may progress to be considered full participants. Dannels (2000) describes part of this progression as "socializing students into professional identities."

Wenger (1999) highlights that communities of practice produce "abstractions, tools, symbols, stories, terms, and concepts that reify something of that practice in a congealed form," (p. 59) i.e., communities translate an abstraction of practice to the status of object. Reification is complimentary to participation (Wenger, 1999) and describes both the process of reifying, as well as the product, the fixed form "given the status of object" (p. 59). In our project, students bring to the coaching session a reification representing their initial strategy in the form of a memorandum. Another example of a reification present in both the chemical engineering community and the student community is a “material balance.” This phrase represents a core chemical engineering concept, and associated procedures, derived from the conservation of mass. While the concept of “material balance” is an abstraction, when chemical engineers and chemical engineering students discuss a “material balance,” it is an objectified tool.

Nolen et al. (2012) used a situative perspective to examine engagement in project-based learning within a government and politics course. Like Nolen et al. (2012), we use the concept of “joint enterprise” to examine negotiations of a team’s goal. Also similar, in our case, each team’s joint enterprise is initially defined by the overall project objectives, which we describe as Student Project Objectives. We focus on the negotiation of teams’ joint enterprises which occurs between the coach and students during the design coaching session. While the project objectives provide an initial anchor for a team’s joint enterprise, each team can approach the project by implementing different community tools and taking a different overall approach. In fact, no two teams in the history of the project (more than 50 teams) have taken the same path or negotiated their joint enterprise in the same way.

2.3.2 Feedback

Providing students with feedback is likely one of the most effective ways instructors can help students as they move towards more central participation and develop fluency with the shared repertoire of a community. Hattie and Timperley (2007) broadly define feedback as “information provided by an agent (e.g., teacher, peer, book, parent, self, experience) regarding aspects of one’s performance or understanding” (p. 81). Based on an assessment of hundreds of meta-analyses from 180,000 studies, Hattie (1999) concluded that “the most powerful single moderator that enhances achievement is feedback” (p. 13). While feedback has been shown to strongly influence student performance and learning, explicit research on feedback in project-based learning is sparse, especially in complex, situated projects.

In general, there is limited agreement on what characterizes “effective” feedback, especially in ill-structured, open-ended projects. Hattie and Timperley (2007) suggest that feedback is more effective when the feedback is related to the achievement of and progress towards specific goals and that less complex feedback may be more effective than more complex feedback. They also suggest that feedback focused on the individual rather than the project and goal is not effective. Elaborated feedback, feedback in which an explanation is provided rather than a simple “right” or “wrong,” may be more effective than a simple mark or grade. Shute (2008) contributed a literature review on formative feedback which supports these suggestions and provides tabulated lists of “things to do,” “things to avoid,” timing related issues, and learner characteristics to consider when providing feedback. Feedback has previously been grouped as either affirmative feedback or corrective feedback (Hewson & Little, 1998; Klausmeier, 1992). Affirmative feedback acknowledges a correct response and may include praise. Corrective feedback has been described by Black and Wiliam (1998) to have two main functions: (1) to direct, and (2) to facilitate. They describe directive feedback as telling the recipient what must be corrected whereas they describe facilitative feedback as providing suggestions to guide the recipient toward his/her own revisions. In some cases, discussion includes neither corrective nor affirmative feedback; these cases can be considered as “neutral” discussion.

In this study, we classify episodes of discourse using one of these four types: affirmative, directive, facilitative, and neutral. We then extend our group's use of the episodes framework (Gilbuena, Sherrett, Gummer, & Koretsky, 2011; Gilbuena, Sherrett, & Koretsky, 2011) to analyze the discourse, described in the methods section of this paper, to investigate the characteristics of feedback. We will illustrate how these characteristics support student participation by scaffolding feedback on students’ joint enterprise, and on the tools and practices of the disciplinary and industrial communities in which this project is situated.

In this paper we use a situative perspective to examine how the characteristics of feedback interactions between a coach and student teams in project meetings are likely to facilitate students’ legitimate peripheral participation in three communities of practice: the chemical engineering community, the semiconductor industry community in which the project is situated, and the student community. We also posit that the characteristics presented in this paper are likely applicable to other project-based learning environments.

To explore the intricacies of the interaction and the feedback process in-depth, we apply a case study methodology (Case & Light, 2011). We combine the case study methodology with analysis of the discourse, which allows us to identify and follow themes in discourse and chunk those sections of discourse with coherent themes into episodes. We can see a structure of how these episodes are organized within the coaching session. In addition, each episode has a sub-structure. Both of these structural components scaffold the discourse. Acknowledging that different types of feedback will likely result in different types of skill development activities, we also describe the types of feedback and how they relate to the other aspects of the interaction, i.e., the themes and structure.

2.4 Research Design

This study is a subset of a larger ethnographic study of student learning in industrially-situated virtual process development projects. The methodology for this paper is comprised of a case study of four student teams and a single coach. Analysis of the discourse using episodes was used as a way to examine coaching session transcripts for details of the interactions that are likely to facilitate students' legitimate peripheral participation. The data collection includes field notes and audio recordings of teams throughout the project anytime two or more members of a team met. While we focus on the transcripts of meetings in which student teams interacted with a coach, the fine grain data also allows the researchers to study the teams in detail throughout the entire project. The case study affords an in-depth exploration of the elements and the structure of the coach-student interactions in this project, providing information about how and why feedback is tailored to individual teams. We also illustrate the aspects of the feedback process that appear to be common, at least between the teams investigated. Student work products and post-project interviews were also considered.

2.4.1 Setting & Instructional Design

This paper concentrates on work at a research and degree granting public university located in the Northwest U.S. The Virtual Chemical Vapor Deposition (CVD) Process Development Project embodies a project-based learning pedagogy, consistent with Thomas' (2000) five criteria that a project must meet to embody project-based learning. According to Thomas, in order to be considered project-based learning, a project must: be central to the curriculum; be focused on a questions or set of questions that "drive" students to encounter central concepts and principles of a discipline; involve students in a constructive investigation; be significantly student-driven; and, be realistic. These types of projects can help students become more familiar with the shared repertoire of a disciplinary community because they are intended to "drive" students to engage with aspects of that shared repertoire (e.g., concepts, principles, tools, discourse).

It was the second of three projects in a capstone laboratory course, typically taken by students in their final year of an undergraduate chemical, biological or environmental engineering program; the other two projects were more traditional physical laboratory projects. Students were organized into teams of three and maintained their team composition throughout the course.

The Virtual CVD Process Development Project provides opportunities for student teams to develop and refine solutions to an engineering project through experimentation, analysis, and iteration. For this project, students were placed in the role of semiconductor process engineers. Student teams were tasked with the objective of optimizing an industrially-sized virtual CVD reactor, which deposits thin films on polished silicon wafers. Performance metrics include high film uniformity at the target thickness, high utilization of an expensive and hazardous reactant, and minimization of development and manufacturing costs. If one performance metric alone is optimized, it is generally at the cost of another. To achieve their objective, teams must find suitable reactor input parameter values (temperatures along the reactor, flow rates for two reactants, pressure, and reaction time). Their final "recipe," one of the final deliverables, consists of a set of values for these input parameters that yields the best results with respect to the performance metrics. This project offers students an opportunity to integrate learning from their prior coursework towards the completion of an engineering project, a perspective explicitly taken by the coach.

One limitation of this study is that students interacted with virtual equipment rather than physical equipment. While this aspect of the context can influence the ways students participate, the developers of the project have begun to investigate student perceptions of the project, finding that students generally perceive it to be comparable to industrial projects in which they expect to participate in the future (Gilbuena, Sherrett, & Koretsky, 2011). From a cognitive apprenticeship perspective, the developers have also found evidence to suggest that "cognitive partnerships are formed between students and the virtual laboratory" (p. 567) (M. Koretsky, Kelly, & Gummer, 2011).

A typical student team devotes 15 - 25 hours to this three-week project. Key project milestones and corresponding activities involving feedback interactions are summarized in Table 2.1. The feedback analyzed in this paper occurred during two 20-30 minute coaching sessions, shaded in blue in Table 1, between the student teams and the coach. During the coaching sessions the coach acts as a mentor or boss would in industry. In the design coaching session, student teams deliver a memorandum that includes information about the team's project plan, including values for their first run variables, a strategy for subsequent runs and experimental data evaluation, and an entire project budget (in virtual dollars). In the update coaching session students deliver a second memorandum, with an update on their progress.

Table 2.1. The timeline of the Virtual CVD Process Development Project and Opportunities for Feedback.

Timeline	Key Project Information, Artifacts, Activities & Milestones	Student-Coach Interactions & Opportunities for Feedback
Project Begins	• Project context is framed • Project goals and performance metrics are introduced • Issued laboratory notebook	The coach delivers an introductory presentation on the industrial context, engineering science background, the Virtual CVD Reactor software, and project objectives and deliverables. Feedback is limited to in-class interaction.
~End of Week 1	• Design coaching session ○ Memorandum with values for initial experiment, experimental strategy, and budget	During a 20-minute coaching session, feedback occurs as the coach and student teams interact, using the memorandum as an anchoring artifact for information exchange and discussion. If initial experimental values, strategy, and budget are acceptable, student teams are granted access the Virtual CVD Reactor software.
~End of Week 2	• Update coaching session ○ Memorandum with progress to date	Feedback occurs in this second 20-minute meeting in which coach and student teams interact, again using the memorandum as an anchoring artifact for information exchange and discussion. Discussion focuses on progress to date, issues, and path forward.
~End of Week 3	• Final recommendation for high volume manufacturing • Final written report • Final oral presentation • Laboratory notebook	Teams give a 10-15 min oral presentation to the coach, other instructors, and other students. Teams then entertain a 10-15 minute questions and answer session that affords additional interaction and feedback. Final project feedback consists of grades and written comments on final deliverables.

2.4.2 Participants

The twelve undergraduate student participants came from two cohorts of approximately 80 students each. Two teams were selected to participate in this study from each cohort. The process for choosing teams to participate addressed several factors, the most fundamental of which was simply schedule; teams were only chosen if a researcher was available during the team's laboratory section and projected work times. The perceived willingness of a team to participate was also a contributing factor to team selection. This included perceived willingness for both informing the researcher of all team meetings as well as verbalizing thoughts during meetings. A team's perceived willingness was a major criterion for selection because of the limited window of data collection associated with the project. It should be noted that students' academic performance (e.g. GPA, class standing, test scores) was not a contributing factor to team selection. Three of the teams were mixed-gender teams and the fourth team consisted of all female students. A total of eight female students and four male students participated in this study. The gender distribution in the participants for this study is not typical of engineering students as a population, which is a limitation of this study. However, we focus our qualitative efforts to afford a deeper understanding of professional skills in one capstone engineering project and provide a basis for future exploration. More than half of the students had previous experience in engineering internships or laboratory research positions.

One coach provided feedback to all student teams. This coach has coached over 60 teams in the same capstone course over several years and has many years of thin films processing experience. The coach has also published research papers and developed courses on the subject. In addition, the coach has published research papers in engineering education and devotes significant effort to providing students with an engaging, carefully scaffolded, industrially situated learning environment.

2.4.3 Data Sources & Collection

Data sources include transcripts of audio recordings of student teams, researcher field notes, student work products, Virtual CVD Reactor database logs, and post-project, semi-structured student interviews. Throughout the entire project, every time two or more members of a participating team met, a researcher met with and audio recorded the team. Those audio recordings were transcribed for the four student teams (labeled Team A, Team B, Team C, and Team D). In addition to audio recording, the researcher took field notes, which generally include comments about what activities individual team members were engaged in (e.g., team member 1 was searching the internet for sources while team member 2 constructed an excel spreadsheet), information not otherwise captured on audio (e.g., website addresses), and notes of particular interest to the researcher.

Student work products include the following items: laboratory notebooks in which students were instructed to detail their thoughts, calculations, and work throughout the project; all memoranda; final reports; final presentations; and electronic files, such as spreadsheets in which students developed mathematical models. Work products that served as deliverables in the project were photocopied at the end of the project. Students were asked to carbon copy the researcher on email correspondence and to email the researcher copies of work products that were not deliverables, but were used by students as they progressed in the project. Virtual CVD reactor logs were recorded as students interacted with the virtual equipment; every time a team ran an experiment, the time of the experiment and variable values associated with that experiment were recorded in a database.

Finally, a graduate student researcher conducted semi-structured interviews with six of the twelve participants individually up to 6 months after project completion. In some cases, two graduate student researchers were present during interviews. The purpose of the interviews was to get the students' reflective perception of the project and aspects of the project. Participants were explicitly encouraged to provide comments and criticism of the project. A variety of questions were asked during the interview ranging in open-endedness. The initial question set included questions regarding perceptions of the overall project, what students remembered about the project, students' objectives for the project, the strategy used to complete the project, what students expected from the meetings with the coach, how the interaction with the coach influenced their progress on the project, team dynamics, and ideas for project improvement. Interviews were audio recorded and transcribed.

2.4.4 Data Analysis

This study uses the episodes framework to examine the feedback that occurred in the coaching sessions of the industrially-situated project. Episodes have been used as a framework for analyze discourse in other educational settings (Linell & Korolija, 1997; Roschelle & Teasley, 1994; Schoenfeld, 1983; van Dijk, 1982; Wells, 1993).

However, the term “episodes” is relatively vague; it has been used to describe entire situations, such as an entire class period, as well as smaller subsets of discourse. T. A. van Dijk (1982) presented a broad description of episodes as follows:

> “…an episode is first of all conceived of as a part of a whole, having a beginning and an end, and hence defined in temporal terms. Next, both the part and the whole mostly involve sequences of events or actions. And finally, the episode should somehow be 'unified' and have some relative independence: we can identify it and distinguish it from other episodes” (p. 179).

Adapted from van Dijk’s (1982) definition, we define episodes as thematic units of discourse within the meeting setting that have a central theme and a relatively clear beginning and end.

In addition, as analysis was performed, a substructure of episodes was found that included up to four stages: surveying, probing, guiding and confirmation. This emergent substructure was then incorporated into methods. Figure 2.1 illustrates a simplified version of the episode substructure. In the *Surveying* stage, the coach surveys by reading the memo and asking broad questions or simply letting students describe their initial strategy for the project in an attempt to identify students’ current level of participation in the community and fluency with community practices and discourse. During this time, the coach attempts to identify potential issues, i.e., areas in which students appear novice-like in their practices. Identification of a potential issues leads to the *Probing* stage where the coach asks probing questions regarding the potential issue in order to assess if it is indeed a problem. If the coach assesses that an issue is present, the *Guiding* stage begins and the coach attempts to guide the students toward a more expert-like participation. Finally, in the *Confirmation* stage confirming linguistic markers, such as “okay” (often by both coach and students) conclude the episode and then a new episode begins. Table 2.2 presents a detailed description of each stage and an example episode coded by stage. In addition, also similar to stanzas, smaller episodes can be embedded within larger episodes, i.e., one themed discussion can take place in the context of a larger themed discussion.

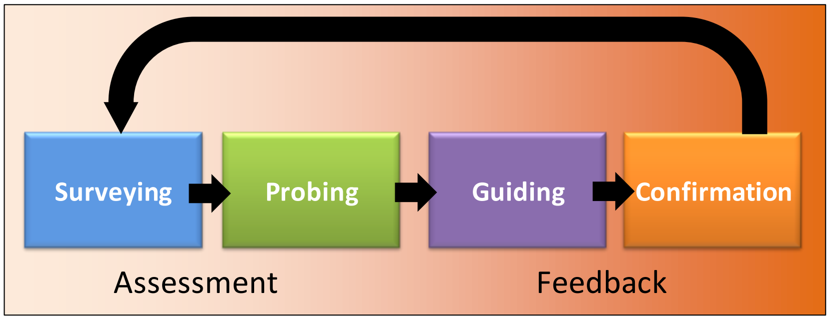

Figure 2.1. Episode structure with more assessment present in surveying and probing and more feedback in guiding and confirmation components. The process is iterative and all components are not required for each coaching session.

Table 2.2. Descriptions of each of the four parts of episodes. C denotes the coach and S1, S2, and S3 are students.

Episode Stage	Description	Example episode on “intra-group validation” and “situate”
Surveying	This stage consists of the instructor becoming familiar with the team and their approach. It also includes the instructor trying to identify potential areas for further discussion and probing, areas in which students a lack of fluency in the community tools and practices the coach is trying to emphasize. Surveying is based in part and loosely on an unwritten “check-list” of common issues from past years. This list will be discussed in more detail in the results.	C: [upon conclusion of mass balance episode] And are you confident of these numbers? S1: Barely S 2: That’s just the minimum to get the deposition so that would require 100% utilization on only the wafers. So that doesn’t include the reactors.
Probing	In this stage the instructor probes the students by asking directed questions on specific concepts to further identify the level of the students’ fluency in disciplinary tools and practices and the students’ understanding of how those tools and practices fit within this project.	C: So, S1, you’re confident…So does that mean that you did the calculations? S 1: Yes. C: I see. Did you do the calculations (to S2)? S 2: No. C: And S3? S 3: I didn’t work it out by hand.
Guiding	The guiding stage occurs after the instructor has identified issue. This stage generally consists of the instructor guiding students either to make them aware of aspects that had not attended to or to guide students toward an increased fluency with tools and practices of the community. Most of the time guiding occurs through a series of dialogue with the instructor asking leading questions in order to help students discover or recall a more complete expert-like engagement with tools and practices of the community. While facilitative guiding is often preferred, directive feedback may also be given.	C: All right, so this is something where on your homework, or even more so, if you get a method right you get most of the credit, right? S1,2,3: Yes C: On this thing, if you get a method right, do you get most of the credit. No. S1 is generally very accurate. But what else do you think you can do?
Confirmation	During this stage, consensus or acknowledgement of understanding occurs between instructor and students. In some cases, a conclusion is stated by the team and verified by the instructor. In other cases the instructor confirms the student statement followed by a justification or explanation. Confirmation can also merely consist of short statements, such as “okay.” This stage signifies the end of an episode, after which a new topic is brought up and the cycle repeats with another episode.	S 2: Have everybody check and do it also. C: Yeah, you could have independent checks on that. I mean, you don’t want to spend several thousands of dollars to learn that…Oh, I forgot to carry the zero. I’m not saying it’s right or wrong, that’s just more of a team strategy.

The coaching session transcripts were initially characterized by parsing the discourse into a series of episodes. Independent analysis was performed by two researchers. The first author was one of the two researchers for all transcripts. In most cases the researchers agreed on the parsing, and in cases with discrepancies the researchers discussed the episodes until they reached agreement. The episode stages were also coded. Most coaching sessions began with an introduction episode that primarily included some form of greeting and pleasantries. Introductory episodes were not analyzed in this study. For the remainder of episodes, themes initially emerged through careful reading of the transcripts by multiple researchers. Theme names were identified using participant words from the transcripts and in some cases modified to more general terms that represented similar themes across teams and were consistent with terms in literature. After an initial list of themes was developed, it was revised as additional transcripts were analyzed. Episodes analysis was performed on transcripts of the design coaching session for all teams.

Episodes were classified by the types of feedback found in literature: neutral, affirmative, or corrective, with corrective episodes designated as either directive or facilitative. Episodes were coded as neutral if there was no affirmative or corrective feedback; episodes that had no guiding and simply ended in “ok” were designated as neutral. Episodes were coded as affirmative if the coach said an affirmative statement like “that’s reasonable” or “great” and provided no corrective feedback. Episodes were designated as directive if the coach explicitly requested action and facilitative if guiding took place without an explicit request for action.

2.5 Results & Discussion

In this section, we discuss four characteristics of interaction in the design coaching session of this project: a list and categorization of episode themes, the structure and flow of episodes during the coaching session, the sub-structure present within individual episodes, and the types of feedback present. First, we present a categorization of episode themes found in the coaching sessions for all teams, with a summary of the proportions of episode themes in each category. This summary of multiple teams illustrates the similarities and differences between teams and provides a broader context for the remaining in-depth examination. We compare the teams' structure of themes within the coaching sessions and describe how the different categories are intertwined and how the negotiation of each team's joint enterprise plays out in this structure. The examination of the structure of themes begins to illuminate why differences exist between teams and illustrates how the structure is flexible enough to support those differences. Next, we describe in-depth one episode theme that was the same for all teams but varied greatly in the specific discourse contained within the episode. We use this example to discuss the sub-structure, termed episode stages, contained within an individual episode. Through a discussion of the reification a team brings to the meeting and participation in the discussion, episode stages further illustrates why differences exist between teams, even for the same theme. In addition, we discuss how the episode stages may provide a tool that instructors can use to structure interaction to identify students' current level of participation and, if needed, help students progress towards more central participation with respect to a particular activity. Finally, we discuss the different types of feedback, possible reasons for the use of different types, and in what proportions these types are found in the coaching sessions.

2.5.1 A Summary of Episode Themes

Episodes analysis identified 129 episodes and we compiled a list of episode themes from the design coaching sessions of the four teams. We parsed the list into three general categories, as described in Table 2.3. Some themes were found to be focused on the input parameters of the reactor and the stated project objectives; we grouped these themes into the category of Student Project Objectives. Some themes were more focused on objectives of the coach to help students learn and participate in community activities; these themes were grouped into a category of Coach Objectives. The coach objectives category has subcategories that attend to a) the technical concepts, content, procedures and strategies as well as b) professional skills. A third category, called Project Contextualization, groups themes that focus explicitly on situating the project in the industrial context, discussing physical equipment characteristics, or comparing this project to the schoolwork students are more familiar with completing. While all of the discourse contributes to contextualization of the project, the Project Contextualization category includes episodes that explicitly reference the context. Three episodes total did not fall into these categories and were excluded.

While we place episode themes into different categories, the episodes in one category were not isolated from the discussion in other categories. Episodes are often nested (i.e., one episode may be contained within a larger episode) and feedback on different categories is intertwined. For example, an episode about communication might be nested within a larger episode about the need to apply particular procedures; the communication episode might highlight the need for using appropriate discourse while communicating the results of such an activity.

Table 2.3 Summary and description of themes in design coaching sessions.

Major Theme Category	Subcategories, Themes and Descriptions
Student Project Objectives	• *Input Parameters* – Determination of values for the parameters students are required to specify when performing experiments, including discussions about temperatures (five zones), flow rates (two reactants), time, pressure, and measurement strategy • *Performance Metrics* – The explicitly stated project objectives including thin film uniformity, budget, reactant utilization
Coach Objectives	• *Core Technical Content, Procedures, Concepts, & Strategies* o *Experimental Design & Strategy* – High level discussion about the students current experimental approach and strategy o *Context of Models* –Explicit discussion about the development, usage, and context of models (both quantitative and qualitative) in this project o *Kinetics* – Discussion about reaction kinetics often including concentration, activation energy, reaction rate and film growth rate o *Transport* –Primarily related to diffusion of reactants between wafers o *Material Balance* – Contained within discussions of the usefulness of material balance in this project are often episodes relating to particular parameters needed to calculate a material balance, specifically, density o *Significant Figures* – Rounding input parameter values with appropriate precision and considering the implications and practicality of rounding values • *Professional Skills* o *Communication* – Both written and verbal forms of communication, episodes with this theme not only include discussion about how to convey technical information, but also include discussion about the purpose for using particular words and presenting different types of information. For example, episodes with this theme may include feedback on the purpose of a memo, memo formatting, information literacy (e.g., citing sources as a way to justify chosen parameters and convey credibility), the use of disciplinary and industry-specific discourse, etc. o *Teamwork* –Team strategies and team dynamics o *Project Management* – Scheduling meetings and planning work schedules to meet project milestones o *Impact of Engineering Solutions on the Economic and Societal Context* – Relating the implications of students' engineering decisions for the company within the economic market as well as implications of students' engineering decisions for society o *Written Documentation* – Primarily related to documenting project work in the team-issued laboratory notebook in order to have a record of work for future use o *Self-Regulation* – Discussion which generally includes feedback promoting metacognitive skills, self-monitoring, and self-evaluation both on the individual and team level
Project Contextualization	• *Connecting to the Industrial Context* – Reinforcing the industrial context of the project, episodes with this theme are generally small and found nested within other episodes. For example an episode connecting to the industrial context might reference how an equipment operator would respond to the students' proposed strategy or parameter values. • *Instructional Design* – Focus on the instructional design of the project, often contrasting how students this project compared to the way they approach typical homework. • *Physical Reactor Characteristics* – Clarification of the reactor characteristics including the distribution of wafers in zones of the reactor, the spacing between wafers, and the overall reactor design

Teams had a range of 29 to 37 total episodes with an average of 32 in the design coaching session. Figure 2.2 shows the number of episodes for each team in each of the major categories, with the two primary Coach Objectives subcategories also shown. Approximately 31% were coded as Student Project Objectives, 38% as the Coach Objectives of Professional Skills, 30% as the Coach Objectives of Core Technical Content, Concepts, and Strategies, and 9% as Project Contextualization. Episodes themed as the Student Project Objectives subcategory of Input Parameters provided the context for approximately 30-40% of the total coaching session episodes. In some cases, episodes were coded with multiple themes; therefore the total number of episodes for each team shown in Figure 2 is slightly larger than the actual total number of episodes present in the design coaching session.

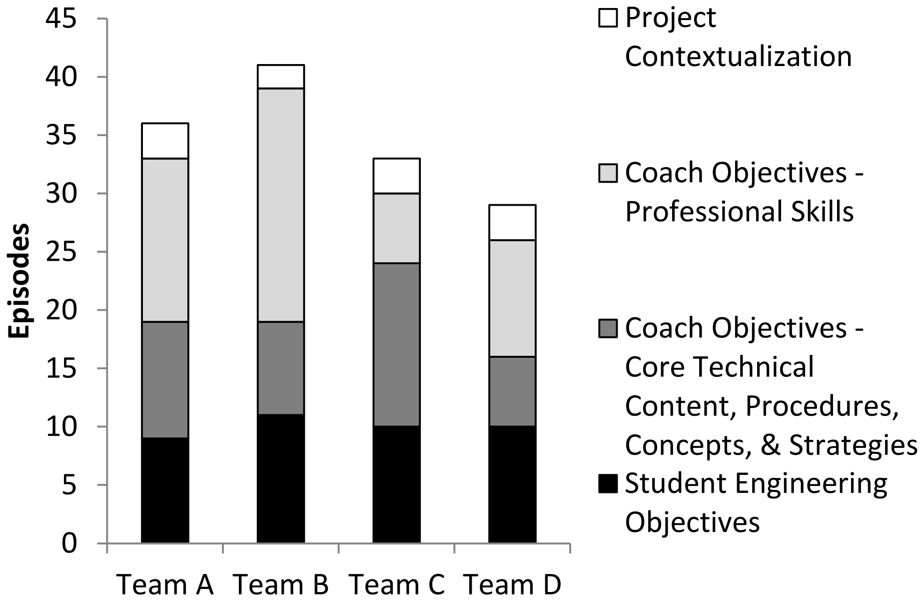

Figure 2.2 Number of episodes for each team in each of the major categories and the two Coach Objectives subcategories

Some episode themes were found to be present in most design coaching sessions, while other episode themes were only present for a subset of the teams. In addition, no two design coaching sessions contained exactly the same set of themes; each coaching session was unique and carefully tailored to each team's particular strategy.

A list and categorization of interaction themes provides a useful tool for instructors to consider when giving feedback. This particular categorization of themes provides a useful tool for the instructor in the project discussed in this paper. By compiling a list and explicitly considering which aspects of the feedback pertain to the stated Student Project Objectives and the coach's objectives for the meeting, the instructor can assess whether s/he is giving feedback on the aspects of the project that s/he deems as most important. For other instructors considering adopting the project discussed in this paper, the list of common themes described here provides an initial list of themes for them to consider when providing students with feedback. Finally, for instructors in other project-based learning environments, we suggest that clearly identifying the important themes in the project within the construct of the major categories described above (Student Objectives, coach objectives, project contextualization) provides a basis for exploring how to give students feedback on each of these themes, and which themes are more or less important for students to progress in a community of practice.

2.5.2 A Structure of Feedback: Negotiating a Joint Enterprise through the Flow and Embedding of Episodes

When we look at the structure of the entire design coaching session, we can begin to see, in more detail, how teams are similar and how they differ. One commonality is that the Input Parameters subcategory in Student Project Objectives or the Coach Objective of Experimental Design and Strategy often provided the larger context, within which other themes were embedded and discussed. We can see this embedding of episodes in the overall flow of episodes for Team A shown in Figure 2.3. The 20-minute coaching session for this team consisted of approximately 2,200 words. In Figure 2.3, the horizontal length of each box represents each episode, scaled according to the word count. Student Project Objectives are denoted with the white boxes, Coach Objectives are denoted with the boxes containing a grid pattern, and Project Contextualization episodes are denoted with shaded boxes. The flow of discourse is represented from left to right, and top to bottom. In Figure 2.3, we have illustrated how episodes are embedded within the context of larger episodes by embedding boxes, such as the “Sources” box within the larger context of discourse, in this example the “Input Parameters” box (shown in the top “row” of episodes in Figure 2.3).

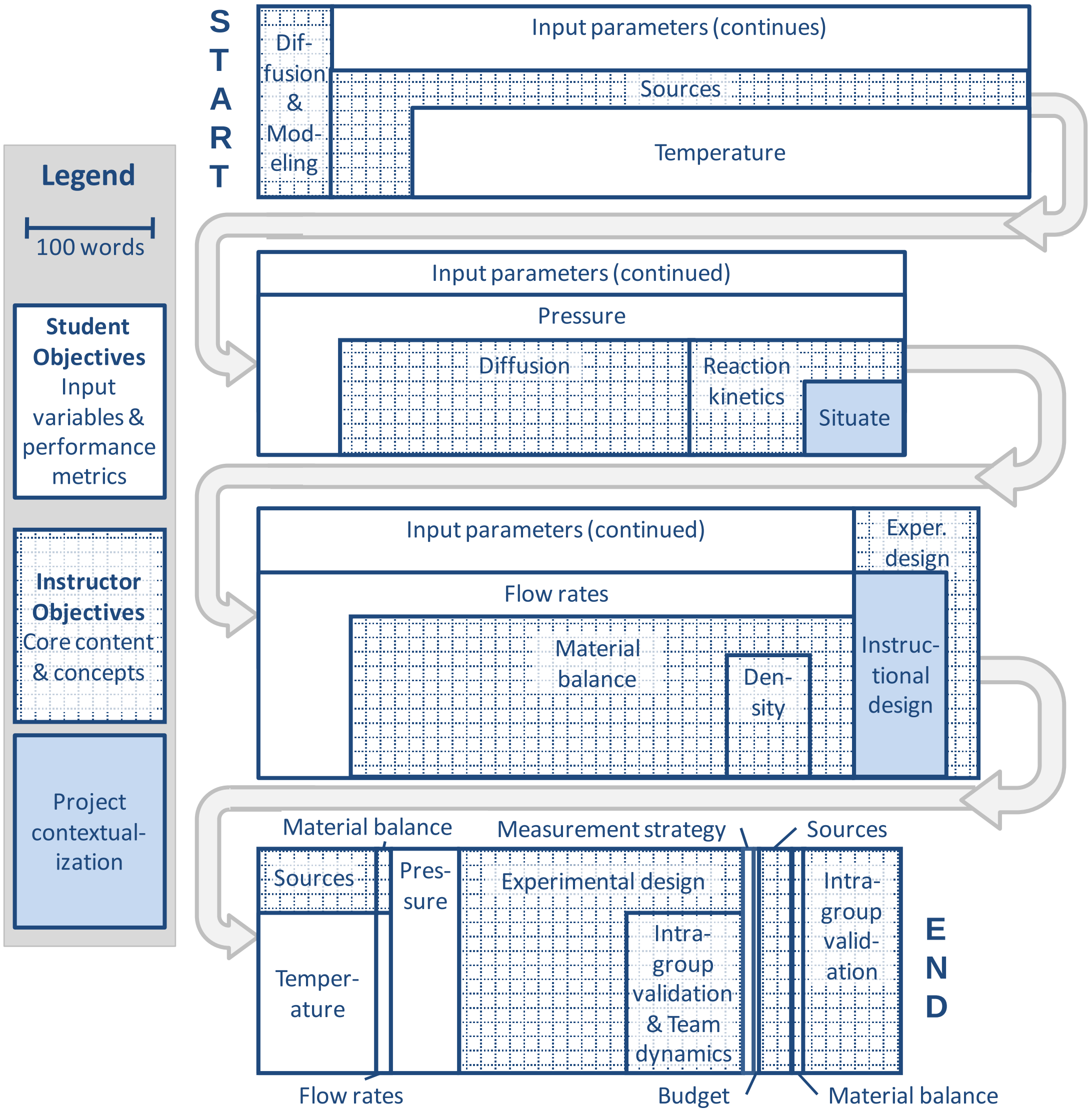

Figure 2.3 Chronological representation of structure and flow of episodes in a Team A's design coaching session.

In the following description, we first describe a portion of the meeting, and then reflect on that portion of the meeting in terms of the structure of episodes and joint enterprise negotiation between the teams and coach. We use this description/reflection technique to describe the coaching session for Team A.

The coach generally begins a design coaching session by reading over the team's memorandum and asking broad questions about the team's strategy or about how the team determined their initial experimental parameters. In the first episode for Team A the coach asked a general question about the team's strategy and the team responded with details about their intent to use mathematical modeling. This episode ended and the coach asked another broad question about how the team had determined their initial input parameters, the parameters the team needed to specify for their initial experiment prior to gaining access to the experimental equipment.

The broad questions about the Student Project Objectives were likely the coach's way of attempting to connect to the team's joint enterprise. In addition, the memorandum the team brought to the coaching session presented a reification of their initial approach. This reification provided some indication of the team's prior participation in the activities of the chemical engineering and disciplinary community and contains information about their joint enterprise. Because the team's joint enterprise is expected to be anchored in the objectives specified for the project, this is one aspect of every team's joint enterprise that is likely to be the same. By asking broad questions about the Student Project Objectives, the coach gathered information about the particular approach for each team and was able to learn more about the team's joint enterprise beyond the stated project objectives. As the coach gathered more information about the team's joint enterprise, the coach, a more central member in both the disciplinary and industrial communities of practice, offered feedback to help the students transfer tools and practices they learned as part of the student community to this project and become more fluent with community tools and practices that are appropriate for their specific joint enterprise. This negotiation of joint enterprise can be seen as we walk through more of the coaching session.

In the second “row” of episodes in Figure 2.3, the coach asks the students specifically how they determined their value for pressure, one of the input parameters. In determining a pressure value, the students had focused on the concept of diffusion. The coach guided the students towards considering an alternate concept, reaction kinetics. This discussion of reaction kinetics was punctuated by a short episode connecting reaction kinetics (and implicitly pressure) to the consequences of having a slow reaction for the company in the economic market. A similar pattern, with different specific episode themes can be seen in the third “row.”

In this part of the coaching session both “diffusion” and “reaction kinetics” are reifications in the chemical engineering community (and the particular student community in which the students reside). The first relates to a concept and way of understanding the movement of molecules, while the second relates to how fast chemicals react in a system. The coach, being a more central member of the chemical engineering community and having many years of experience with coaching teams in this project, probably recognized that reaction kinetics might serve as a more productive way for the team to consider the input parameter of pressure. The coach’s moves in the negotiation pushed for the inclusion of reaction kinetics in the team’s joint enterprise. In addition to attending to the chemical engineering community, the coach connected the concept of reaction kinetics to the industrial community, which may have been an attempt to both engage students because of the “real” connection as well as reinforce the importance of reaction kinetics as a community tool. In the latter way, this move serves to reinforce the coach’s position in the negotiation.

Within this negotiation, we can see the structure of the flow of episodes and how they are intertwined, which was found to be common across teams. Student Project Objectives were often found to provide the context for the Coach Objectives. The Project Contextualization episodes were commonly embedded within discussion of one of the Coach Objectives. Within the Coach Objectives, Professional Skills episodes were often embedded within a more technical discussion. This aspect may be because the coach recognized that engineering students often undervalue professional skills. The coach incorporated professional skills within the likely more valued technical content and emphasized the need for professional skills in industry. This placement of professional skills within technical content also served as part of the joint enterprise negotiation.

The last “row” illustrated in Figure 3 represents approximately the final quarter of discourse and consists of the meeting wrap-up discussion. During this time, students may ask final questions regarding aspects they are unclear about. In addition, many topics previously explored in depth are touched upon as a reminder of what aspects of the student’s strategy merit attention. In the case of this team, the coach only noted two items that s/he required the team to address before gaining access to the experimental equipment. The coach views these directive items as especially important, and in many cases are required of all teams that have not previously addressed them.

This last “row” illustrates both the differences and the commonalities between teams. There is a subset of Coach Objectives that the coach requires students to attend to. This subset represents activities in the community of chemical engineering that are so important that every team should participate in those activities and so they are required to do so. However, there is also a subset of the Coach Objectives that varies in importance depending on the strategy of each team and their joint enterprise.

The three theme categories are interwoven as the students and instructor discuss the experimental design strategy of the team. Episodes in the core content and concepts and project contextualization categories were found to be nested within episodes in the inputs and performance metrics category. This feedback, perceived as effective by students (Gilbuena, Sherrett, & Koretsky, 2011; M. Koretsky et al., 2011), starts primarily focused on Student Project Objectives. Coach Objectives are tools incorporated, as appropriate, to help students progress in the disciplinary and industrial communities of practice and progress in their joint enterprise. Project Contextualization episodes seem to be used by the coach to validate the utility of the Coach Objectives, which from a situative perspective reinforces the coach’s position in the joint enterprise negotiation. These episodes also possibly increase student motivation through the reinforced authenticity of the project.

This structure of themes and negotiation in project-based learning meetings between a coach or instructor and a team of students provides an interesting way to consider the interaction. From an analytical standpoint, the negotiation patterns are somewhat apparent and we can hypothesize that one pattern over another might be more or less effective for encouraging participation in a community of practice while affording agency in the definition of their joint enterprise. From a practitioner standpoint, while further investigation is warranted, we believe the pattern presented above is effective for this project and may be effective for other project-based learning environments in which an educator has meetings with teams of students.

2.5.3 A Structure of Feedback: Stages within Episodes and a Discussion of the Duality of Reification and Participation

In this section we will examine in more depth the differences in feedback using episode stages to compare a single common episode, as an illustrative example, between the four teams. All of the teams had at least one episode focused on the theme of material balance. Material balance is a core chemical engineering concept, and a corresponding procedure, derived from the conservation of mass. Students are shown how to apply this concept to process engineering problems in a course in their sophomore year, in the student community. Doing a material balance (i.e., the formulation, procedures, and evaluation associated with a material balance) is a common activity in the chemical engineering community of practice, often one of the first activities community participants engage in when encountering, designing, optimizing or assessing a new system. This activity can save a chemical engineer time and money by highlighting physical constraints of a system. The coach emphasizes this concept as applicable for determining the flow rates, two of the input parameter values. Material balance is one of the “required” Coach Objectives. Even if teams have determined flow rate values based on seemingly reputable literature, the coach requires teams to use a material balance in order to verify their values. If a team has performed a material balance, in many cases, the coach asks to see the calculations, which also provides an opportunity to emphasize the role of the laboratory notebook for documenting the team’s work. The coach explicitly tries to promote “knowledge integration,” a learning theory concept that is cognitively-based and focuses on helping students connect internal mental structures and incorporate new knowledge into existing mental structures (Linn, 2006).

We can also view the emphasis on material balance as promoting student participation in a common community activity and highlighting how practices from the student community align with those in the chemical engineering community, not only in executing the set of procedures, but also in identifying the cases in which material balance applies. In addition, there is an aspect of disciplinary discourse associate with doing a material balance. Students in two teams described the set of procedures without identifying that set of procedures according to their community accepted name, material balance. Using appropriate disciplinary discourse symbolizes students’ legitimate participation in the community.

While all teams participate in a material balance themed episode, the characteristics of the episodes are quite different in terms of size, content, depth and the amount of guidance provided. Here we use the construct of episode stages to illustrate some of the differences for four teams (Team A, Team B, Team C, Team D).

Summary plots of the word counts and percent of word counts in each stage for these four episodes are shown in Figure 2.4.

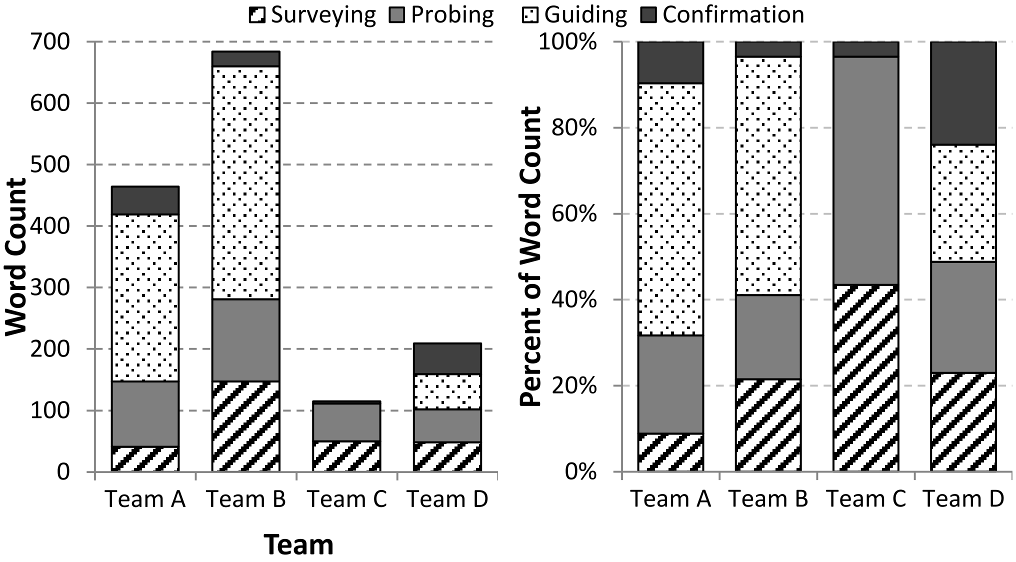

Figure 2.4 Comparison of Material Balance episodes: (left) word counts for episode stages, (right) word count percentages for episode stages

Two of the four teams, (Team A and Team B) had not performed a material balance prior to the Design Coaching Session. The total word count in Figure 2.4 (left) clearly shows that the material balance episodes for these two teams are longer (more than twice as many words) than the material balance episodes for the other two teams. Next if we consider both word count (Figure 2.4, left) and the relative proportion of episode stages (Figure 2.4, right), Team A and Team B experienced more guiding than Team C and Team D. Not only did they spend more discussion on the theme, but also a larger percentage of discussion consisted of guiding from the coach. Because the coach considers this concept to be an important concept every team should use in their completion of this project, it is not surprising that attention was paid to this concept and that even the teams that had performed a material balance had a material balance episode.

It is interesting to juxtapose the context of this episode theme for the four teams. In the remainder of this subsection, we will describe the material balance themed episode for each team, illustrating their differences in more depth. We will follow each description with a reflection on how each team's interaction can be considered via the duality of participation and reification.

Team A

Team A was one of the two that had not performed a material balance prior to the design coaching session. During the episode, the coach probed regarding the selection of the team's flow rate values. The team had based their values on a scientific paper. It becomes clear that the students had not accounted for the difference in size between the experimental equipment in the paper and the experimental equipment with which they would be working. The coach used leading questions to guide the team towards considering a material balance to assess the reasonableness of their values. Near the end the coach gave a directive statement:

> *"I really think that you need to do a material balance to see if that is a reasonable number."*

The students agreed with the coach, discussed what values they need for that calculation, and the episode ended. After the coaching session the team did a material balance and as a result, expressed more confidence in their flow rate values.

Reflecting on this team's episode, their reification of their initial project approach, i.e., their memorandum, provided an indication that the team had not participated in this important chemical engineering community activity. However, when this concept was discussed, the students quickly recognized its applicability. Their response may indicate that they were fluent in how to perform the activity, i.e., use the tool, just not as fluent in recognizing when it was applicable. In this way, we see the duality of participation and reification in that a lack of participation also corresponded to a lack of indication of that participation in the reification. The feedback in this episode promoted participation in this common chemical engineering community activity by requiring that the team do a material balance.

Team B

Team B presented an interesting case. The material balance episode for this team was more difficult to parse than the other teams. Episodes for this team were generally longer than those of the other three teams and appeared to have fewer clear confirmations. The length is illustrated by a material balance episode of 684 words, almost twice as many words as the average and more than six times larger than the smallest material balance episode described. This team had not performed a material balance. In the beginning of the episode the coach asked the students if they could think of a way to calculate the flow rate value. While the students alluded to possibility of use a material balance, they appeared to be confused about how to apply the concept in their case. The coach guided the students to consider reasonable engineering assumptions that would afford their use of a material balance and the coach elaborated, describing for the students how to make those assumptions. The episode ends with the coach asking the students if the approach made sense and the students replying that it did.

Team B's episode, while similar in stage structure, was quite different than that of Team A's. Team A appeared to have been comfortable with the concept, but lacking in the fluency of when to apply this community tool. Their reification of their initial project approach provided an indication that the team had not participated in the activity. Similar to Team A, we again see the duality of participation and reification in that a lack of participation also corresponded to a lack of indication of that participation in the reification. However, this team may be less central in the chemical engineering community with respect to this particular activity because they required significantly more guiding to even realize its applicability and how to use it.

Team C

Team C had written in their memo that they had done a "mass balance." As one might expect, the material balance episode is very short (115 words). The coach merely surveyed and probed on calculation verification and the reliability of their reference for density, one of the parameters students use in the material balance calculations.

"Mass balance," in this case, is another recognized phrase to describe the calculations. It is clear from Team C's reification that they had already engaged in this chemical engineering community activity and were able to articulate it with disciplinary discourse. This episode also illustrates that not all episode stages are present in all episodes; there was no guiding stage because the students had addressed all of the coach's questions with regard to material balance. In other cases, no surveying in verbal discourse is directly present because surveying information was gained either from silently reading the team's initial approach reification (memorandum) or from discourse in previous episodes.

Team D

In Team D's material balance episode, material balance was a concept they had thought about and performed calculations on prior to the design coaching session. During the design coaching session, the material balance episode began with the coach asking about the calculations the team had described in their memorandum. They had described the calculations of a material balance, but had not identified it as such. Then, in a sub-episode, the coach emphasized documenting work and calculations (specifically the material balance calculation) in the team's laboratory notebook. The coach emphasized the role of the laboratory notebook as a tool to help the students progress in the project. The coach reinforced the value by referencing students' prior industrial experience with laboratory notebooks in internships. The coach also suggested a teamwork or collaboration strategy the three students could use as they all interacted and contributed to the laboratory notebook artifact through their documentation activity. Next, the coach prompted the students by asking how they might convey their calculations more concisely. During this communication labeled sub-episode, the coach guided the students with leading questions, until the students identified their calculations as a “mass balance.” The coach then elaborated with the following statement:

> *Coach1: Alright, so if you tell me, that we performed a mass balance or mole balance, material balance may be the best thing, this is really a mole balance, we, we performed a material balance to determine the input flow rates, then, then I would say ok.*

Finally this team’s material balance episode ended with the coach reiterating the importance of documentation and the potential usefulness of the documentation in the laboratory notebook. The coach also suggested that if s/he had additional questions about the team’s material balance and had the team documented their calculations in their laboratory notebook, they could have referenced the laboratory notebook to help answer additional questions.

This episode illustrates another aspect of feedback. This team had participated in the material balance activity, but was not fluent in the discourse of chemical engineering community enough to use it in their memorandum. Within the seemingly technical material balance episode, most of the feedback focused on professional skills, including experimental documentation and disciplinary discourse. Because they had already completed the procedure but hadn’t identified it as one unit, the coach emphasized that it was a concept they could communicate with two words of disciplinary discourse rather than a longer description of the procedure of individual calculations and that those two words should have been in their memorandum. It appears that with respect to this community activity, this team was more peripheral than Team C, and more central than Team A and Team B.

As illustrated by the material balance episode, the episodes stages afford comparisons between coaching sessions on the number and flow of episode topics, depth of specific topics, percent of time or discourse spent on episode stages, as well as many other opportunities for analysis. In addition, for the practitioner, the structure of episode stages provides a construct to frame feedback specific to each team. Through surveying and probing, instructors can assess where students are. This assessment is crucial in order to be able to provide different teams or students with appropriate feedback. Through guiding and confirmation instructors can adapt feedback to help students engage in community activities to facilitate learning. As part of this process, students begin to ascertain where they are relative to reaching their goals and can move more productively towards their goals and towards more central participation in a community of practice.

2.5.4 Types of Feedback

The distribution of the type of feedback given in these episodes varied from team to team. The number of episodes for each team, categorized by the type of discussion and/or feedback, is shown in Figure 2.5. Each episode was categorized in one of the following categories: neutral discussion, affirmative feedback, directive corrective feedback, or facilitative corrective feedback. While some episodes may have contained multiple types of discussion and/or feedback, they were coded based on interpretation of the main message. For example, if feedback was primarily facilitative, but an episode ended with the coach explicitly requiring action of the students, the episode was coded as directive. Similarly, if an episode contained some affirmation, but primarily contained facilitation to help students change their current path or approach, the episode was coded as facilitative.

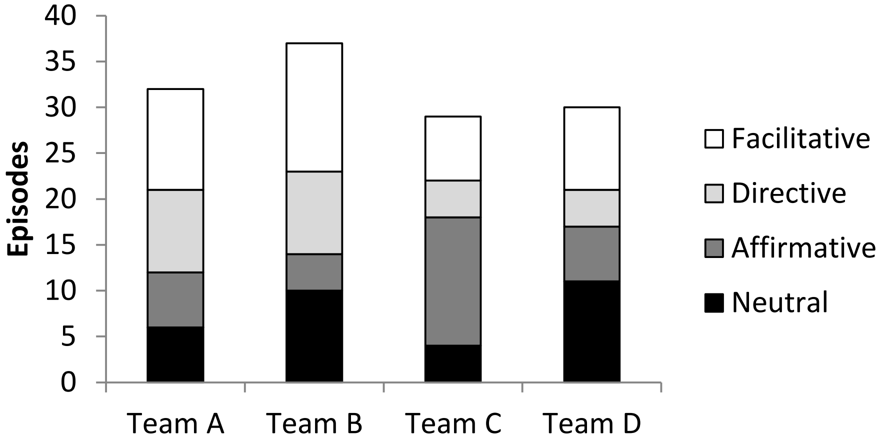

Figure 2.5 Number of episodes for each team, categorized by the type of discussion and/or feedback

As illustrated with the material balance discussion earlier, one factor that contributes to the discourse in the design coaching session is the content of the memorandum each team delivers to the coach at the beginning of the meeting. This factor also seemed to contribute to the types of feedback given. Team D had addressed most of the common “required” Coach Objectives. However, the team had not communicated their plan and reasoning well in the memorandum. This team had several short episodes in which the coach verified that s/he understood what was being communicated without offering affirmation or correction. Similar to Team D, Team C had come to the design coaching session with the common coach objectives already adequately addressed. This preparation can be seen in the data shown in Figure 2.5, where the least amount of corrective feedback was given and nearly half of their episodes had affirmative feedback.

By contrast, Team B had come to the meeting late, and appeared unprepared. There was even an episode near the beginning of the meeting in which the coach asked the team if they wanted to postpone the meeting until the team was more prepared. The team declined. In their coaching session, this team had the lowest number of episodes with affirmative feedback. They also had a few long episodes focused on Core Content, Concepts, Procedures and Strategies in the Coach Objectives. In addition, Team B, likely due to their lack of preparation, had many shorter episodes that focused more directly on Professional Skills, many of which were neutral. The type of discussion and/or feedback in the design coaching session for Team A was fairly balanced between neutral, affirmative and the two types of corrective feedback, with about the same proportion of facilitative and directive feedback. This team had come to the coaching session relatively well prepared, but lacking references in their memorandum. Considering all four teams, it is evident that different types of feedback are given in these design coaching sessions to varying degrees and that the preparation of the team appears to influence the distribution.

Team preparation can be considered to be representative of the community activities in which the teams had participated prior to the design coaching session. In this way, their reifications (their memoranda) likely provided the coach with some indication regarding their level of participation and provided information about the types of activities the team would most benefit from participating in. We suggest that using a variety of the types of feedback is appropriate, depending on the other aspects of the project and on the students themselves. If certain activities are crucial, perhaps more directive feedback is appropriate. However, although the final feedback on a theme might be directive, it is also important to emphasize that facilitative feedback can be used in conjunction. In many cases in this project the coach asks leading questions until the students identify the approach the coach is trying to guide them to. At that point, the coach may end an episode with directive feedback, but only after the students had identified an approach themselves; i.e., in some cases, while the coach requires students to participate in certain activities, prior to that requirement in the coaching session students may verbalize that the activity is useful for their approach.

2.6 Conclusions

In this paper we presented four characteristics of feedback: a list and categorization of episode themes, the structure and flow of episodes during the coaching session, the sub-structure present within individual episodes, and the types of feedback present. We showed how each of these characteristics provides a useful tool to scaffold interaction in project-based learning. We illustrated similarities and differences between teams and described how the different categories are intertwined and how the negotiation of each team's joint enterprise plays out in the flow and structure of episodes within a coaching session. We discussed the episode sub-structure, termed episode stages, and illustrated differences between teams with a discussion of reification and participation. We showed how episode stages provide a way for instructors to structure interaction to identify students' current level of participation and, if needed, help students progress towards more central participation with respect to a particular activity. Finally, we discussed the different types of feedback, possible reasons for the use of different types, and in what proportions these types were found in the coaching sessions.

The episodes framework and findings in this paper form a basis to provide recommendations for other educators implementing situated projects in their courses. This framework may be used by instructors implementing the Virtual CVD project in a similar setting. This "plug and play" approach may also be useful for instructors who have little time to prepare for the Virtual CVD project or who lack experience or confidence with structuring these types of interactions. An instructor may simply consider the categorization of themes presented, the structure of coaching sessions, and employ the surveying, probing, guiding, and confirmation pattern to offer feedback. However, it should be noted that the list of themes of episodes presented in this paper are based on coaching sessions that occurred after the coach had multiple years of experience in coaching students in this project. These have been refined based not only on evolving instructional objectives but also on aspects of the project that students have consistently had problems with throughout the years. Furthermore, while an explicit or implicit list of themes is a useful tool to support instructors, the themes and nature of each episode and coaching session ultimately depend on the coach and the team that is being coached. Terms such as "Are there any other questions?" encourage a wide range of topics. While a themes list is a useful tool, it is in no way comprehensive in predicting the content of every episode.

We also believe the episodes framework may be employed in other project-based learning environments. An instructor can create her/his own categorization of themes. In addition, in any project that has meetings an instructor can consider the pattern of addressing student joint enterprise themes and including coach objectives as tools to help students progress in their joint enterprise. Even in projects without such structured meetings, instructors can use the surveying, probing, guiding, and confirmation to provide feedback in a wide variety of projects.

To emphasize the transferability of characteristics of feedback presented in this paper, we provide the following example. The second author has used the episode stages in meetings held with his high school physics students. In this situation, the students were presenting a memorandum outlining their design for a mechanics project in their advanced placement physics class. The project placed students in roles of undergraduate interns in a research team attempting to develop a device to deliver fragile cargo (i.e. medical supplies) to high risk areas by air drop. In the meeting the instructor (the second author) served the role of the students' mentor. He used the episodes framework to survey, probe on particular themes, guide students, and finally confirm with the students that they were on the right track. Themes of these episodes were based primarily on elements he deemed essential to the project and secondarily on issues that arose during the meeting. While the situated, ill-defined nature of the project was similar to the project studied in this paper and the students also prepared a memorandum, many aspects of the project were different: educational level of the students (high school seniors), project content (focused on mechanics and dynamics), shorter meetings (five minutes), and the project scope (much smaller). However, the episodes stages and a sort categorization of themes provided the instructor, a first year high school teacher, with the scaffolding needed to feel confident and well prepared heading into the meetings.

While the episodes framework is presented, effective planning and execution of such student-instructor interactions is not trivial. As an instructor, the art of performing as both instructor and "project supervisor" benefits from both preparation as well as experience. In these areas, our model can only assist with the former.

2.7 Acknowledgments

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3. Feedback on Professional Skills as Enculturation into Communities of Practice

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3.1 Abstract

Background

Professional skills are believed to be a critical aspect of an engineer’s job. Providing students with feedback on professional skills can help students further develop these skills.

Purpose (Hypothesis)

We hypothesize that an in-depth focus on feedback provided with respect to professional skills in an industrially-situated project will afford a more nuanced understanding of what it means to have professional skills in this project and, by extension, in engineering. Additionally, providing students with feedback on professional skills provides increased access to disciplinary and industrial communities of practice while simultaneously influencing students’ engagement in more technical activities.

Design/Method

We explore our hypotheses with a case study from situative perspective using discourse analysis. We ask the following research questions:

1. What proportion of the coaching sessions attends to professional skills? What types of professional skills are addressed and what types of feedback does the coach provide?
2. How does this feedback provide access to communities of practice?
3. How do interactions in this project between a coach and student teams allow for a better understanding of what it means to have professional skills in engineering and influence student development with respect to those professional skills and more technical aspects of the project?

Results

Professional skills were commonly incorporated in coaching sessions, with attention paid to communication, experimental documentation, teamwork, the impact of engineering solutions on the economic and societal context, and project management. Most of these episodes were nested within the context of core disciplinary content and concepts. The types of feedback given varied and included affirmative and corrective feedback and included coaching moves of elaboration and revoicing.

Conclusions

If educators want to help students become more central participants in a disciplinary or industry-specific community of practice, their feedback should include attending to professional skills The ways educators integrate professional skills and the feedback they provide students on professional skills helps to determine how the students view these skills, how they participate in the activities involving these skills, and whether they consider these skills to be part of engineering.

3.2 Introduction

While few studies have actually examined "everyday" engineering practice, professional skills (e.g., teamwork and communication) are believed to be a critical aspect of an engineer's job (Trevelyan, 2007; Trevelyan, 2010). Providing students with feedback can help students further develop these skills and it has been suggested such feedback is best when situated in the context of engineering projects (Prados, 1997). We hypothesize that in such a context, students are more likely to take up feedback on professional skills because these skills will be viewed as an integral part of what an engineer does. There are two parts to providing students with feedback on these skills: (a) we first must have a firm understanding of what it means to have professional skills in engineering, and (b) we need to know how to effectively provide students with feedback on these skills.

The case study described in this paper focuses on discourse as students receive feedback while they engage in an ill-structured engineering project, previously described (Koretsky, Kelly, & Gummer, 2011; Koretsky, Amatore, Barnes, & Kimura, 2006, 2008). Throughout this project student teams receive feedback on a variety of topics (e.g., experimental design and strategy, modeling, reaction kinetics, teamwork, and communication) from a faculty member who acts as their supervisor and mentor; we call the faculty member the coach. We hypothesize that an in-depth focus on feedback provided with respect to professional skills will afford a more nuanced understanding of what it means to have professional skills in this project and, by extension, in engineering. We also begin to explore feedback techniques used by the coach to help students develop professional skills and the influence of that feedback on students' subsequent project activities. In this context, we begin to explore our hypothesis with the following research questions:

1. What proportion of the coaching sessions attends to professional skills? What types of professional skills are addressed and what types of feedback does the coach provide?
2. How does this feedback provide access to communities of practice?
3. How do interactions in this project between a coach and student teams allow for a better understanding of what it means to have professional skills in engineering and influence student development with respect to those professional skills and more technical aspects of the project?

This research contributes to the long term goal of the authors to understand how engaging engineering students in ill-structured engineering projects facilitates the development of their engineering skills, including professional skills.

3.3 Background & Theoretical Framework

3.3.1 Professional Skills

Professional skills, sometimes called "soft"(Shuman, Besterfield-Sacre, & McGourty, 2005) or "generic"(De La Harpe, Radloff, & Wyber, 2000) skills, are generally believed to be very important aspects of engineering practice. This belief is emphasized by industry representatives (Connelly & Middleton, 1996) and some engineering educators (Shuman et al., 2005). In some cases, practicing engineers spend nearly two thirds of their time interacting with people (Trevelyan, 2010). Critical drivers such as "rapidly changing technology, particularly information technology, corporate downsizing, outsourcing, and globalization" (Shuman et al., 2005, p. 3) provide the continually increasing need for engineers to be proficient in professional skills. Therefore, it is imperative such skills are intentionally developed in engineering students. In this section we present a description of professional skills in engineering education. We start with a discussion of which skills are commonly described as "professional skills." Next we discuss the inclusion of these skills in accreditation outcomes, commonly cited issues with teaching these skills, and strategies educators have used to include these skills in engineering curricula through program-wide initiatives, individual courses, tools and methods. Finally we summarize the recommendations from the literature for teaching professional skills.

While the importance of professional skills is generally recognized, the way educators and industry representatives define what “professional skills” means and which skills fit into that category, varies widely. When it comes to clearly defining the term “professional skills,” most researchers provide a list of included skills rather than defining the category. Even the lists of skills that fit into the category of professional skills vary. As noted by Colwell (2010), “if one were to ask educators in…engineering…what is meant by the term ‘soft skills’, there would likely be some consensus on the list, but each educator asked would probably have a different list” (p. 3). Despite the variation, many authors representing practicing engineers (Connelly & Middleton, 1996), alumni of engineering programs (Passow, 2007), and engineering educators (Passow, 2007; Shuman et al., 2005) agree that the following skills are professional skills:

- Teamwork
- Communication (both written and oral)
- Project management
- Leadership
- Self-awareness

Additional skills often described as professional skills include social skills, cultural sensitivity, dealing with diversity, adaptability (Koenig, 2011), decision making (Howe & Wilbarger, 2006), documentation (Fentiman & Demel, 1995), ethical responsibility, knowledge of contemporary issues, and an ability to understand the impact of engineering solutions in a global, economic, environmental, and societal context (*Criteria for Accrediting Engineering Programs 2012-2013*, 2012). Like the category of professional skills each of the skills that fit within the category of professional skills also has a vague and fairly broad definition.

With growing attention from industry (Katz, 1993; Nguyen, 1998) and in the literature (Shuman et al., 2005) given to professional skills, accreditation organizations began to include these skills in their outcomes. The Accreditation Board for Engineering and Technology (ABET) engineering criteria began to explicitly require professional skills as student outcomes in 2001 (Felder & Brent, 2003) and has continued to include them in revisions since (*Criteria for Accrediting Engineering Programs 2012-2013*, 2012). ABET came to see these skills as needed by all engineering graduates. The following six of the eleven outcomes specified in the ABET engineering criteria fit within the literature list of professional skills (Shuman et al., 2005):

- an ability to function on multi-disciplinary teams (3.d)
- an understanding of professional and ethical responsibility (3.f)
- an ability to communicate effectively (3.g)
- the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context (3.h)
- a recognition of the need for, and an ability to engage in lifelong learning (3.i)
- a knowledge of contemporary issues (3.j)

These criteria have spread globally through the International Engineering Alliance, a joint alliance among the Washington Accord, the Sydney Accord, and the Dublin Accord. In this alliance, the ABET professional skills have been explicitly included, described, and expanded upon as attributes and competencies that a graduate of a sanctioned program must possess (*IEA Graduate Attributes and Professional Competencies*, 2009).

While ABET criteria and industry demands mandate that engineering educators teach professional skills, helping students develop these skills is more difficult than it may seem. Many educators view professional skills as important aspects of practice. However, there is sometimes resistance from engineering students and educators to emphasize these skills in the curriculum. There are many reasons engineering faculty still struggle with teaching these skills. Cajander et al. (2011) suggest "that many educators have an intuitive grasp of what professional skills are, but struggle to give a clear definition of them and to define rubrics for their assessment" (p. 1). Other reported reasons from computer science include limited room in the curriculum, lack of experience or familiarity with professional skills, and a view that professional skills are not core to the discipline being taught (Spradling, Soh, & Ansorge, 2009).

Despite the challenges, educators have made an effort to incorporate professional skills in undergraduate and graduate education. Changes have been made in curricula ranging from the program level (Cajander et al., 2011), to entire standalone courses (Mohan, Merle, Jackson, Lannin, & Nair, 2010), to integrating professional skills as part of "integrative" courses (Humphreys, Lo, Chan, & Duggan, 2001; Palmer, 2000), to offering professional skills modules (Seat & Lord, 1999). In addition, professional skills have simply been integrated as a part of design courses with a variety of focus on professional skills (Dabbagh & Menascé, 2006; Davis et al., 2011; Kremer & Burnette, 2008) and integrated into cooperative learning experiences (Pimmel, 2001). A recent study surveying 444 programs from 232 institutions about the nature of engineering design courses showed that these courses increasingly attend to professional skills, with professional skills comprising a majority of the most frequently taught topics (Howe & Wilbarger, 2006; Wilbarger & Howe, 2006).

The ABET accreditation process has also served as the basis for several development of tools and methods targeted at assessing the proficiency of students with professional skills. For example, researchers reported on the College of Engineering at Virginia Tech using ePortfolio to document and assess the ABET professional skills criteria (McNair, Paretti, Wolfe, & Knott, 2006). In their use of ePortfolio, faculty specified definitions of the criteria, along with three levels of expectations that represent a progression from factual knowledge at level 1 to level 3 which aligns "with contextual knowing and with synthetic and evaluative tasks" (McNair et al., 2006, p. 4). Another tool, originally termed the curricular debrief and now termed the Engineering Professional Skills Assessment (EPSA), was developed at Washington State University to measure all of the ABET professional skills criteria simultaneously (Kranov, Hauser, Olsen, & Girardeau, 2008; Kranov et al., 2011). This assessment places students on teams and tasks them with a complex, real-world scenario, giving them merely 45 minutes to "determine the most important problem/s and to discuss stakeholders, impacts, unknowns, and possible solutions" (Kranov et al., 2011, p. 2). Other more commonly used tools such as performance reviews and peer assessments have also been reported.

In order to help engineering students acquire proficiency in professional skills, Shuman et al. (2005) echo the words of John Prados (1997) in advocating for a new engineering education paradigm "built around active, project based learning;

horizontal and vertical integration of subject matter; introduction of mathematical and scientific concepts in the context of application; close interaction with industry; broad use of information technology; and a faculty devoted to developing emerging professionals as mentors and coaches rather than all-knowing dispensers of information" (p. 1).

3.3.2 Situative Learning

Situative learning theory provides a useful perspective with which to consider how engineering students develop professional skills. Similar to Sawyer and Greeno (2009), we adopt the term situative learning because we believe that all activity, cognition, and learning is situated in some context, i.e., there is no such thing as non-situated learning. We agree with Hutchins (1995) that knowledge can be acquired and can change within individuals. However, we employ a situative perspective similar to that of Lave and Wenger (1991) to shift our focus from internal, cognitive mental structures of students to discuss how novices develop professional skills through feedback that facilitates participation in a community of practice. Considering the development of professional skills through the lens of situative learning, projects representative of engineering practice should serve as the context within which professional skills are developed. Paretti (2008) reinforces this idea with specific attention to written communication, stating that it is "a situated activity rather than an independent, abstract mechanical skill" (p. 492). The same is likely true of other professional skills.

Lave and Wenger describe a community of practice as “a set of relations among persons, activity, and world, over time and in relation with other tangential and overlapping communities of practice” (Lave & Wenger, 1991, p. 98). Specifically, they describe three dimensions of communities of practice: mutual engagement by participants, a joint enterprise or goal with some form of mutual accountability, and a shared repertoire such as discourse, tools, concepts, and ways of doing things. In our study we consider three simultaneous communities of practice: first, the community of chemical engineering, which is disciplined-based; second, the semiconductor industry community which is industry specific; and third, the student community. While each of these communities can be defined separately, they may also overlap, e.g., chemical engineers can work in and participate in the semiconductor industry. We focus primarily on how feedback helps students develop fluency in a subset of the shared repertoire of each of these communities. Specifically, we focus on professional skills described in the literature including teamwork, communication, project management, etc. Discourse is especially pertinent for communication.

In this paper, we refer to discourse of chemical engineering (the discipline of our participants) as *disciplinary discourse* and discourse specific to the semiconductor industry (the specific industrial context for our authentic engineering project) as *industry-specific discourse*. Lave and Wenger (1991) refer to novices as legitimate peripheral participants, who engage in community activity at the periphery of the community initially. As novices engage in community activities over time, and become more familiar with the community, its social structure, power relations, and conditions for legitimacy, they may progress to be considered full participants. Dannels (2000) describes part of this progression as “socializing students into professional identities.” We describe instances where attention is paid to *conditions for legitimacy*, which indicate a community participant’s legitimate belonging to the community.

Along with the situated context, providing students with feedback has been shown to be one of the most important tools used by faculty to help students close the gap between actual and desired performance. Feedback provides one way faculty (i.e., more central participants) can support students (novice participants) in becoming more fluent with the shared repertoire, and more specifically professional skills, in a community of practice. However, few studies have examined the role feedback on professional skills plays in helping engineering students develop. In this paper we focus on the influence of feedback provided by a faculty member, termed the coach, helps individual student teams become more fluent with professional skills in an ill-structured engineering project.

3.3.3 Feedback

Hattie & Timperley (2007) broadly define feedback as “information provided by an agent (e.g., teacher, peer, book, parent, self, experience) regarding aspects of one’s performance or understanding” (p. 102). An assessment of hundreds of meta-analyses from 180,000 studies showed that “the most powerful single moderator that enhances achievement is feedback” (Hattie, 1999, p. 8). We can consider feedback as an influential way more central participants in a community can help novice members develop and move towards more central participation. While feedback has been shown to be so influential, explicit research on the role of feedback in helping students develop professional skills in engineering education is sparse. In a study of advanced writing skills in upper-level undergraduate engineering, Yalvac, Smith, Troy, and Hirsch (2007) emphasize the importance of feedback and coaching in two of three “lessons learned” suggestions for teaching advanced writing skills. Findings from a study of mostly first-year engineering students credited student-instructor interaction and feedback with students’ perceived development in “group communication skills,” occupational awareness, problem solving skills, and engineering competence (Bjorklund, Parente, & Sathianathan, 2002). Another study of first-year engineering students (Moreno, Reisslein, & Ozogul, 2009) showed that feedback is positively related to learning gains in more technical work. These results are consistent with studies in other disciplines (Kuh & Hu, 2001).

In general, there is limited agreement on what characterizes “effective” feedback, especially in industrially-situated, open-ended projects that scaffold students’ participation. These types of projects allow students to be legitimate peripheral participants in a community of practice, but in a “safer” context than full participation. The safety is found in the way these projects include extra assistance through coaching and the reduced risk associated with failure. Hattie and Timperley (2007) suggest that feedback is helpful when it is related to the achievement of and progress towards specific goals. They suggest that the complexity of feedback matters, i.e., simpler feedback may be better than more complex feedback. They also suggest that feedback focused on the individual rather than the project and goal is not effective. Elaborated feedback, feedback in which an explanation is provided rather than a simple “right” or “wrong,” may be more effective than a simple mark or grade. Shute (2008) contributed a literature review on formative feedback which supports these suggestions and provides tabulated lists of “things to do,” “things to avoid,” timing related issues, and learner characteristics to consider when providing feedback.

Feedback has previously been grouped as either affirmative feedback or corrective feedback (Hewson & Little, 1998; Klausmeier, 1992). Affirmative feedback acknowledges a correct response and may include praise. Corrective feedback has been described by Black and Wiliam to have two main functions: (1) to direct, and (2) to facilitate. Directive feedback tells the recipient what must be corrected whereas facilitative feedback provides suggestions to guide the recipient toward his/her own revisions (Black & Wiliam, 1998). In some cases, discussion includes neither corrective nor affirmative feedback; we term these episodes “neutral” discussion. Acknowledging that different types of feedback will likely result in different types of skill development activities, we incorporate types of feedback, coding episodes as affirmative, corrective feedback, or neutral.

The ill-structured, open-ended engineering project described in this paper offers students an opportunity to “participate in realistic adaptations of actual engineering practice within a controlled environment that removes some of the commercial, physical, and social constraints of industry,” much like the systems described by Svarovsky and Shaffer (2006). We believe that providing students with feedback from an experienced coach on professional skills within the context of such industrially-situated, ill-structured engineering projects is likely to help students develop professional skills and be able to use those skills in future engineering projects.

In this paper we focus on feedback on professional skills in the coaching sessions and students' use of professional skills later in the project. We posit that the feedback on professional skills provides students with guidance as they navigating from peripheral positions in an industrial and a disciplinary community of practice towards more central participation. To explore the intricacies of the feedback process and the influence of feedback on professional skills in-depth, we apply a case study methodology (Case & Light, 2011). We combine the case study methodology with the framework of episodes (Gilbuena, Sherrett, & Koretsky, 2011) which allows us to parse discourse between student teams and the coach into thematic units and follow the themes in both written and verbal discourse related to professional skills.

We draw upon the summarized list of professional skills from the literature to identify which episodes of discourse are related to professional skills. After identifying the list of professional skills present in episodes in this project, we provide examples of feedback on each of the types of professional skills identified. We then examine the role of feedback in student teams' use of professional skills and more technical activities throughout the project by tracing themes in one team's entire project transcript. We also code episodes by feedback type.

3.4 Methodology

The methodology for this paper is comprised of four case studies of student teams and a single coach. The data collection includes field notes and audio recordings of teams throughout the project anytime two or more members met. The case study affords such fine grain data allowing the researchers to study the teams in detail throughout the entire project, providing a project wide picture of professional skills and the ways feedback on professional skills can provide students with access to and encourage student participation in a community of practice. Episodes analysis provided a method to examine the design coaching session transcripts in detail and afforded an exploration of the role of feedback on students' development of professional skills, starting with the interactions between the student teams and the coach and, through keyword searches, branching outward both forward and backward in time.

3.4.1 Setting

We have studied an innovative learning system (Koretsky et al., 2011; Koretsky et al., 2006, 2008). Central to the learning system is the Virtual Chemical Vapor Deposition (CVD) Reactor that provides a context for teams of students to practice engineering process development. This study is a subset of a larger investigation of student learning in ill-structured engineering projects and took place at a large public university. The project described in this paper, the Virtual CVD Process Development Project, was the second of three projects in a capstone laboratory course, typically taken by students in their final year of an undergraduate chemical, biological or environmental engineering program. Students in the course were organized into teams of three and maintained their team composition throughout the course. The other two projects in the course were based on more traditional laboratory experiments. The Virtual CVD Process Development Project places students in the role of semiconductor process engineers tasked with optimizing an industrially sized reactor for high volume manufacturing. A typical student team devotes 15 - 25 hours to this complex, three-week project. To optimize the reactor, they must integrate prior knowledge from previous courses. The desired learning objectives for the project include both the development of professional skills (e.g., teamwork, communication) and the integration of core engineering science concepts (e.g., material balances, reaction kinetics, diffusion).

Key project milestones and corresponding opportunities for feedback are summarized in Table 3.1. The feedback analyzed in this paper occurred during two 20-30 minute meetings, referred to as coaching sessions and shaded in Table 3.1, between the student teams and a faculty member, who we call the coach. During the coaching sessions, the coach acts as a mentor or supervisor in industry. In the design coaching session, students deliver a memorandum that details values for their initial experiment, a strategy for subsequent experiments, and an entire project budget (in virtual dollars). In the update coaching session, students must deliver another memorandum with an update on their progress after they have conducted several experiments using the virtual reactor. Feedback in both coaching sessions is intended to be tailored to engage students in identifying gaps in their current approach and directing attention to methods for addressing those gaps.

Table 3.1: Timeline and opportunities for feedback in the Virtual CVD Process Development Project.

Timeline	Key Project Information & Milestones	Student-Coach Opportunity for Feedback
Project Begins	• Project context is framed • Project goals and performance metrics are introduced • Issued laboratory notebook	The coach delivers an introductory presentation on the industrial context, engineering science background, the Virtual CVD Reactor software, and project objectives and deliverables. Feedback is limited to in-class interaction.
~End of Week 1	• Design coaching session ○ Memorandum with values for initial experiment, experimental strategy, and budget	During a 20-minute coaching session, feedback occurs as the coach and student teams ask questions of each other and discuss. If initial experimental values, strategy, and budget are acceptable, student teams are granted access to the Virtual CVD Reactor software.
~End of Week 2	• Update coaching session ○ Memorandum with progress to date	Feedback is given by the coach in this second 20-minute meeting in which student teams and coach discuss progress to date, issues, and path forward.
~End of Week 3	• Final recommendation for high volume manufacturing • Final written report • Final oral presentation • Laboratory notebook	Teams give a 10-15 min oral presentation to the coach, other instructors, and other students. Teams then entertain a 10-15 minute questions and answer session that affords additional feedback. Final project feedback consists of grades and written comments on final deliverables.

3.4.2 Participants

The twelve undergraduate student participants came from two cohorts of approximately 80 students each. Two teams were selected to participate in this study from each cohort, making four teams total with three students each. The process for choosing teams to participate addressed several factors, the most fundamental of which was simply schedule; teams were only chosen if a researcher was available during the team’s laboratory section and projected work times. The perceived willingness of a team to participate was also a contributing factor to team selection, including perceived willingness for both informing the researcher of all team meetings as well as verbalizing thoughts during meetings. A team's perceived willingness was a major criterion for selection because of the limited window of data collection associated with the project. It should be noted that students' academic performance (e.g. GPA, class standing, test scores) was not a contributing factor to team selection. More than half of the students had previous experience in engineering internships or laboratory research positions. Three of the teams were mixed-gender teams and the fourth team consisted of all female students. A total of eight female students and four male students participated in this study. The gender distribution in the participants for this study is not typical of engineering students as a population, which is a limitation of this study. However, we focus our qualitative efforts to afford a deeper understanding of professional skills in one capstone engineering project and provide a basis for future exploration.

One coach provided feedback to all student teams. This coach has coached over 60 teams in the same capstone course over several years and has many years of thin films processing experience. The coach has also published research papers and developed courses on the subject.

3.4.3 Data Collection & Analysis

Data sources include audio recordings and transcripts of student teams, researcher field notes, student work products, and post-project, semi-structured student interviews. Every time two or more members of a team met, they were audio recorded and those audio recordings were transcribed for the four student teams (Team A, Team B, Team C, and Team D) as they worked throughout the entire project. Researcher field notes include the researchers account of the student team as they worked and may include what team members were actively doing (e.g., team member 1 was searching the internet for sources while team member 2 constructed an Excel spreadsheet), information not otherwise captured on audio (e.g., website addresses), and notes of particular interest to the researcher. Student work products include the following items: laboratory notebooks in which students were instructed to detail their thoughts, calculations, and work throughout the project; all memoranda; final reports; final presentations; and electronic files, such as spreadsheets in which students developed mathematical models. Semi-structured interviews were completed with all participants up to 6 months after project completion.

Transcripts of meetings between the coach and the student teams were parsed into a series of thematic units using the episodes framework. Each episode in this work has a central theme that has been found to fit into one of three general categories (Gilbuena, Sherrett, Gummer, & Koretsky, 2011), a clear beginning and end, and contains up to four stages: surveying, probing, guiding and confirmation (Gilbuena, Sherrett, & Koretsky, 2011). Some smaller episodes have also been found to be nested within larger episodes, i.e., one themed discussion takes place in the context of a larger themed discussion.

Episodes were classified as either professional skill related or not professional skill related. The episodes that related to professional skills were characterized as including affirmative feedback, corrective feedback or neutral discussion. After identifying and coding all of the professional skill related episodes present in all four coaching sessions, the individual descriptive theme names were grouped based on commonalities. These groupings were then compared to the list of professional skills commonly found in the literature.

For each of the episodes, a list of keywords was created based on the discourse present and the descriptive theme name. For example, for an episode that emphasized the importance of citing sources, the keyword list would likely include “cite,” “citing,” “source,” “reference,” as well as words associated with the particular aspect of the project that required the citations. In addition, common alternate wordings were added to the list (e.g., material balance can also be known as a material balance). This list of keywords was then used to search throughout team meeting directly following the coaching session and the interviews for instances that appeared to be connected to the feedback in the coaching session. The list of keywords was iteratively modified as instances were found. When the iterative keyword search was completed the first author compiled all instances that referenced the overarching topic in chronological order.

Team A was chosen to investigate in greater depth and examine the role of feedback in facilitating students’ use of professional skills and in how students participate in more technical community activities. Team A was chosen for this in-depth investigation since the number of episodes containing corrective feedback in this team’s design coaching session was balanced between professional skills and technical concepts and content. Thus, this team provides an opportunity to examine a case where there may be high interaction between the two. The results should be interpreted with this selection in mind.

For Team A, all corrective episodes were examined and grouped into unifying topics. These unifying topics represented an overarching thread that connected multiple episodes. Corrective episodes were examined because students are most likely to participate differently as a result of corrective feedback and unlikely to change participation behavior based on neutral or affirmative feedback. The transcript exploration was conducted similarly with keyword searches with keywords related to the unifying topics. Table 3.2 summarizes the unifying topics, type of corrective feedback and keywords used for Team A.

Table 3.2. Summary of unifying topics and corresponding types of feedback in design coaching session

Unifying Topic	**Type of Feedback**	**Keywords**
Choosing a method to determine flow rate values	Directive	• material, mass, balance, flow, rate
The importance of citing sources	Directive	• cite, citing, sources, reference, credibility, cred, appendix
Team strategies	Facilitative	• check, calculate, calculation, review • complex, complicate, in depth (and variations), difficult
The impact of pressure	Facilitative	• pressure, diffusion, concentration

The story of students’ activities pre, during, and post feedback with regards to each of the professional skills related episodes was formed. The activities prior to feedback inform us about the team’s initial project activities and the ways in which they participated in those activities. The activities after the feedback can inform if students’ activities have changed compared to the initial activities and if they have changed, the surrounding discourse offers evidence as to why. In all instances we searched for disconfirming evidence and evidence of alternate reasons for changes in activity. This search allowed us to reconstruct the story of activity engagement with respect to episode themes and is useful because it illuminates the complexity and the intertwined nature of these categories (professional skills, technical concepts and content) that we all too often consider so distinctly separate.

3.5 Results & Discussion

3.5.1 Feedback on Professional Skills: A Survey of Four Teams

In order to examine what proportion of the coaching sessions attends to professional skills and what types of professional skills are addressed (research question 1), we identified the episode themes in the first coaching session for all four teams. Initially episodes were assessed as either related to professional skills or not related to professional skills. Figure 1 shows the percent of professional skill related discourse out of the total discourse for each team, as measured by episode count (unfilled bars). Out of an average of 29 episodes, approximately 40% of the episodes contained some discussion of professional skills. Figure 3.1 also reports the percentage of words spoken (word count) as an indicator of the degree to which feedback was given on professional skills.

In most cases the episodes on professional skills were embedded within a larger, more technical discussion. For example, the coach and a team might be discussing the team’s strategy for determining one of the input parameters. Within that discussion the coach might ask what literature references the team used to determine the value. If the team hadn't cited any sources in their memorandum, the coach would likely emphasize the importance of providing citations in written communication because the citations serve as a way to provide information to the reader and to establish or reinforce credibility.

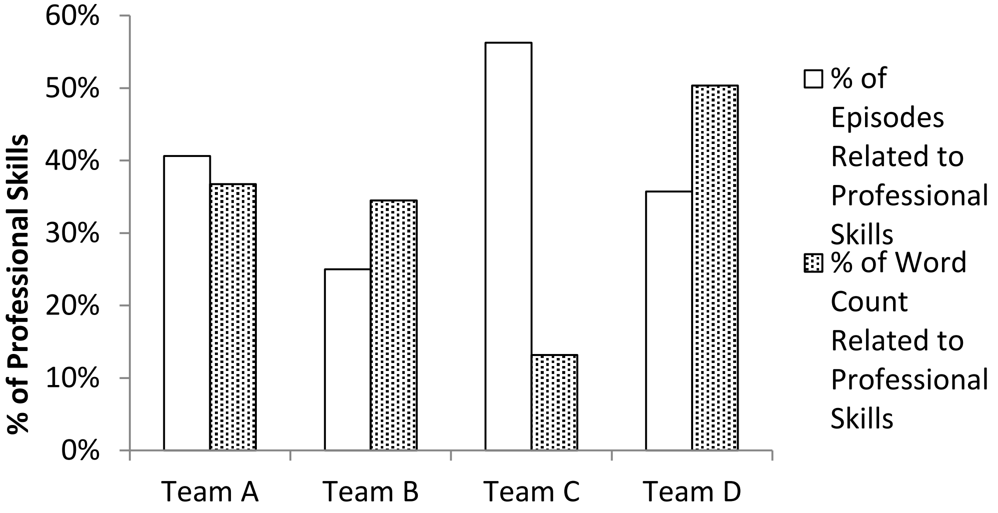

Figure 3.1. Percent of coaching session discourse that includes professional skills

In order to determine the types of professional skills present in the design coaching session, the subset of episodes related to professional skills was further divided into professional skills subcategories. We used the literature list of professional skills combined with our observed professional skills to guide this grouping. The specific professional skills that were identified in the design coaching session for the participant teams are as follows:

- Communication (written and verbal)
- Experimental Documentation
- Teamwork
- Impact of Engineering Solutions on the Economic and Societal Context
- Project Management

Like the term "professional skills," each of the subcategories also has a vague and fairly broad definition. While literature discusses the need for these types of skills, the form that they take in practice is rarely described.

The most common professional skill addressed was written communication. This is not surprising since student teams are expected to deliver a written memorandum to the coach at the beginning of the meeting. In addition to professional skills categorization, episodes were also grouped by type of feedback or discussion, including the following groups: neutral discussion, facilitative corrective feedback, directive corrective feedback, and affirmative feedback. The results of this grouping are illustrated in Figure 3.2.

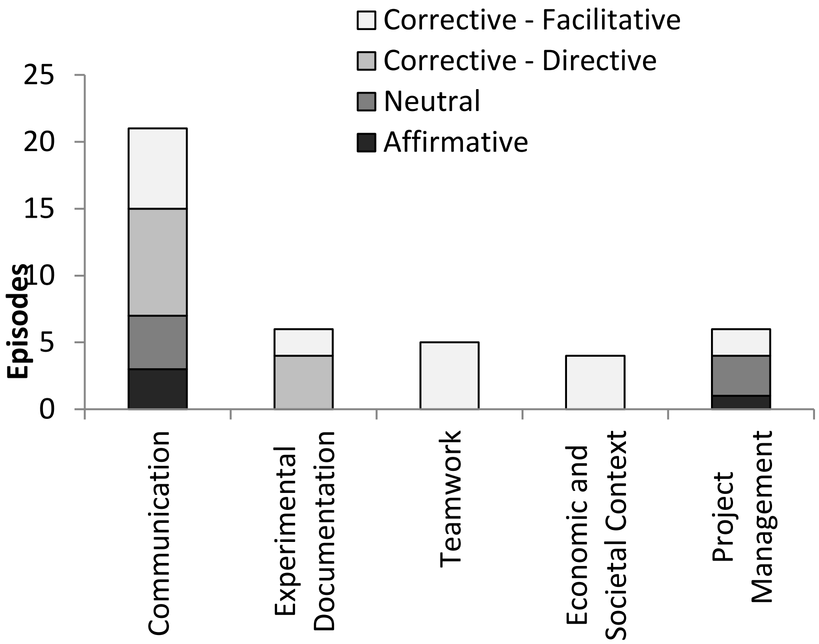

Figure 3.2. Distribution of episodes categorized by type of discussion/feedback within the professional skills episodes

Interestingly, all of the feedback related to the impact of engineering solutions on the economic and societal context was facilitative. The coach guided students to consider the impact without directing action. The same was true of teamwork. It is likely that the coach considers these two skills to be flexible and adaptable. In addition, neither of these skills are easily monitored or assessed in the project, so directive feedback is not particularly warranted. However, the writing skills and verbal communication were commonly directive. One reason for the directedness in the written communication is that the coach required two teams to modify their memoranda before they could proceed with the project and gain access to the virtual equipment.

In the following subsections we describe more in-depth instances of the coach providing four student teams with feedback on each of these subcategories of professional skills. We specifically frame the description to identify how the feedback relates these skills to the disciplinary community of practice of chemical engineering and industrial community of practice of the semiconductor industry. In some cases our descriptions of feedback are accompanied by examples of evidence of the influence of the feedback on the professional skill highlighted. These examples are not meant to be representative. They are meant to provide an exemplar of the influence of feedback on professional skills. We hope that with these illustrations, we can help clarify some aspects of how each of these skills are embodied through coaching and highlight the ways feedback on these skills can help students navigate from novice towards expert in the different communities of practice in which they reside.

Communication

Communication was the most prevalent theme for the professional skills related episodes, present in both verbal and written form. Not surprisingly, some episodes included feedback on straight-forward items such as formatting and typographical errors. Some feedback, however, highlighted a more complex and nuanced aspect of communication; specifically, the way communication conveys a degree of participation in a community of practice, e.g., a degree of legitimacy. Moreover, we can identify the communication as being pointed towards two distinct, albeit overlapping communities, one in the semiconductor industry and the other in the discipline of chemical engineering. The ways that we observed in which feedback in communication is directed towards legitimacy in each of these communities of practice is presented next.

Semiconductor Industry Community

Verbal communication episodes were commonly focused on clarifying industry-specific discourse. These episodes tended to be short, and nested in other more substantive episodes. For example, Team C showed a lack of fluency with industry-specific discourse during a larger discussion of modeling and reaction kinetics. While asking some clarifying questions, the coach asked about wafer size in the episode shown below. Here we see the coach offering subtle corrective feedback on industry-specific discourse.

> *Coach: And their size are* (sic)*?*
> *Student 3: 200, or sorry, 20 centimeters*
> *Coach: 200 mm*
> *Student 3: Yeah, 200 mm, so it's 200 mm size*

The project is situated in the semiconductor industry. In this industry, engineers refer to wafer sizes in units of either millimeters or inches, but never in centimeters. There are also standard wafer sizes (e.g., 300 mm, 200 mm, 150, mm, etc.). While the student's response of "20 centimeters" is scientifically correct, it reveals the student's position as a novice within the community. If the student had been talking with a boss or colleague in the semiconductor industry, the student would have been perceived as not aware of or fluent in the discourse of the industry. This mistake would have symbolized the student's lack of experience, and possibly lack of credibility and legitimacy in the community. The coach subtly corrected the student by revoicing (O'Connor & Michaels, 1996) the appropriate units. Revoicing is a feedback technique that was commonly observed in the professional skills discourse examined in this study (O'Connor & Michaels, 1996). The student then repeated the quantity with the appropriate units. This use of appropriate units may indicate the student has either borrowed (Bakhtin, 1981) or took up that correction, at least for this instance using the discourse of the semiconductor industry. While this type of feedback may help the student become more fluent in the discourse of the particular industry in which this project is situated, we propose that feedback in this type of episode has the potential to be more general. When feedback is given more explicitly, it might make the student more aware that in any industry the use of specific words can convey legitimacy.

Other industry-specific communication episodes focused explicitly on credibility, in some cases including explicit corrective feedback. In one episode from Team B the coach questioned whether the students would retain credibility if they presented to an operator in industry input parameters with an excessive number of significant figures. The coach hypothesizes that the students would lose "*floor credibility*," referencing the manufacturing facility floor, and that the students would be perceived as novices, as "*someone who did a calculation*" without considering the practical implications.

Disciplinary Community of Chemical Engineering

While the previous example of discourse illustrates a lack of fluency in industry-specific discourse, other episodes illustrate lack of fluency in more general disciplinary discourse. Again these communication episodes tended to be embedded within more technical episodes. Feedback on disciplinary discourse included several disciplinary concepts. For example, an episode from Team C occurred within discourse about calculating a mass balance (also known as a material balance), a core chemical engineering concept, for the purpose of determining one of the input parameters.

> *Student 3: the minimum* [material needed for the system] *would be, um, the total deposition divided by the, the total mass deposited and then convert that to moles deposited divided by the time.*
> *Coach: So what do you call what you just did? Conceptually?*
> *Student 3: The average depositing…*
> *Student 1: Mass balance*
> *Coach: A mass balance*

In this episode, student 3 shows a lack of fluency in the broader discourse of the discipline. The coach offered clear corrective feedback, first asking a leading question. Then when two students answered, the coach revoiced the correct answer.

Student 3's initial response above outlines the set of procedures without identifying the underlying concept (mass balance). While Student 3 was technically correct, had the student used such a description with an expert practicing chemical engineer, the engineer would have likely perceived the student to be a novice, not fluent in the disciplinary discourse. A core concept like mass balance should be understood by experts in chemical engineering. Certainly calculations can be the topic of discussion, but they are better communicated when they are introduced with disciplinary discourse. The use of disciplinary discourse establishes legitimacy through communication.

A similar mass balance episode occurred with Team D. However with Team D, the coach elaborated on one of the purposes for using the phrase "mass balance". This episode, like the previous example, takes place within the context of using a mass balance to determine one of the input parameters. After asking a leading question and revoicing the correct answer given by the student in Team D, the coach added:

> *Coach: Alright, so if you tell me that we performed a mass balance or mole balance, material balance may be the best thing, this is really a mole balance, we, we performed a material balance to determine the input flow rate* [one of the input parameters], *then I would say ok.*

Two comments from a member of Team D in an interview after project completion demonstrate that the student is more fluent in disciplinary discourse:

> *"so, learned a lot, <u>learned that the key phrase is, uh what should you do, a material balance</u>, which I'm taking design and it's really true cause like in design it's also like oh just do an energy/material balance and see what you can get from that first"*
> *"like I said, like the whole material balance concept that, that's like it's something you learn sophomore year and you don't necessarily really keep in mind as you go through, but it's a really essential element of chemical*

> *engineering and just gives you like, makes you step back and think about like the big picture of what's going on"*

We cannot be certain that the feedback given in this project, or the project itself caused this student to become more fluent in disciplinary discourse, or encouraged participation in this set of procedures as a community activity. However, the student attributed the project with this enculturation and with connecting a practice learned in the student community to the chemical engineering community.

In both mass balance episodes, the coach offered clear corrective feedback to help the students identify, and apply disciplinary discourse. In general, the level of corrective feedback was much greater for episodes about disciplinary discourse than for episodes about industry-specific discourse (as discussed above). It is likely that the coach realizes that the industry-specific discourse is not common in other industries and that students will eventually practice in wide variety of industries. While student use of the industry-specific discourse is important, it is likely viewed as less critical than student use of disciplinary discourse that will likely be applicable regardless of the industry the students end up practicing in.

Credibility was also explicitly the focus of feedback to help students participate in the chemical engineering community, especially related to references. The activity of citing sources in written communications, while seemingly straight-forward, conveys many aspects of a team's degree of legitimate participation in the chemical engineering community of practice. Small (1978) describes citing sources as a "symbolic act" that connects ideas to documents and helps create common terminology with common usage and meaning, contributing to the common discourse.

Gilbert (1977) describes “scientific papers as ‘tools of persuasion’” (p. 115) needed to persuade members of a community to share an author’s “opinions of the value of his [or her] work” (p. 115). Clearly this activity is intended to communicate the sources of information in a written artifact. However, it also makes known the effort devoted to the activity of investigating proper parameters, conveys an understanding of the community by connecting to credible sources within the community, and therefore communicates the credibility of a team and a team’s chosen values. Likely because of these reasons, citing sources was a common theme for episodes in design coaching sessions. In most of these cases, the coach asks students about the sources of information written in their memo. If the students have not cited any sources, the discussion is commonly like the following example from Team A.

> *Coach1: So, I want to know what your references are when you say*
> *Student1: That’s a good temperature range*
> *Coach1: When, when you, when you, when you say first run parameters were based on literature and internet research. So if the temperature range is based on a paper, that’s probably a more, um, that’s a robust source than some google search*
> *Student 1, Student 2: Right*
> *Coach1: So if you’re basing it on a paper, say the temperature range is as recommended by. . . you know* [student1’s last name] *et al. 1*
> *Student1: Okay*
> *Coach1: and then you have that reference right.*
> *Student1: Okay*
> *Coach1: And that gives credibility to that.*
> *Student2: Okay*

Experimental Documentation

We define the professional skill experimental documentation in relation to providing a record of project work that documents ideas, experiments, analyses, etc. *in situ* as a team progresses towards completing the task. Similar communication, experimental documentation is common practice in both the chemical engineering community and in the specific industrial community in which our task is situated. For example, companies are issued patents based on the records that engineers and scientists keep in their laboratory notebooks. However, unlike communication, this type of documentation is not necessarily intended to serve as a mediating artifact in a discussion or to be a polished protocol of a procedure. Episodes related to experimental documentation were almost exclusively related to documenting work in the team's laboratory notebook.

We found evidence of feedback on this professional skill in the coaching sessions for two of the four teams. The two teams spent multiple episodes and approximately 40% of their professional skills word count on discussion related to this skill. They were generally instructed to use the notebook as a "*palette*" that should contain "*any thoughts, ideas, analysis*" as stated by the coach when talking with Team D.

In several cases, the value of developing this skill was motivated by contrasting typical practice in the school community with the purpose it serves in the context of the industrial community of practice. For example, the coach motivates students in Team C to thoroughly document their work as follows:

> *Coach: This is like a 3 week thing 'cause that's how we do it in the school year, but in practice, you know, you can imagine this type of project might be 8 months.*
> *Student 1: kind of forget what you did*
> *Coach: And you have other projects going on. So if you…can get in the habit of recording not just what you did, but why you did it*
> *Student 1: mmhmm* [indicating yes]
> *Coach: As you revisit it, as your thoughts change, that can be helpful.*

These two teams, Team C and Team D, in which experimental documentation episodes were observed were part of the latter cohort. The emergence of feedback on this skill in the coaching sessions corresponds to a deliberate instructional modification between years. Unlike the earlier year, in the latter year an emphasis was placed on carefully recording work in the laboratory notebook. This case shows an example of how a slight reframing of instructional design can incorporate development of a needed professional skill. We believe that making explicit the types of professional skills addressed in the coaching sessions in our project can help instructors in other engineering design contexts identify such modifications in their projects as well.

Teamwork

Episodes themed around teamwork generally encouraged team strategies that are often used in industrial and disciplinary communities of practice, but less common in the student community to which the students are accustomed. Feedback on teamwork was rarely focused on typical topics like skillful conflict management (Mayer, 1998) or dealing with team members that do not do their fair share of the work. Instead it focused on the types of team strategies discussed by Mohan et al. (2010) such as being aware of the strengths and skills of other team members, and helping each other monitor individual contributions to the team. We also found episodes focused on coordinating work with other team members, in one case in the context of taking turns so that all members contributed to the laboratory notebook, and in several other cases in the context of implementing a sort of peer review process.

A common team practice in the student community is to divide the work load so that individuals on a team are solely responsible for a somewhat isolated part of a team project. This distribution of labor occurs in the industrial community and was even suggested in one very short episode as a strategy Team C could use while making changes to their design memorandum. However, a common practice in both the disciplinary and industrial communities is for engineers to engage in peer review, asking colleagues to double check the accuracy of calculations, experimental designs, and other plans. For two teams the coach's feedback guided students to consider employing a peer review, rather than strictly assigning particular team members to isolated, specific tasks.

In the case of Team B, feedback was given after the team had already performed a calculation. The coach asked how confident the team was in their values. The student who had performed the calculation was confident. The other two students, however, were not. The coach guided the students with leading questions, until one student suggested "*independent checks*." The coach revoiced the student's recommendation and elaborated with an emphasis on the economic implications of their calculation with the following statement.

> *Coach: You could have independent checks on that, 'cause it's, you know, you don't want to spend seven thousand dollars to learn that, oh, I forgot to carry a zero or something. Um, I'm not saying it's wrong or right, I'm just suggesting that's just more of a team strategy type thing.*

In this case, the coach emphasized that inaccurate engineering solutions can have significant economic consequences. Luckily for students, in this project the economic consequence is in virtual dollars, rather than sacrificing real company money. While the distinction between virtual dollars and real currency may slightly decrease the authenticity of this project, it also provides students with scaffolding and a safer environment in which to make mistakes and learn and grow from those mistakes.

In these cases with feedback on team strategies, we can see opportunities to provide students with alternate ideas about the purpose of teams and their role on teams in both the disciplinary and industrial communities of practice. Team members can help each other grow and learn, monitor each other, and act as peer reviewers to verify that solutions have been determined properly and prevent embarrassment and costly mistakes. Also illustrated in the teamwork episodes, there are potential opportunities for further improvement, e.g., perhaps the coach should be providing more feedback on conflict management and other team issues discussed in literature.

Impact of Engineering Solutions on the Economic and Societal Context

Engineering solutions have consequences. History is riddled with catastrophes that were a result of an incorrect calculation, lack of attention paid to auxiliary equipment, and poor assumptions. These consequences reach far and wide, impacting the bottom line of companies, the quality of air and drinking water, populations of animals, and the everyday lives of the people that use the products of engineering solutions. Similar to teamwork, the feedback on the impact of engineering solutions on the economic and societal context shift students’ participation from the student community to the disciplinary and the industrial communities of practice. Three of the four teams had an episode themed around the impact of engineering solutions on the economic and societal context, all of which were primarily economic in nature. The case discussed above in the “Teamwork” section and a second case are very similar, both referencing the general economic consequences of an incorrectly calculated value. However, in the third case the coach connected engineering solutions more explicitly to the industrial community of practice. This third case occurred in Team A’s coaching session within the context of reactions rates. The coach related the implications of a slow reaction rate in industry in the following interaction.

> *Coach: Right, and what’s the problem with that in a high volume manufacturing facility?*
> *Student1: You have waste*
> *Student3: You can’t get things done very fast*
> *Coach: You can’t get things done very fast*
> *Student1: Oh, okay*
> *Coach: And so you…*
> *Student3: ‘Cause it’ll, I mean it’ll still get deposited, it’ll still get there*
> *Coach: right*
> *Student3: it will take a lot longer*
> *Coach: right*
> *Student3: and it’s not ideal for*
> *Coach: so that you’re making less product than your competitor is*
> *Student3: So you might be uniform, you know,*
> *Coach: you might be uniform*
> *Student3: you might have high utilization but you know, oh we take 4 hours.*
> *Coach: yeah*
> *Student3: Wait 4 hours? Why are you taking 4 hours?*
> *Coach: Yeah.*

This episode appeared to be especially engaging for Student 3, who at end of the episode verbalized an imagined conversation with perhaps an unhappy industry supervisor. In this case the coach emphasized more than the direct cost of unnecessary experiments, but the greater economic context in which the engineering solution from this project would impact the company’s competitiveness in the market.

Project Management

Project management episodes also occurred in three of the four coaching sessions. Project management deals with the planning, scheduling, execution, and monitoring of projects (Kerzner, 2009). Project management activities can take a similar form regardless of the particular community. The episodes in the coaching sessions related to project management were primarily concerned with one of the following two aspects of project management: scheduling a meeting (e.g., scheduling a follow-up meeting to discuss a revised memorandum) and the overall project timeline and milestone expectations. We provide an example of the latter. Team D initiated a conversation about the overall project timeline and milestone expectations. In this episode one student questioned about what was expected for their update meeting, which occurred one week later. The coach hyperbolically stated that they could have their project complete by the next meeting (i.e., they would be done with the three-week project one week early). The coach then elaborated with more realistic expectations in the following monologue.

> *Coach: I would expect that you would be able to have some reflection on where you are at now, so that you'll be at some different point a week from now and that you can touch in on say where you were...Really, where you go between here and the final, is going to probably be different than any other group based on, you know, what your creative and uh, analytical thought*[s] *are on that. So it's really hard to say exactly what next week will look like, alright...it's another opportunity for feedback for you. You might want to consider that, so, where is reasonable to get, where you know. If there's kind of like a note you want to brainstorm about or something.*

In the above statement, it appears that the coach emphasized the agency that each team has in completing the project. The feedback in this example prompted the students to reflect on what they believe is reasonable and to come to the update meeting with questions. This excerpt appears to be reinforcing the open-ended nature of the project, and in that way helping students participate in an aspect of project management that is less common in the student community, but fairly common in both the disciplinary and industrial communities of practice. While projects are somewhat common in the academic setting (i.e., the student community), they are often more defined with milestones throughout the project set for students by an instructor. In this project, meeting times and the final deliverable milestones are set by the instructor. However, the pace the team takes during the three-week project is up to the team.

Unlike many industrial projects, students are not required to have Gantt charts or detailed project plans. An overall project timeline is specified for students at the start of the project and includes the scheduled meetings with the coach, after the first and second week, and the final presentation at the end of the third week. However, teamwork may present another opportunity for the coach to provide more feedback that can help enculturate students into the industrial community or disciplinary community. It is not uncommon for teams of students to “cram” before the final presentation, similar to the common student community practice of “cramming” before a test. Students have remained awake, working on their final report until 2am or 3am. While this type of intense work does occur in both the chemical engineering community and the industrial community, we would posit that it occurs much less often because participants in those communities have developed more effective project management skills. More intentioned discussions and feedback to students about their project management activities might be useful.

3.5.2 The Role of Feedback on Professional Skills: An In-depth Investigation

In the previous section, we investigated four teams to show that feedback on professional skills entails almost half of the coach-student interactions. We gave illustrative examples of feedback on these skills, and provided a couple of examples of the role of feedback on student development of professional skills. In this section, we examine Team A in greater depth to illustrate some of the complexities of the role of feedback in facilitating students' participation in professional skills activities as well as more technical activities.

In the design coaching session of Team A, six of the episodes were primarily affirmations and six episodes were neutral. The influence of neutral discussion and affirmative feedback were not explored because there is likely to be little evidence that students acted differently as a result of these interactions. Nine episodes contained primarily directive feedback on two central, unifying topics: choosing a method to determine flow rate values, and the importance of citing sources in written communication. Eleven episodes in the design coaching session contained primarily facilitative feedback. One was nested within the context of one of the two larger directive episodes discussed above. The remaining facilitative episodes centered around two unifying topics: the impact of pressure and team strategies.

Each of the unifying topics and the role of feedback in the activities associated those unifying topics are unpacked in the following subsections. The first two subsections discuss the directive topics in the design coaching session. These are items the coach required the students to attend to and include in a revised memorandum prior to receiving approval to continue with the project. During the design coaching session the coach wrote both of these items in a "to do" list in the top right corner of the team's first memorandum. The last two subsections discuss the facilitative topics in the design coaching session.

Choosing A Method to Determine Flow Rate Values – Directive Feedback

For the design coaching session, students are required to specify two flow rate values as input parameters for their initial experiment. At a team meeting the day before the design coaching session, the students expressed uncertainty in their values for the flow rates. They proceeded to review literature and based their flow rate values on a journal article. During a flow rate episode in the design coaching session, the coach questioned the students regarding how they had selected their flow rates. They responded that they had referenced a journal article. However, during the interaction, it became clear that the students had not accounted for the difference in size between the reactor in the paper and the reactor in the task. The coach guided them with leading questions towards using a material balance to assess the reasonableness of their chosen values. The students confirmed that they were able to do so. Near the end of the material balance episode the coach gave a directive statement, *"I really think that you need to do a material balance to see if that is a reasonable number."*

The students agreed. After a little more discussion about the values needed for the calculation, the episode ended. The coach reiterated the directive statement in three very brief episodes later in the design coaching session.

At the very end of the coaching session there was a facilitative episode initiated by the coach about a team strategy for "*the calculation*" that would ensure accuracy in the resultant values. Given the context, the coach is likely referring to the material balance procedure, as it was the only procedure involving calculations that the team was directed to complete. In addition, to asking about how the students would ensure that their numbers were right, the coach contrasted this chemical engineering community practice with the common student community practice of using the textbook by saying, "*you can't check the back of the book, right?*" One of the students suggested two options, in the following statement.

> *Student 3: we can hand it to each other and have everybody review it or we could do it individually and see how the numbers match up*

The coach responded and suggested that the team might want to think about how to make sure their numbers are right, without reinforcing either of the options suggested by the student.

After the design coaching session, the team met to address the items that were required before they could proceed with the task. In this team meeting, the students reflected as follows on the material balance part of the design coaching session:

> *Student 1: So, I don't know why we didn't think of this, mass balance.*
> *Student 3: I know right?*

The students elaborated that they had tried to consider which figures to use in the memo, and which other aspects to include, but from the coaching session, realized "*wait, it should be reasonable.*" Student 3 immediately performed the calculation. Along with attending to the directive feedback, the team also incorporated the facilitative feedback on the team strategy and chose to have multiple students perform the calculation independently; Student 2 also did the calculation. The two students compared their answers, iterated until they got the same results, and expressed appreciation for the activity afterwards:

> *Student 3: Okay awesome stuff. When we get these numbers it's going to rock. I'm happy that we got these. For one I am really confused that we didn't figure this first. For two I am happy that we don't have this haphazard number no more. All the other ones are based off of things we looked up and yesterday we were just like sccms that's a good number. And we got pretty close considering we kind of guessed*
> *Student 1: Oh no, it wasn't a randomly picked number*
> *Student 3: Yeah it wasn't completely random but it still wasn't exactly for our process*
> *Student 1: But it does show the fact that we were so close because if you don't account for the excess it is even closer right? It does show that these references that we are looking at have somewhat of an idea on what they're doing. I guess they are about the same size reactor*

Then Student 1 also performed the calculation and confirmed the result, causing Student 1 and Student 3 to express increased confidence in their values.

> *Student 3: Yeah, I am pretty confident considering I ended up getting the exact same numbers. So…*
> *Student 1: I definitely think we got it right*
> *Student 3: I feel a lot better this time around*

Here we see an instance of facilitative feedback on a peer review type team strategy, likely influencing the students' participation in a common more technical activity in the chemical engineering community.

During this activity, not only did the students verbalize being more confident in their values from the technical calculation, they also reflected on the credibility of the literature source on which they had based their initial flow rate values, present in Student 1's comment, "*It does show that these references that we are looking at have somewhat of an idea on what they're doing.*" The reference must have had "an idea of what they were doing" if the author of the reference had similar values. This reflection is possibly connected to the other directive unifying topic in the design coaching session, the importance of citing sources.

The Importance of Citing Sources – Directive Feedback

As discussed previously, the activity of citing sources in written communications conveys much more than just the source of information, which makes citing sources a common theme for episodes in design coaching sessions. Before the coaching session, the team listed research papers and websites used in a document, but had not included references in their memorandum. The team had also briefly discussed needing more than a single source as a basis for values and needing sound reasons for their values.

> *Student 2: For this memo, where do we find this information to come up with these values?*
> *Student 3: I don't know right now.*
> *Student 1: We need to have reasons. We can't just say these sound good based on background.*

While the team had considered several sources, they had not realized the communication value in citing those sources in their memorandum. During the design coaching session, this communication theme was attended to multiple times. Initially, the coach asked the students if they had the literature sources with which they had determined their input parameters. While the sources were not in the memorandum, one student responded that the team had a document in which they were tracking the information and that some of the information was also in their laboratory notebook. This episode ended affirmatively with the coach stating, "*oh great*."

However, only a couple of episodes later within an episode focused on temperature (one of the input parameters), the importance of citing sources was revisited, four times. Two of these episodes focused on evaluating and communicating the credibility of sources. In this credibility discussion, sources like archival journals were compared to company websites with an emphasis on the different types of bias each source likely has. This interaction illustrates a way faculty can provide students with legitimate access to a community of practice and help students recognize the roles of different community members and different resources.

The other two times this theme was revisited were more focused on the actual act of citing sources. The coach explicitly requested, with directive feedback, that students cite their sources in an appendix to their memorandum in order to justify what they had written. Like the previous unifying topic, the coach required them to do so before they could move forward with the project and after the meeting the students almost immediately attended to the request.

In the team's update memorandum, they cited no sources, even though they had used a textbook for the basis of mathematical model and had referenced a website for one of the values in the model. In the update coaching session, the coach asked about the source for the value (activation energy), which was stated in the update memorandum. Ending this very brief episode, Student 3 responded, "*The website is on a sticky* [note] *downstairs. I'll put it in the appendix.*" The activation energy value will be revisited in the team strategies discussion later in this section. In the task final report, the team included a list of literature sources.

It appears the students recognize that the coach values citing sources in the written communication. The students also demonstrated the practice of evaluating the quality of sources and consciously considered this type of evaluation; as seen in the previous subsection, the students explicitly considered the credibility of one of their sources. However, while the students seem to have adopted, and clearly participated in, the practice of citing sources, it is unclear if they have yet fully grasped the subtleties communicated while citing sources in the chemical engineering community.

Team Strategies – Facilitative Feedback

In their initial coaching session, Team A had two episodes in which they discussed teamwork with the coach. These two episodes made up 21% of their word count associated with professional skills and about 8% of the entire coaching session. One of the teamwork episodes happened prior to the team performing the critical material balance calculation. This episode was discussed previously in the discussion of the Choosing a Method to Determine Flow Rate Values subsection.

The second teamwork strategy episode in Team A's coaching session was focused on helping the students monitor each other. Because the team appeared to be attempting a very complicated model, the coach suggested the team take a "*jump back*" and "*real simply*" consider the system. It appears the coach was trying to help the team avoid making errors due to an unwieldy model. Likely recognizing that Student 1 was the champion for the complexity, the coach provided team strategy feedback directed at Student 3 to help mitigate Student 1's propensity for complexity. The exchange of discourse is presented below.

> *Student 3: 'cause if you add too many things, if you add in too many things and you consider absolutely everything important, then you're gonna end up having something that changes so many variables that you won't be able to design a reasonable experiment* [indiscernible].
> *Coach: So, so that's a good check for you to do,* [Student 3], *is to say hey, you know, um* [Student 1] *likes to think about things on really high levels. Is this getting too complex? Okay, because the higher level you think on things, if you can get it working that's great, but the more likely that you might have a little thing that's not working. Alright, so that's kind of a useful thing about a team and team dynamics. Everybody brings these inclinations and strengths and, you know the, your ability to negotiate through those is also gonna be important in addition to making those decisions. Right?*
> *Students: Yeah*
> *Coach: Okay*

This strategy appears later in the task when the team is discussing their path forward for the last week of the task. In the discussion, Student 1 appears to be using the strategy suggested by the coach, monitoring himself/herself, and expresses, "*this sounds really in-depth, and we don't have that much time before next week.*" A little later in the same meeting, Student 1 and Student 3 engaged in a "*philosophical debate*" about how to get one of their model values, the activation energy reference earlier. Student 1 advocated for calculating the value from their data, while Student 3 advocated for using a published value. After going back and forth a few times, Student 3, acting in the role suggested by the coach in the design coaching session, stated, "*my argument kind of coincides with the argument of doing the entire thing too in-depth,* *you are going to add more layers of work to this.*" While we cannot be certain of causality between the feedback given in the coaching session and this later team discussion, the students do appear to be employing the team strategy suggested by the coach. It is plausible that the feedback contributed to students' use of this strategy; the feedback may have helped the students be more aware of or confident in using this type of self and team member monitoring. No evidence was found to suggest that the team had intentionally decreased complexity in their work prior to the design coaching session.

Investigation of this team strategy later in the project illustrates how this professional skill potentially influenced the team's technical strategies. In the update coaching session, the coach provided additional feedback during an episode about activation energy. This feedback included citing sources and the method for finding an appropriate activation energy value. Recall from the previous subsection that the activation energy the students had found in "literature" was from a website. No additional information was given to the coach about the source, which possibly brought into question the credibility of the source. In addition, the coach often emphasizes connecting students' experimental data collected in this project to reaction kinetics (a common concept discussed in a senior level course). This combination of potentially poor source credibility and common coach emphasis, likely prompted the coach to guide the students toward calculating an activation energy value from their data rather than simply using the value from the website. In an effort to reduce complexity in the project, as suggested by the coach's facilitative feedback in the design coaching session, the students neglected a common practice in the chemical engineering community, i.e., using their data to determine the activation energy for their particular reaction and system. As students participate more in the community, they become more expert-like in identifying where and when to apply particular strategies, when to reduce complexity and when complexity is necessary. This example, illustrates one way the feedback from faculty members can help students in that process. In addition, it illustrates how feedback on a team strategy such as team member monitoring may have an influence on the more technical activities in which students participate.

The Impact of Pressure – Complex, Facilitative Feedback

Like flow rate values, students must also choose an initial value for pressure, another input parameter, before they can proceed with their experiments. Students had considered a variety of references to find an initial value for pressure. They had also identified and focused on diffusion, a concept discussed in a junior level course. While pressure was not included in many of their diffusion discussions, the students explicitly related two aspects of diffusion directly to pressure. Discussions of these two aspects resulted in incorrect conclusions regarding both. Later, the team wrote their design memorandum that they wanted to keep pressure low and that their initial pressure value was based on estimation.

During the design coaching session there was a group of facilitative episodes on this topic. An episode themed around pressure provided the context for two sub-episodes, one with the theme of diffusion and the other with the theme of reaction kinetics. During the diffusion episode, the team was guided to conclude that diffusion is not the only way pressure affects their performance metrics, which led to the second sub-episode on reaction kinetics. The students were guided to recognize that pressure affects reaction rate. Embedded within the reaction kinetics episode is another sub-episode which connected the task to the industrial community, connecting the concept of reaction kinetics (and implicitly, the implications of pressure) to its impact on high-volume manufacturing. This episode was discussed in the earlier section about the impact of engineering solutions on the economic and societal context and is given below.

> *Coach: Right, and what's the problem with that in a high volume manufacturing facility?*
> *Student1: You have waste*
> *Student3: You can't get things done very fast*
> *Coach: You can't get things done very fast*
> *Student1: Oh, okay*
> *Coach: And so you…*
> *Student3: 'Cause it'll, I mean it'll still get deposited, it'll still get there*
> *Coach: right*
> *Student3: it will take a lot longer*
> *Coach: right*
> *Student3: and it's not ideal for*
> *Coach: so that you're making less product than your competitor is*
> *Student3: So you might be uniform, you know,*
> *Coach: you might be uniform*
> *Student3: you might have high utilization but you know, oh we take 4 hours.*
> *Coach: yeah*
> *Student3: Wait 4 hours? Why are you taking 4 hours?*
> *Coach: Yeah.*

As discussed previously, Student 3 appears to be very engaged in this episode. This episode illustrates an instance in which feedback from the coach can highlight for students their role as process development engineers in the economic context of the semiconductor industry community while simultaneously attending to the chemical engineering community in which relating parameters to core concepts like diffusion and reaction rate is a common activity.

Another interesting note comes from a detailed investigation of Student 3's pattern of participation in the design coaching session. The episode illustrated above occurred after about half of the total discourse in the design coaching session. Prior to this episode, Student 3 had contributed somewhat minimally, most often responding with "okay." In the first approximate half of the design coaching (discourse prior to the above episode) Student 3 accounted for less than 6.6% of the total discourse. During the second half of the design coaching session, Student 3's participation increased to account for more than 20% of the discourse in the second half; student 3 roughly tripled her/his proportion of verbal engagement compared to the first half of the meeting. It is possible that the above professional skills episode, gave Student 3 an opportunity to engage and participate in such a way that promoted participation in additional activities in the design coaching session. Of course, it is also possible that the episodes later in the design coaching session were simply of more interest to Student 3 than the episodes in the first half. However, this increased participation is interesting.

Following the coaching session, the team discussed pressure as it relates to diffusion and stated that they needed more. As they progressed through the task, they continued to primarily reference diffusion when discussing pressure until one student, Student 3, created a mathematical model. Student 3 then began to emphasize the impact of pressure on reaction kinetics, the same emphasis the coach had given in the design coaching session. This sentiment was reiterated several times throughout the meeting. However, the very last reference to the impact of pressure occurred in the team's last meeting; again Student 1 and Student 2 referenced decreasing pressure to increase diffusion, with no mention of reaction kinetics or reaction rate. Student 1 and Student 2 had not engaged in the modeling activity that Student 3 had. This lack of participation in the chemical engineering community activity is clear in their disciplinary discourse and apparent lack of fluency with how these concepts in the community relate.

3.6 Conclusions

Professional skills were found to be commonly incorporated in coaching sessions, with attention paid to communication, experimental documentation, teamwork, the impact of engineering solutions on the economic and societal context, and project management. On average about 40% of the total coaching episodes related to professional skills. Most of these episodes were nested within the context of core disciplinary content and concepts. The types of feedback given to students were found to vary and include affirmative and corrective feedback with specific techniques of elaboration and revoicing commonly present in feedback.

We have presented detailed examples of interactions related to professional skills from one project. In doing so, we provided additional information about how each of these skills is defined within engineering. In order to research student development with respect to professional skills, it is necessary for us first to have a firm grasp of the definitions of these professional skills. To help students become more fluent with these professional skills, we also need to understand the ways in which we can facilitate this type of development. For example, one purpose of communication is to express and convey ideas such that another individual can understand. However, another purpose of communication, as seen in these examples, can also be to symbolize legitimate participation in a community of practice. Proper choice of wording and references illustrate that a peripheral member of a community is becoming fluent in the discourse of the community and signals their progression towards more central participation. Lack of doing so, symbolizes that an individual is a novice in the community. If educators want to enculturate students into a disciplinary or industry-specific community of practice, their feedback should include attending to professional skills, and specifically, these conditions of legitimacy. In our case, most of the episodes including feedback on conditions of legitimacy provided students with corrective feedback to help them properly apply and interpret. We have also tried to highlight the ways in which feedback on professional skills and students' use of professional skills can influence more technical aspects of their project work.

We believe that professional skills are an integral part of what an engineer does. Fluency in these skills demonstrates a level of participation in a community of practice, in our case the community of chemical engineering and to a lesser degree the community of the semiconductor industry. Echoing the words of Paretti (2008), and expanding her suggestion to include all professional skills, if we want students to value these skills and consider them to be integral activities in their respective communities of practice, we must “help students understand the ‘why’ of [these professional skills], because only then can they begin to grasp the ‘how’” (p. 500). We believe a start to helping students with these skills is to first make them explicit and identify how they are defined and how they contribute. We use the instructional design and feedback to facilitate student growth with respect to these skills. This approach is likely applicable in other engineering design contexts as well. The ways educators integrate professional skills into courses and the feedback educators provide students on professional skills helps to determine how students view these skills, how they participate in the activities involving these skills, and whether they consider these skills to be part of engineering.

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4. Use of an Authentic, Industrially Situated Virtual Laboratory Project to Address Engineering Design and Scientific Inquiry in High Schools

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4.1 Abstract

This paper is intended for engineering educators, high school curriculum designers, and high school teachers interested in integrating authentic, project-based learning experiences into their classes. These types of projects may appear complex, but have many advantages. We characterize the successful implementation of one such project, the *Virtual Chemical Vapor Deposition (CVD) Laboratory Project*, in five high schools. Central to the project is a virtual laboratory that simulates a manufacturing process in the integrated circuits industry. It provides opportunities for students to develop and refine solutions to an authentic engineering task through integration of science knowledge, experimentation, analysis, reflection, and iteration. The flexibility in instructional design and the robust, no-cost access enables versatility. The authenticity of the project is shown both to motivate students and develop their epistemological beliefs. The project is also shown to promote student cognition through knowledge integration, engineering design strategies, and evaluation and reflection. In addition, the project allows for teacher assessment of students' progress towards this type of cognition and enables them to identify opportunities to modify their instructional design to promote learning. Finally, we discuss potential barriers to adoption.

Keywords: Knowledge Integration, Project-Based Learning, Virtual Laboratory, High School, Experimental Design

4.2 Introduction

Over the last seven years we have developed, implemented and been assessing the Virtual Chemical Vapor Deposition (CVD) Laboratory Project (M. Koretsky, Kelly, & Gummer, 2011; M. D. Koretsky, Amatore, Barnes, & Kimura, 2008; Milo D Koretsky, Barnes, Amatore, & Kimura, 2006). Since 2008, more than 600 high school students have completed this project in 26 cumulative classes at 5 high schools. We employ technology to simulate a complex industrial process that would not be accessible to students in a conventional laboratory environment and allows future engineers to practice the skills they will need in industry, in much the same way a flight simulator is used for training pilots. The Virtual CVD Laboratory Project was developed as a capstone experience for university engineering students. However, we recognized that, with appropriate curriculum modification, this project could fill a critical need at the high school level. This paper discusses the adaptation of the Virtual CVD Laboratory project at the high school level.

Informed by research on student learning, the American Association for the Advancement of Science (AAAS), in its Benchmarks for Science Literacy - Project 2061, describes the need for fundamental shifts away from rote learning and content knowledge, and the necessity for transitioning to pedagogical approaches that emphasize process, critical thinking, and problem solving within multiple contexts (2061., 1994). This group also stresses the need for all students to obtain scientific literacy. Such emphasis is reinforced by the National Science Education Standards (NSES) (Assessment & Council., 1996) with the call for a “step beyond ‘science as a process.’" Engineering can provide a particularly powerful context to meet these goals through the integration of math, science and technology coupled with the development of problem solving and design skills.

The ideals communicated in Benchmarks and the NSES continue to drive curricular reform. Fifteen states now have explicitly labeled engineering components within standards (Strobel, Carr, Martinez-Lopez, & Bravo, 2011), and some states such as Massachusetts (C. o. Education & Education, 2006) and Texas (Certification, January 9, 2004), have issued a separate State Engineering or Technology Standard. At the high school level, 14 states have explicitly included an engineering design component and an additional 10 have explicitly included technology design in state standards (Purzer, Strobel, & Carr, 2011). There have been recent discussions regarding creating National Standards for K-12 in Engineering(Bybee, 2009); however, the Committee on Standards for K-12 Engineering Education recommends integrating engineering core ideas into existing National Standards for science, mathematics, and technology (C. o. S. f. K.-E. Education & Engineering, 2010).

While the incorporation of engineering into K-12 state standards is diverse and varies in scope, there is general alignment with the broad framework presented in the recent National Research Council report, *A Framework for K-12 Science Education (C. o. C. F. f. t. N. K.-S. E. Standards & Council, 2011)*. The framework is constructed across three dimensions: practices, cross-cutting concepts, and core disciplinary ideas. The report emphasizes the use of this framework to accomplish the goal of having “students, over multiple years of school, actively engage in science and engineering practices and apply crosscutting concepts to deepen their understanding of each fields' disciplinary core ideas," (p. ES-2) and that "introduction to engineering practice, the application of science, and the interrelationship of science and technology is integral to the learning of science for all students" (p. 1-4). Moreover, the authors assert, "that helping students learn the core ideas through engaging in scientific and engineering practices will enable them to become less like novices and more like experts" (p. 2-2). This framework is reported to be instrumental in the Next Generation Science Standards currently being developed (N. G. S. Standards, 2011).

Laboratories offer students one way to actively engage in science and engineering practice. They also develop students' beliefs about the nature of science, i.e., "the epistemology of science, science as a way of knowing, or the values and beliefs inherent to scientific knowledge and its development" (p. 833) (Lederman, 2007). The passing of and continued support for the America COMPETES Act (Lederman, 2007) recognizes the consensus in the scientific community regarding these integral roles of the laboratory experience and explicitly mandates improved laboratory learning and "development of instructional programs designed to integrate the laboratory experience with classroom instruction" (p. 694)(Gordon, 2007). Although a substantial case can be made as to the value of a curricular approach with this emphasis, pedagogical decisions must account for the realities of limited resources, especially time and budgets. The latest reauthorization of the America COMPETES Act (Gordon, 2010) acknowledges these limits and promotes the use of technology to "enhance or supplement laboratory based learning" (p. 32). Virtual laboratories offer an attractive curricular option from a budgetary standpoint; once software has been developed, the transfer cost is relatively small, consisting mostly of developing teaching materials and teacher expertise.

Virtual laboratories have been used as a teaching tool since the early 1980's (Dowd, 1984; Moore & Thomas, 1983; Sparkes, 1982). They are often used to replace physical laboratory equipment that is too expensive to purchase and maintain or too complex, dangerous or time consuming for students to use (Huppert, Lomask, & Lazarowitz, 2002). There are reports of successful integration of various virtual laboratories directed specifically at content-specific domain knowledge at the high school level in biology (Horwitz, 1996), chemistry (Murray, 2007), and physics (Dede, Salzman, & Bowen Loftin, 1996; Yang & Heh, 2007).

Rather than being designed around curriculum-specific science content like the virtual laboratories described above, the Virtual CVD Laboratory Project is based on having students complete an engineering task that is situated in industry. This approach can make instruction more meaningful for students by making it more authentic. Through project-based learning and the excitement of interactivity, students are engaged and encouraged to use higher cognitive skills. This authentic culture couples the ability to learn with the ability to use knowledge in a practical context. Through this activity, students are also introduced to engineering as a future career. These aspects can be especially effective for students with non-conventional learning styles. This paper describes the implementation of the Virtual CVD Laboratory Project, such that other high school teachers can reasonably integrate it into their courses to provide students with an authentic and dynamic, project-based learning experience.

4.3 Claims

We make four claims regarding the Virtual CVD Laboratory Project as it is implemented at the high school level:

1. The demonstrated, successful use of this project in a variety of high school classes illustrates the project's **versatility**;
2. The authentic nature of the project provides **motivation** for students;
3. The project promotes ways of thinking and types of **cognition** that are not developed by 'confirmation experiments' but are necessary for cultivating student ability in scientific inquiry and engineering design; and
4. The project moves students' **epistemological beliefs** towards those of practicing engineers and scientists.

4.4 Philosophy and Context

The Virtual CVD Laboratory Project is intended to provide an authentic engineering environment in which students learn through applying knowledge and skills to a practical and challenging engineering task. As implemented at the high school level, this project embodies the integration of practices, crosscutting concepts, and core ideas, three dimensions which have been identified as "needed to engage in scientific inquiry and engineering design" (p. ES-1) (C. o. C. F. f. t. N. K.-S. E. Standards & Council, 2011). These dimensions are present in this project to varying degrees depending on the instructional design. A cumulative summary of dimension components that have been incorporated into this project at the high school level is given in Table 4.1.

Table 4.1. Components of practices, crosscutting concepts, and core ideas (C. o. C. F. f. t. N. K.-S. E. Standards & Council, 2011) that have been incorporated into the Virtual CVD Laboratory Project.

Science & Engineering Practices	Crosscutting Concepts	Core Ideas*
1. Asking questions (for science) and defining problems (for engineering) 2. Developing and using models 3. Planning and carrying out investigations 4. Analyzing and interpreting data 5. Using mathematics, information and computer technology, and computational thinking 6. Constructing explanations (for science) and designing solutions (for engineering) 7. Engaging in argument from evidence 8. Obtaining, evaluating, and communicating information	• Patterns • Cause and effect: Mechanism and explanation • Scale, proportion and quantity • Systems and system models • Energy and matter: Flows, cycles, and conservation • Structure and function • Stability and change	Engineering, Technology, and the Application of Science (2 of 2) ETS 1 – Engineering design ETS 2 – Links among engineering, technology, science, and society Physical Sciences (2 of 4) PS 1 – Matter and its interactions PS 3 – Energy Earth and Space Sciences (1 of 3) ESS 3 – Earth and human activity Life Sciences (1 of 4) LS 1 – From molecules to organism: Structures and processes
*numbers in parentheses after each disciplinary area refer to the number core ideas addressed by this project out of the total number of core ideas identified by the Committee on Conceptual Framework for the New K-12 Science Education Standards. Crosscutting Concepts and Science & Engineering Practices are complete.		

Project-based learning (PBL) provides a pedagogical approach consistent with this framework. PBL has engaged students in engineering design at all levels in K-12 education (Sadler, Coyle, & Schwartz, 2000) and has involved students in learning and doing scientific practices (Krajcik, McNeill, & Reiser, 2007). The project discussed in this paper embodies a project-based pedagogy that incorporates engineering experiences into classroom practice, similar to projects described by Krajcik et al. (2007). One review of research on PBL put forth five criteria that projects must meet to be considered PBL experiences (Thomas, 2000). The first criteria is that projects must be (1) central to the curriculum. The next two address student ***motivation*** and the last two criteria address ***cognition***.

The two criteria described to promote student ***motivation*** are that projects must be (2) student-driven, and (3) authentic, real-life challenges (Thomas, 2000). According to the National Research Council (NRC) report *How People Learn*, students value situated, authentic projects more highly than traditional coursework and, consequently, are more motivated and more willing to invest time and effort into learning (*How People Learn: Brain, Mind, Experience, and School*, 2000). This assertion has been demonstrated in several project-based learning environments which reported high student motivation and involvement (Blumenfeld et al., 1991; Bradford, 2005; Hill & Smith, 1998). However, while student motivation is necessary, Blumenfled et al. (1991) emphasize the need for a strong link between motivation and cognition.

Cognition is the basis for the last two criteria for project-based learning environments, which require that a project (4) consist of driving questions that lead students to confront concepts and (5) contain central activities that promote transformation, construction and integration of knowledge (Thomas, 2000). In this paper, we explicitly address how the Virtual CVD Laboratory Project promotes the integration of knowledge and metacognition. Linn et al. (2006) describe knowledge integration as “when teachers use students' ideas as a starting point and guide the learners as they articulate their repertoire of ideas, add new ideas including visualizations, sort out these ideas in a variety of contexts, make connections among ideas at multiple levels of analysis, develop ever more nuanced criteria for evaluating ideas, and regularly reformulate increasingly interconnected views about the phenomena" (p. 1049). Promoting knowledge integration, especially within authentic, situated learning environments, has been shown to be an effective and durable teaching approach (*How People Learn: Brain, Mind, Experience, and School*, 2000). Finally, reflection and evaluation play a critical role in metacognition, the act of assessing and regulating one's own learning. This type of regulation has been shown to enhance one's learning and ability to transfer what is learned to new contexts (*How People Learn: Brain, Mind, Experience, and School*, 2000).

Epistemology is an important aspect of project-based learning pedagogies that is often not addressed. We define students' epistemological beliefs about engineering as their ideas about what it means to learn, understand, and practice engineering. The sophistication of high school students' epistemological beliefs has been positively linked to the likelihood of integrating knowledge (Qian & Alvermann, 2000), undergoing conceptual change, critical thinking, motivation, communication, and the ability to learn from team members (Hofer & Pintrich, 1997). Studies in engineering have posited that complex, ill-structured projects can enhance epistemological beliefs (Marra, Palmer, & Litzinger, 2000). It has also been suggested that virtual laboratories are a rich environment that affords the opportunity for growth of epistemological beliefs (Antonietti, Rasi, Imperio, & Sacco, 2000). A desired curricular outcome of the Virtual CVD Laboratory Project is to give students experience with an authentic, iterative, ill-structured problem such that they will develop more sophisticated epistemological beliefs that move towards those of practicing engineers and scientists.

4.5 The Virtual CVD Laboratory Project

The Virtual CVD Laboratory Project was created as an undergraduate chemical engineering laboratory project. The purpose was to fill a gap in the curriculum and provide students with a different type of laboratory experience than found in traditional laboratories. In a traditional laboratory, students often perform confirmation experiments in which they follow a prescribed investigation path and focus on getting the equipment to function properly in order to collect data. While these laboratories provide students with needed hands-on experience using physical equipment and can show students theory in practice, they have limitations. Time and materials constraints restrict the degree to which students can direct their own investigation. Students may even begin to have the epistemological belief that part of the nature of science and engineering is simply to run experiments to confirm an expected result as opposed to gathering information to guide the direction of investigation. Using a project-based learning pedagogy, the Virtual CVD Laboratory Project was created and used in college courses (M. D. Koretsky et al., 2008; Milo D Koretsky et al., 2006). It was then appropriately modified and extended to the high school level.

This project is situated in the electronics manufacturing industry and specifically focuses on one of the processes used to manufacture transistors, which form the building block for integrated circuits (ICs). The particular process is the deposition of a thin film on a batch of 200 wafers. While this topic is complex, it is readily made relevant to students through discussion about the many products that use ICs from this manufacturing process, such as their computers or cell phones. As with all manufacturing processes, there are performance metrics that are used to evaluate the quality of the product and process. These metrics include film uniformity, film thickness, reactant utilization, and development budget. The instructional design determines which performance metrics are explicitly evaluated. Additional information about the Virtual CVD Laboratory Project as well as an overview video including a brief description of project development, an illustration of some student activities, and student and teacher interview excerpts can be found at http://cbee.oregonstate.edu/education/VirtualCVD/. Interviews shown in the video were entirely separate from the interviews described in this paper.

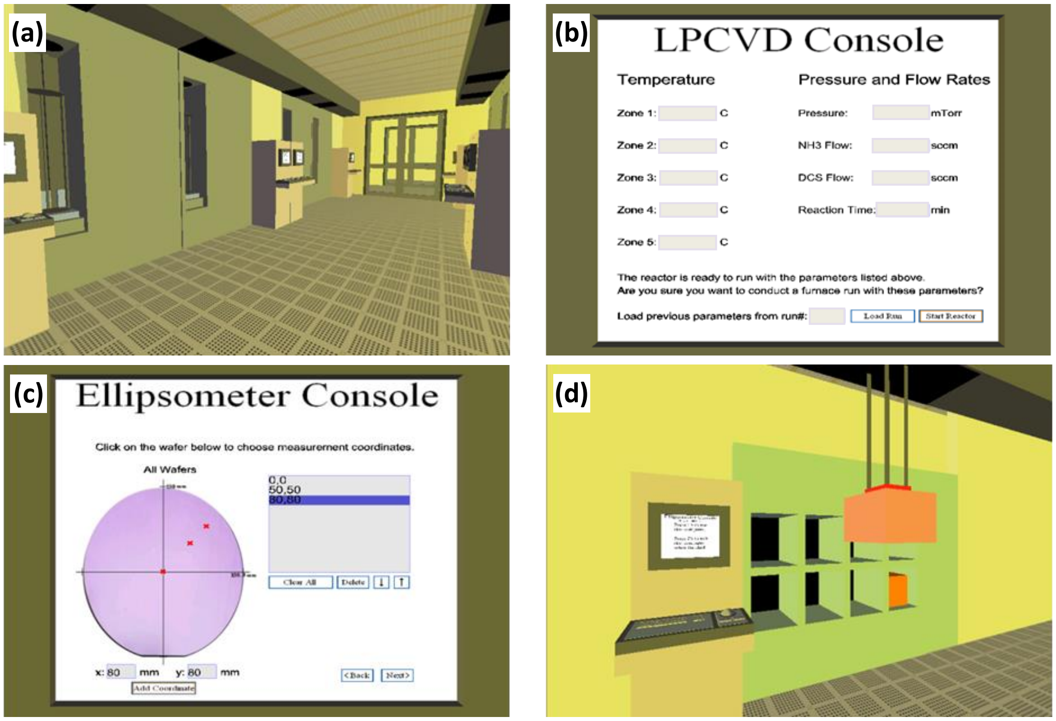
The project utilizes two essential components, the Software Design and the Instructional Design. The Software Design provides students with virtual equipment and data collection and gives the teacher a tool for project management and assessment. The Instructional Design, discussed in later sections, scaffolds the project and tailors it to the particular goals and objectives of the teacher.

4.5.1 Software Design

The Software Design is identical for all implementations and affords transportability. It is divided into two parts, the Student Interface and the Instructor Interface.

Student Interface

The Virtual CVD Laboratory student interface is comprised of both a 3-D option and an HTML option. The 3-D interface is recommended for use and can be made available on school computers or downloaded and installed on students' personal or home computers. Similar to many video games, the students navigate through a 3-D environment. This environment represents a virtual clean room that is modeled after a microelectronics fabrication facility. Screen capture images of the student interface are shown in Figure 1. Depending on the school’s information technology (IT) infrastructure, the teacher may opt instead to use the HTML interface. The HTML interface consists of a web-based interface with still images and text input fields and provides less interactivity.



LPCVD Console

Temperature

Zone 1: C
Zone 2: C
Zone 3: C
Zone 4: C
Zone 5: C

Pressure and Flow Rates

Pressure: mTorr
NH3 Flow: sccm
DCS Flow: sccm
Reaction Time: min

The reactor is ready to run with the parameters listed above.
Are you sure you want to conduct a furnace run with these parameters?

Load previous parameters from run#:

Ellipsometer Console

Click on the wafer below to choose measurement coordinates.

All Wafers

0,0
50,50
80,80

x: 80 mm y: 80 mm

Figure 4.1. Images of the student interface (a) navigating in the reactor bay, (b) inputting reactor variables to run the reactor, (c) choosing measurement positions in the ellipsometer console, and (d) watching wafers as they load into the ellipsometer.

To perform an experiment, students navigate to the reactor and input nine process variables: reaction time, reactor pressure, flow rate of ammonia (NH_3), flow rate of dichlorosilane (DCS), and the temperature in five zones in the reactor. The reactor behavior in this process is modeled after actual industrial equipment and based on scientific concepts and content. After entering the variable values and running the reactor, students navigate to one of the ellipsometers where they implement a measurement strategy choosing which wafers to measure, as well as the position of the points on each wafer. In some cases the measurement strategy is prescribed for students. The measurement results can be viewed in the student interface or exported to an Excel file for further analysis. For a more detailed view of the Software Design, a silent video walking through the virtual facility is available at http://cbee.oregonstate.edu/education/VirtualCVD/html/downloads/demo.mpg.

Instructor Interface

The instructor interface is a web interface that provides teachers with a convenient way to manage and administer the Virtual CVD Laboratory Project. In the instructor interface, teachers can change reactor characteristics, view student progress, assess student performance, and access instructional materials. Instructional materials include PowerPoint presentations and assignments used in other classes (high school, community college, and university levels), informational videos, and background information about CVD. Process error, measurement error, and systematic error can also be specified, adding the authenticity of real data and the ability to change operating conditions between cohorts.

4.6 Methods

To support the proposed claims, the Virtual CVD Laboratory Project implementation processes of five teachers were examined. The five high schools at which they teach have student populations ranging from approximately 350 students to 1100 students. The first teacher, who we call Teacher A, was involved in the pilot of the Virtual CVD Laboratory Project at the high school level. It was first implemented in a high school with a student population of approximately 1000 students. Teacher A collaborated with a graduate student during the curriculum development and implementation process. Teacher A was also involved in the preparation and presentation of multiple workshops based on the pilot experience. Workshops were designed to give attendees an overview of the Virtual CVD Laboratory Project and inspire them to use it in their classes [37]. Participation was incentivized by a small monetary stipend. Implementation of the Virtual CVD Laboratory Project by four workshop attendees who were teachers (Teachers B, C, D, and E) at other high schools is also examined. After use, the teachers reported on the implementation process.

Teachers B, C, D, and E completed a post-implementation questionnaire which described results of their implementation. It included questions about the following aspects: course information, student demographics, time spent on preparation and delivery, implementation activities and comments, intent to use the Virtual CVD Laboratory Project in future years, and how the project fit within their curriculum.

In addition, semi-structured interviews were conducted with Teachers A and B, after each had used the Virtual CVD Laboratory Project in class for more than two years. The intent was to gather more information on the implementation process and a deeper understanding of the teachers' perspective. These interviews were transcribed and the transcripts were examined for statements regarding the implementation process and the claims in this paper. Teacher and student perceptions provide support for and additional insight into the claims of promotion of motivation, cognition, and epistemology.

Implementation artifacts were collected from all five teachers. These artifacts provide an audit trail of the adaptation and implementation in the different high schools and include curricular schedules, assignments provided to students, and examples of student work. The examples of student work were selected by the each teacher, intended to represent high, medium and low performing students. Student work was the primary source for evidence relating to cognition, and also provided information about student motivation and epistemology. The Virtual CVD Laboratory instructor interface was used as a data source and provided supporting data on the usage history for each teacher which included number of classes, number of student groups, and project timeline.

4.7 Instructional Design – Pilot at the High School Level

The Virtual CVD Laboratory Project was used in eight classes (one section of *Introduction to Engineering* and seven sections of *Chemistry*) during the 2007-2008 academic year. In total, 123 teams completed over 1,500 runs and made over 60,000 measurements. The curriculum leveraged materials developed for undergraduate students, but modified and further scaffolded instruction to be level appropriate. A key element in the success of the pilot was involvement of a graduate student (one of the authors) in the high school curricular development and initial classroom delivery. While four teachers were involved in the pilot implementation, perceptions and data regarding these classes is from only one of those teachers and the graduate student collaborator. The pilot implementation is discussed in greater detail elsewhere (M. Koretsky, Gilbuena, & Kirsch, 2009).

4.7.1 Introduction to Engineering

Introduction to Engineering, comprised of 53 students most of whom were 9th-graders, was team taught by one science and one applied technology teacher. The Virtual CVD Laboratory Project was used to address the student learning objectives of the development of critical thinking and problem solving skills. It was expected to reinforce concepts of engineering design as embodied by the IDEAL model (**I**dentify, **D**evelop, **E**valuate, **A**ct, **L**ook back) (Bransford & Stein, 1993), a model emphasized in class. The project was also expected to provide a context for an introduction to the discipline of chemical engineering. The primary activities and the corresponding class days allocated are shown in Figure 2. The assignment icons are hyperlinked and can be clicked to access the assignment documents given in class.

Initially students were given a handout that emphasized the situated nature of the project. The two teachers acted as owners of a manufacturing company utilizing the CVD process and students, grouped in pairs, were asked to imagine themselves as process engineers. Students were tasked with determining the values of operating variables that would achieve a uniform film deposition upon each of 200 wafers. Simultaneously, they were told that each reactor run and thickness measurement costs money, and challenged to minimize the cost of their optimization process. Two deliverables were required: a written report listing optimized reactor variables coupled with evidence in the form of deposition measurements to substantiate optimization, and a laboratory journal documenting the team's actions and reasoning during the optimization process.

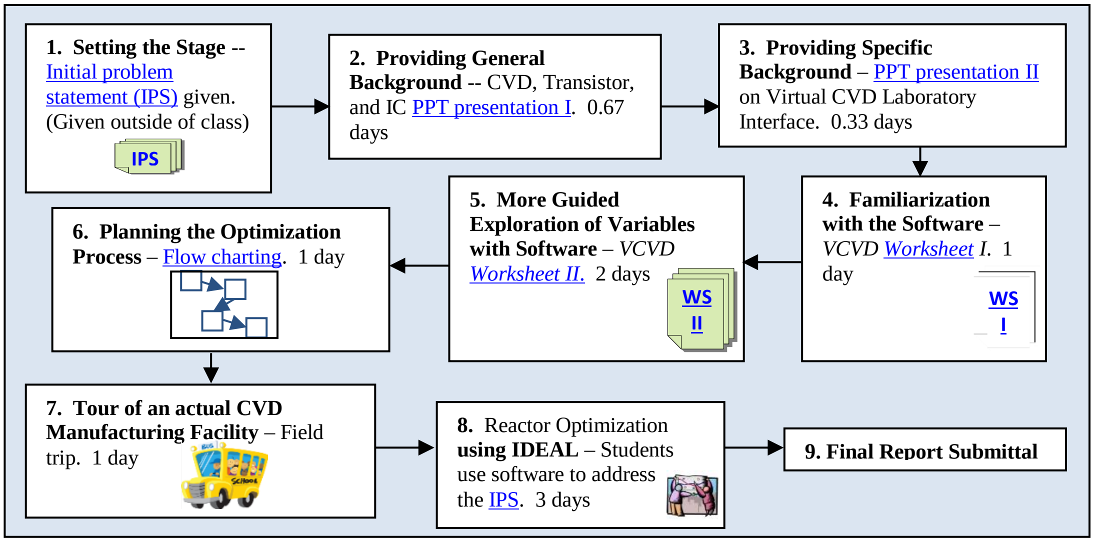


Figure 4.2. Activities for the Virtual CVD Laboratory Project in *Introduction to Engineering* class. Click on links or icons to view assignments.

The Initial Problem Statement (IPS) handout, presented in Step 1, was read by students outside of class. In Step 2, the instructor delivered an introduction PowerPoint (PPT) presentation, PPT presentation I, to provide an overview of transistors and ICs and an introduction to the CVD process used to manufacture transistors. Introduction to the Virtual CVD Laboratory 3-D student interface occurred during Step 3 through PPT presentation II. Step 4 provided hands-on experience in which students were guided through their first run with the step-by-step instructions of Worksheet I (WS I). In Step 5 students were given a second worksheet, (WS II), to complete which provided additional scaffolding. On this second worksheet, students were instructed to sequentially alter specific variables (e.g. change all reactor zone temperatures simultaneously by the same amount, increase the temperature of a single reactor zone, change chemical flow rates, and modify reaction time). Each change was made one at a time, to gain initial insights regarding variable impact on film deposition.

Step 6 asked students to use information gained in prior steps to develop an engineering design strategy for reactor optimization through flow charting. This strategy needed to consider and include several factors. What variables would be optimized first and last? What decision points would initiate advancement to the next stage of their plan? How would they evaluate information they gathered? To facilitate this process, students were asked to illustrate their plan with a flow chart. On a field trip, students toured a CVD facility operated by a local community business partner during Step 7. The tour was limited to viewing the equipment from observation windows; however, it provided students the opportunity to interact with CVD process engineers who responded to student questions. In this way, students obtained additional insights into their optimization plans. This field trip experience increased the sense of authenticity for this project. Next, students were given class time to pursue reactor optimization, originally described in the IPS, in a self-directed manner in Step 8. The project ended in Step 9 with submission of final reports.

4.7.2 Chemistry

The pilot implementation was expanded to 1st-year *Chemistry*, which involved 210 high school students enrolled in seven nearly identical sections taught by three different teachers. The overall goals for the Virtual CVD Laboratory Project in *Chemistry* were similar to the goals for *Introduction to Engineering*. However, whereas the use of the Virtual CVD Laboratory Project was intended to reinforce concepts of engineering design for the engineering students, it was meant to help the chemistry students develop skills in scientific inquiry, develop the ability to identify and quantify relationships between variables, and reinforce the chemistry concepts. Again tasks were framed within the situated context of an industrial manufacturing environment; however, the designated roles changed. Student groups now represented consultants hired by the owners of the company to characterize the CVD reactor operation rather than optimize for a target film thickness. Specifically, students were asked to determine how changing variable values impacts film deposition with the Investigating Factors Impacting Deposition assignment. They had to relate the experimental observations to chemistry topics such as stoichiometry and reaction kinetics. In doing so, they had to decide what and how much information to obtain and how to display their results so that they could convince the owners. In addition, accrued costs were to be minimized. Students responded with uncomfortable questions surrounding the ambiguity of the assignment. What trials should be run? How many data points are sufficient when drawing conclusions about relationships? What graphs should be produced to illustrate the desired relationships? Prior to the dedicated class time for this project students were given the Chemistry Initial Problem Statement (IPS-Chem), a handout similar to but distinctly different from the one given in ITE. The initial homework described in the IPS-Chem was intended to help them connect this project to previous class material. In addition, another pedagogical feature added to help *Chemistry* students answer these questions was a Peer Review process in which they exchanged the first draft of their final report with another group and provided critiques.

Even within the pilot implementation, the differences in learning objectives, assignments, and student roles illustrate our claim of the ***versatility*** of the Virtual CVD Laboratory Project. The next section compares and contrasts all of the high schools that used this project, further illustrating ***versatility***.

4.8 Adaptation and Implementation – A Demonstration of Versatility

In this section, we present evidence that the instructional design of the Virtual CVD Laboratory Project is ***versatile*** and adaptable to needs of students, teachers, class, and context. This evidence includes an account of the different types of classes in which this project has been used, the variety of goals and objectives teachers have addressed with this project, the flexible timelines that have been utilized, and the rich selection of activities that have been chosen to meet the goals and objectives. Table 4.2 summarizes the types of classes in which the Virtual CVD Laboratory Project has been used, the corresponding need in teaching it fulfilled, and the content and concepts it addressed.

Table 4.2. Summary of the needs in teaching and specific concept and content objectives for each class in which the Virtual CVD Laboratory Project was implemented.

Class	Teacher	What need in teaching did the Virtual CVD Laboratory fill? (Goals)	Specific concepts and content addressed (Objectives)
Introduction to Engineering	A	• Provide an authentic, real world project experience • Critical thinking • Problem solving	• Engineering design (IDEAL model) • Introduction to discipline of Chemical Engineering
Chemistry	A	• Provide an authentic, real world project experience • Critical thinking • Problem solving	• Stoichiometry • Reaction kinetics • Identification and quantification of the interaction of variables • Presentation of graphical data and correlations
	B	• Provide an authentic, real world project experience • Give chemistry principles a tangible context • Integration of other classes (math) • Scientific inquiry	• Stoichiometry • Presentation of graphical data and correlations • Interpreting data • Manipulate data
	C	• Provide an authentic, real world project experience • Rely on previous knowledge and apply it to a real life situation	• Stoichiometry • Reaction kinetics • Equilibrium • Redox reactions
Physics	D	• Provide an authentic, real world project experience • Provide an extended engineering project	• Engineering design • Identification and quantification of the interaction of variables • Interpreting large amounts of data
Biology	E	• Provide an authentic, real world project experience • Address new state standards related to engineering design • Cooperate and interact to solve a problem	• Stoichiometry • Reaction kinetics • Engineering design • Identification and quantification of the interaction of variables • Isolation of variables • Hazardous waste issues • Group collaboration

These elements were identified by the teachers in surveys and interviews, as described in the Methods section of this paper. We associate the second element with the teachers' goals and the third element with the teachers' learning objectives. The project has been implemented in a diverse set of classes including: *Introduction to*

Engineering, *General and Advanced Placement (AP) Chemistry*, *General and AP Physics*, and *AP Biology*. These classes range in size from as small as 6 students to more than 50 students. Class demographics range from 100% male students to more than 70% female students, with a variety of ethnic compositions.

Versatility is demonstrated by the wide variety of goals and objectives for these classes. All teachers explicitly stated the goal of providing an authentic, real world project and they typically placed students in the role of engineers or scientists in industry. However, the other goals identified by teachers vary and include developing critical thinking, problem solving skills, promoting knowledge integration, addressing the Oregon State Standard of Engineering Design, and collaborating in problem solving. While diverse, all of these goals address the type of higher order thinking skills cited in the AAAS report.

In general, the objectives can be divided into course specific science content and concepts (e.g., stoichiometry and reaction kinetics in *Chemistry* and *Biology*) and more general engineering skills (e.g., engineering design, presentation of graphical data, identification and quantification of the interaction of variables). While there is overlap in objectives, no two teachers identified the exact same set, which suggests that the project has sufficient versatility for teachers to adapt it to meet learning needs in the context of their class and curriculum. Moreover, there are five objectives that are distinctly unique and presented each in only a single class.

Figure 4.3 shows a timeline of the project delivery for each of the classes. Across each row, a daily account of the activities that a given instructor chose to deploy is shown in chronological order. Many of the activity icons are hyperlinked and can be clicked to access the actual assignments. The overall in-class time ranged from four to nine days, demonstrating flexibility in the timeline. The longest implementations were in the classes where students spent significant project time optimizing the reactor (*Introduction to Engineering* and *Physics*). Although the length of a class day varied, this unit of measurement offers a reasonable basis for comparison.

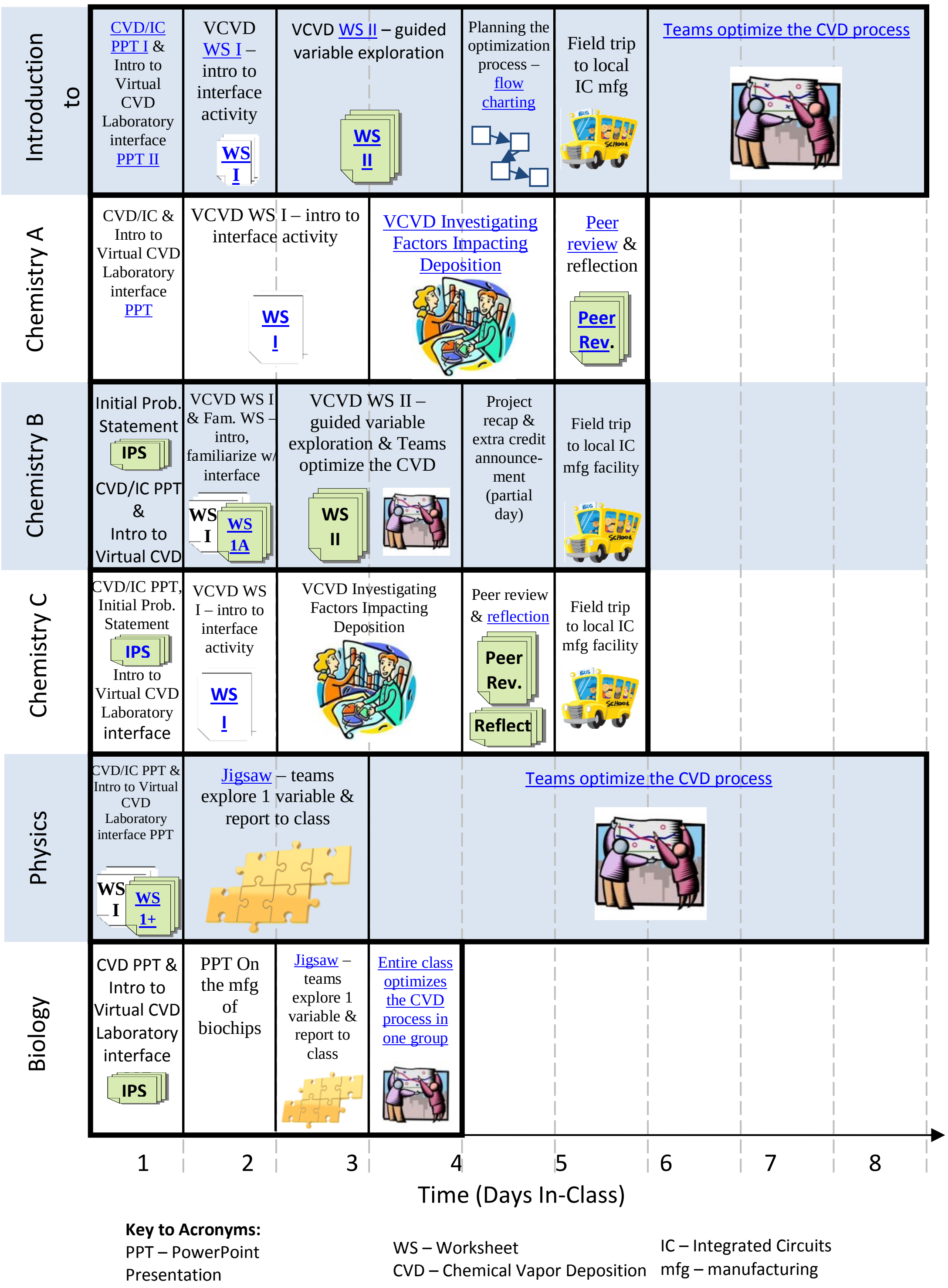


Figure 4.3. Timeline and in-class curricular activities of implementations. Out-of-class activities (e.g., IPS for ITE and IPS-Chem) not shown. Click on links or icons to view assignments.

Another demonstration of the ***versatility*** of the Virtual CVD Laboratory Project is the variety of activities that were employed in instruction. This project affords teachers the ability to structure activities in ways that reinforce the goals and objectives of a specific class; thus each implementation followed its own path. Some classes started the project with a homework assignment, often included in the Initial Problem Statement, similar to preparatory homework included in IPS-Chem. Two classes included in-class preparatory instruction prior to the project on skills and knowledge the students would need (computer basics in *Physics* and reaction kinetics in *Biology*). While all classes had introductory PowerPoint presentations for the project, their content varied to align with the context of the class and background of the students. For example, in *Biology*, the introductory presentation uniquely included "*the manufacture of 'biochips' and layer deposition on DNA microarrays.*"

The guided activity in which students investigated the impact of input variables on film deposition was also accomplished in different ways. Four classes utilized a guided variable exploration worksheet, labeled as WS II or Investigating Factors Impacting Deposition, with each team exploring the input variables; there were varying degrees of scaffolding within and preceding this exercise. The other two classes had each team of students investigate the impact of a single variable and report results of the investigation to the entire class through a jigsaw exercise.

Four of the six classes incorporated an explicit optimization portion of the project, one of which put the entire class on a single optimization team. Another class had an implicit optimization, as evidenced by student work. As shown in Figure 3, the

Introduction to Engineering class included a flow charting activity to scaffold engineering design in the optimization process. Three classes incorporated a field trip to a local IC manufacturing facility to reinforce the authentic nature of the project and provide students with an opportunity to connect with and ask questions of engineers in industry.

Reflection exercises were also executed in different ways by different teachers. Most teachers requested reflection in the final report. All teachers facilitated in-class reflective discussion about the project. Two teachers used the formal Peer Review process to scaffold reflection on the draft of the final report. One teacher asked students to submit a reflection paper on the project as a final assignment.

Finally, assessment of the project varied widely. One teacher primarily evaluated students based on an in-class presentation. Another teacher graded all worksheets and the final report and structured an extra credit rubric in which students were rewarded for: (1) achieving the best film uniformity (how even the film thickness is) while staying within the given budget and (2) achieving the highest reactant utilization (the proportion of input gas that is used to grow the film) within the given budget. The second area encouraged students to conserve reactants, illustrating the idea of green engineering. Because assessment of open-ended projects can be difficult, the flexibility in the number and type of activities in this project affords tailoring assessment to the needs of students and the availability of teachers.

The section above provided evidence of ***versatility.*** The Virtual CVD Laboratory Project has been used in a variety of classes to accomplish a range of goals and objectives with varied project timelines and activities. We next present evidence of the remaining claims through project outcomes.

4.9 Project Effectiveness – Outcomes

4.9.1 Motivation

We claim that the authentic nature of the project provides ***motivation*** for students. Every teacher identified the authentic nature of the project, both as a goal and an outcome. Authentic projects have been shown to increase student motivation (Dede et al., 1996). Although none of the questions to them specifically addressed motivation, four teachers directly commented on perceived student motivation and engagement:

> *"I think that CVD is pretty engaging* [for students]*." (Teacher A interview)*
> *"they have a, um, a limit on the money they are supposed to spend and some of them actually get so into it that they don't care. They will blow through the money because they want to get, like, the perfect answer, which is kind of cool." (Teacher B interview)*
> *"Every student was actively engaged…priceless!" (verbatim, Teacher C)*
> *"Overall a very valuable and motivational lab simulation!" (Teacher E)*

Student opinions of the project were not specifically requested in most assignments and motivation was not explicitly addressed in any assignment. However, students also volunteered comments that support this claim. Two examples illustrate this perspective:

> *"This project was actually really fun to do it was a great way to learn what actually goes on in that type of situation and how stressful it was to get the correct formula."(student Chemistry C)*
> *"In conclusion I would just like to express my appreciation for this assignment. It has really helped me to better understand and comprehend just how tough and exciting a career in this field really is." (student Physics)*

The positive affective responses indicated above are directly coupled to the cognitive challenge of the project.

4.9.2 Cognition

This section provides evidence for the claim that the Virtual CVD Laboratory Project promotes types of ***cognition*** that cultivate student ability in scientific inquiry and engineering design. Specifically, we focus on higher order thinking processes, including knowledge integration, engineering design strategies, and evaluation and reflection. We also show how the project enables teacher assessment of students' progress towards this type of learning in a subsection labeled "teachable moments."

Knowledge Integration

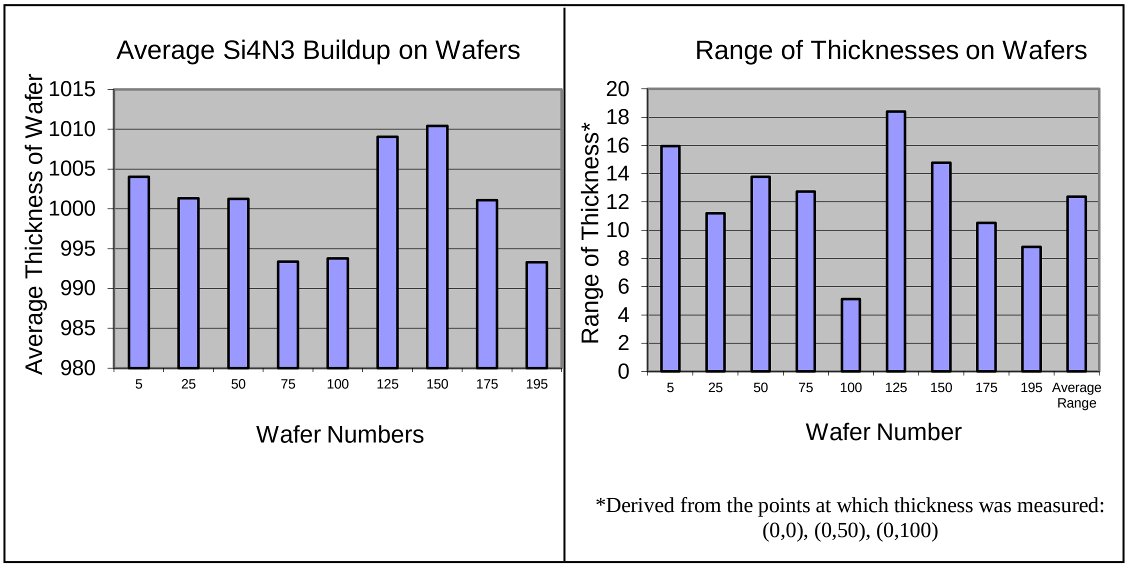
As discussed previously, two teachers explicitly identified knowledge integration as a learning goal for the project. In the post-implementation questionnaire, both teachers commented that their students successfully achieved this goal. For example, one teacher stated:

> *"This unit more than any other unit forced students to fully rely upon their previous knowledge learned in chemistry, and apply it in a real life situation."*

In student work, we see evidence of knowledge integration in two ways. First, students explain phenomena they observe in the project with analogies to more common life experiences. For example, one student team drew an analogy between the variable of deposition time and falling snow:

> *"The best way to explain what happens in the reaction time factor is to think about a snowstorm. Regardless of how thick the snow is falling, the longer it snow [sic], the thicker the snow cover on the ground will be. The longer the reaction time is, the thicker the cover on the wafers will be."*

The second way students demonstrate knowledge integration is by recognizing and activating concepts from other coursework. We illustrate this point with an example in which statistics is used in analysis and communication. Every class required students to create and present graphs to support their claims. Figure 4 shows summary graphs taken directly from one team's final report in *Introduction to Engineering*. This team demonstrates an ability to use knowledge of statistics to provide evidence that they had successfully optimized the reactor variables. They report two graphs; one graph presents average film thickness on a given wafer (i.e., the central tendency) and the other presents the range (i.e., dispersion). The team from Figure 4.4 was not directed to apply their knowledge of statistics; therefore, we propose this integration of knowledge is *genuine*. Contextual and creative integration of statistical methods were demonstrated overall at a surprisingly high level for the 9th grade cohort in *Introduction to Engineering*. We see similar occurrences of knowledge integration, at varying levels, in all six classes.



*Derived from the points at which thickness was measured: (0,0), (0,50), (0,100)

Figure 4.4. Graphical results reported from one team in *Introduction to Engineering.* They report measurements of central tendency and measurements of dispersion. Note: y-axis units are missing.

4.9.3 Engineering Design Strategy

Engineering design strategy was explicitly identified as an objective by three teachers. Not only is engineering design a core idea (ETS 1, shown in Table 1) in *A Framework for K-12 Science Education*, but the intentional focus on engineering design strategy also reinforces the practices of science and engineering described in the framework (C. o. C. F. f. t. N. K.-S. E. Standards & Council, 2011). Engineering design strategy is demonstrated as an outcome in every class; for example, consider again the student team from the statistics discussion above (Figure 4.4). This team explored process and measurement variation. In the Virtual CVD Laboratory, four different ellipsometers can be used to measure film thickness. While in this class, all of the ellipsometers had the same measurement error, some students perceived differences between readings when using different ellipsometers and this particular team made sure to perform all measurements using the same ellipsometer to reduce measurement variation.

A similar example of engineering design strategy occurred at the beginning of the jigsaw exercise in *Biology*; the teacher had initially planned for groups to explore each of the variables; however, during the introductory discussion for this exercise, the students themselves suggested adding a control group to investigate the process and measurement variation. This response again integrates principles of statistics. With support from the teacher, the control group was added to the experimental design. The students that suggested the use of a control group were previously considered to be lower performing students; however, in this case they demonstrated initiative and an ability to identify a missing element of the experimental design. While one might argue that these students advocated for the control group because they perceived it would take less effort, this was not the belief of their experienced teacher who commented on their high performance and commended the exploration of process and measurement variation as an important, authentic engineering consideration. The situated nature of the tasks in the Virtual CVD Laboratory Project seems to create a heightened awareness of possible realistic, complicating factors and an appropriate response to these factors – a desired, ***cognitive*** outcome.

Other teams used statistics to evaluate the impact each variable had on film deposition, influencing their engineering design strategies. For example, a team in *Introduction to Engineering* wrote:

> *"We did not decide to change the temperature zone without thinking about the other parameters and their possibilities first. There were two other choices of parameters that we could have changed: flow rate (keeping the 10:1 ratio) and reaction time. We had learned in our preparation that both flow rate and reaction time had their own effects, both positive and negative, on the wafer deposition. We also noticed, however, that these effects were a little weaker than when we changed the temperature zones. Changes could be made concerning wafer deposition with both the flow rate and the reaction time. These were relatively minor changes, for us, compared to changes that we were able to make by adjusting the temperatures of individual zones 1 through 5. Changing temperature was a factor that we could change with much variability. With the zones, we were able to pinpoint exactly what wafer numbers needed to be thicker or thinner. We decided that we would choose to change the zone temperatures basically to maintain control of our runs and our trials."*

In this description, students identified differences in the relative magnitudes of the impact of variables on film deposition, choosing to work with the more significant variables first (temperatures). In essence they had intuitively performed a *Screening Experiment*, which is covered at the university in courses on Design of Experiments. They also recognized that some variables (zonal temperatures) could be used to affect changes on specific groups of wafers while other variables were better suited to affect changes upon all wafers. This realization directed their optimization strategy.

4.9.4 Evaluation and Reflection

Elements of evaluation and reflection were demonstrated in all the classes in many different ways. For example, a student team from the *Chemistry A* class graphed reaction time versus film thickness, as shown in Figure 4.5. Teams were instructed to use linear regression to quantify the correlation between variables, essentially, asked to develop simple models of the cause and effect relationship between variables and performance metrics. Towards this end, this team evaluated the suitability of using five data points to sufficiently quantify the relationship between film thickness and reaction time.

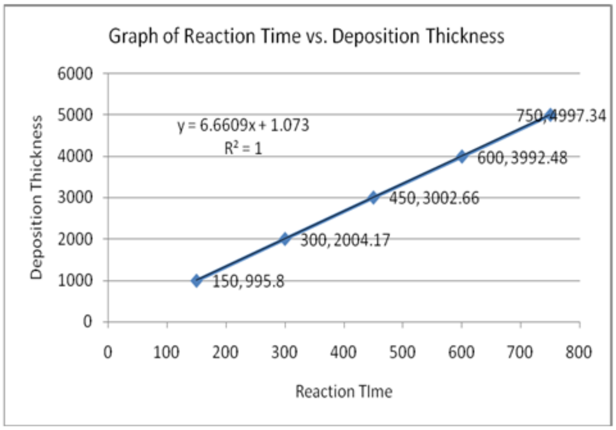


Figure 4.5. Graphical results reported by one team in *Chemistry*, showing their method for determining the effect of reaction time on film thickness. Note: axis units are missing.

> *"We believe that we have collected sufficient data because of the consistency and the number of points we had. If we were only to test 2 or 3 points, we still wouldn't be able to say much about the deposition thickness, because we don't have enough data points. However, we have five total data points (excluding the point (0,0)), which we believe is enough to come up with a rough sketch of the graph. In addition, the data points have an amazing correlation. They are almost perfectly linear. On the graph, it can be seen that the thin, black line matches almost perfectly with the thick, blue line (the one that corresponds to the data points)." (student team Chemistry A)*

One team from *Chemistry C* performed evaluation and reflection in relation to what they could do better. They had achieved a high uniformity within a reasonable budget, but in their final report commented on what they would change or explore further if given additional time on the project:

> *"We did really well and would probably only change our efficiency on how much DCS we used, other than that we did well." (student team Chemistry C)*

In this class, students had been tasked with understanding how variables interacted to produce uniform films and tasked with minimizing the development budget. Conserving reactants was not one of the stated objectives. However, in industry, increasing the utilization of hazardous and expensive gases is important, an aspect apparently recognized by this team.

Another team in *Chemistry C* had simultaneously changed several variables during each of their reactor runs. They presented graphs in their final report and discussed the impact of the variables to the film thickness and uniformity. However, they also noted that the other variables were not held constant in the displayed data sets, making it difficult to form strong supporting evidence for the impact of each variable, individually. One student in this group reflected on the group's strategy and commented that changing a single variable at a time would be a beneficial approach to take.

> *"I would also keep a pattern going, such as changing only the temperature and leaving the* NH_3 *and DCS flow alone. I feel that changing those two greatly changed our outcome."(student Chemistry C)*

The instructional design and implementation of this project promotes reflection and evaluation in students. This was seen in justification of choices made, acknowledgment that a different engineering design strategy could have been more beneficial, and in hypothetical future plans. One project assignment specifically designed to promote reflection, the Peer Review in *Chemistry A*, arose as a result of a teachable moment and is discussed in the following section.

4.9.5 Teachable Moments – Assessment and Identification of Missing Knowledge

Several teachable moments arose during these implementations of the Virtual CVD Laboratory Project which revealed additional opportunities for teachers to modify the instructional design to promote ***cognition***. Four examples are presented below.

The first example of a teachable moment resulted in the addition of a structured reflection activity in the pilot *Chemistry A* implementation. Originally, the project was scheduled to end with the guided variable exploration and final report. However, when the reports were first submitted, it was evident to the teacher that many students were unable to effectively communicate the impact of reactor variables on film deposition. As a result, a Peer Review assignment was added. This exercise included a brief period of instructor-led discussion that sought to identify shortcomings in graphs and relationships between variables. Students exchanged reports with one another and were asked simply, “Would you be convinced by the evidence presented if you were the owner receiving this report?” and “Do you even understand what the graphs are representing?” They were asked to respond in writing to the team whose paper they were reviewing, and to provide a list of questions about the presented results intended to focus the authors’ attention to shortcomings in their analysis and presentation of data. Once papers were returned to their original owners, students had a week to address identified shortcomings and resubmit the report.

The second example of a teachable moment is illustrated by the integration of mathematics content and concepts. To minimize the cost of their experimentation and adequately convey the relationship between dependent variables (e.g., film thickness) and independent variables (e.g., reactor temperature or wafer location in the reactor), students must carefully construct graphs to support their claims. Surprisingly, formulating what to plot was very difficult for many students. When given a textbook problem with a given *x* and a given *y*, they may be proficient. However, with the Virtual CVD Laboratory Project, many teachers noted that some students were overwhelmed with the number of variables and multiple columns of data from which to choose. Students often lacked the clarity to define which of these columns to select as independent and dependent variables. After struggling, frustration, and teacher coaching, the students came to realize the importance of identifying independent and dependent variables. This identification further enables careful consideration of the data that needs to be collected and informs students' engineering design strategy.

The third teachable moment example is related to development of an engineering design strategy in the *Introduction to Engineering* class. Because it was anticipated that students would have difficulty developing an engineering design strategy, the flow charting exercise was intended to scaffold and assist them. Of the twenty-seven student teams in this class, only two teams were observed to actually utilize their flow charts to guide their initial optimization process. Most teams, when entering the self-directed phase, proceeded with optimization in a random fashion despite their previous planning. Students, in general, seem to have difficulty adhering to their plans as opposed to randomly experimenting.

The last noted teachable moment related to cognition in students is a point that requires further study. It has been a common belief at the university level that this project gives low and average performing students an opportunity to excel while some high achieving students struggle. One high school teacher made a similar observation. In *Biology*, two students who had previously performed well in “wet labs” had difficulties in this project. In contrast, several students who had previously performed poorly in “wet labs” excelled in this project with an example being those students, previously discussed, that initiated the control group investigation.

4.9.6 Epistemological beliefs

As discussed above, one goal of all of the teachers was to provide an authentic, real world project through placing students in the role of engineers or scientists in this industrial context. We believe that providing learning in such a context leads to development of students’ epistemological beliefs, i.e., their views about what it means to learn, understand, and practice engineering. Survey responses of university students reported elsewhere (M. Koretsky et al., 2011) indicate that perceptions of the nature of the tasks and the cognitive demands embedded in the Virtual CVD Laboratory Project coincide with more sophisticated epistemological beliefs, even more so than the open-ended physical laboratories in their senior year. However, at the high school level, neither students nor teachers were asked directly about their epistemological beliefs, and this claim warrants more investigation.

There is evidence within the teachers’ comments that suggests this project influences students’ epistemological beliefs. For example, one teacher stated:

> *“There’s definitely a push in education to go more inquiry. When I was in high school and probably when you were in high school, it was more like there was [sic] these set paths, labs that you do and you have to have these results [referring to confirmation experiments]. And there is more and*

> *more wanting them to be like real scientists to do, discover their own stuff. So I'm feeling like this [the Virtual CVD Laboratory Project] is kind of meeting that need too. We need to do, a lot of our chemistry labs are still very prescribed, and so I'm trying to work away from that and this is one way that we are definitely doing it and allowing them to act like real scientists and real engineers." (Teacher B)*

The nature of cognition is more authentic ("go more inquiry") and less prescribed ("set paths") which enables the students to "act like real scientists and real engineers," and by extension view knowledge in engineering as more of an evidence-based reasoning process rather than trusting the word of an authority. This point is succinctly reiterated in one of the surveys:

> *"The value has been that each of my students had the opportunity to taste what engineering was." (Teacher C)*

The following student reflection also suggests students came to consider the project "like real engineers" in the context of industrial practice:

> *"I personally feel that if I were a company I would like all the wafers to be closely related in angstroms" (student in Chemistry C)*

If we return to the ***cognitive*** theme of knowledge integration of statistics, discussed above, the impact of project authenticity on student ***epistemological beliefs*** is also illustrated. One student team used statistical methods to make sense of the project's manufacturing context. Their understanding is demonstrated in the following excerpt from the final report in *Introduction to Engineering*:

> *"Using Microsoft excel, we also calculated that the average wafer deposition is about 999.2 angstroms with a standard deviation of about 6.74. What this means is that 68% of all wafers are between 992.5 and 1005.9 angstroms in deposition, and 98% of all wafers are between 985.7 and 1012.7 angstroms in deposition. Assuming that all wafers produced must be within 15 of 1000 angstroms, only about 1% of all wafers*

> *produced would have to be discarded due to defects."(student team Introduction to Engineering)*

Although implicit, this strategy aligns with concepts of Statistical Process Control taught in industrial engineering. The view of applying process data to predict manufacturing performance represents an unusually sophisticated epistemological belief.

A general and holistic examination of this work leads to the claim that the students' epistemological beliefs become more sophisticated as they complete this project. To investigate this claim further, a reliable and valid instrument like the Epistemological Beliefs Assessment about Physical Science (EBAPS) (Elby, Frederiksen, Schwarz, & White, 1997), which was specifically developed for high school students, could be administered before and after the project.

4.10 Barriers to Adoption

There are several reasons teachers choose not to implement effective educational interventions. We believe that one of the first steps to addressing and minimizing barriers is to identify them and make them explicit. We have initially identified three potential barriers to adoption: IT infrastructure, preparation time, and project assessment.

4.10.1 IT Infrastructure

Beyond having access to a computer, the two primary IT requirements for this project are internet access and appropriate performance specifications. The 3-D interface requires installation and appropriate video drivers in order to operate smoothly. In contrast, The HTML interface requires no installation and minimal performance specifications. During implementation, two teachers exclusively used the 3-D interface, two exclusively used the HTML interface and one used both. Three teachers commented on issues with IT infrastructure, one of whom used only the HTML interface because the 3-D interface could not be installed on school computers, despite simple and successful installation at home. Both teachers that were interviewed expressed the need to check school computers each year to verify that settings and software updates weren't conflicting with the operation of the 3-D interface; both had experienced issues resulting from computer changes. IT infrastructure is a potential barrier for any educational technology and other technology-based educational tools have faced similar challenges (Owston, 2007). Currently, the HTML interface affords the use of the Virtual CVD Laboratory Project for schools that cannot support the 3-D interface. A web-page embedded, 3-D option is in development to help mitigate IT infrastructure issues.

4.10.2 Preparation Time

The preparation time reported for the project ranged from 2 to 30 hours with an average of approximately 15 hours. Several factors are expected to impact preparation time such as course topic, number of classes, number of students, and types of assignments. One teacher had attempted to get colleagues to use this project and cited preparation time as the biggest barrier for them:

> *"for them to take the time to meet with me to learn it, to understand it, and then to work it into their curriculum."*

Another teacher compared the initial preparation time for the Virtual Laboratory Project and hands-on, physical laboratories as similar.

> *"Well for the first time, [if you] haven't done either the hands-on lab or the CVD before, you'd probably end up spending about the same time I would think. It would depend on the hand [sic] on lab of course. If there's a lot of chemicals and a lot of reactions then you have to sit there and fine tune quantities and stuff, that could be longer."*

This teacher further emphasized that required preparation time decreases substantially in years following the initial year, and that the initial time investment is a crucial barrier for any curricular implementation:

> *"if I had to I could probably get up right now and open up one of those old PowerPoints and talk about a transistor and what it is, and how this all fits in, and then describe for them how to log in, and how to generally go about it, what the assignments are about, without doing much prep. But I've done it for two or three years and that's usually, I mean, it's true for any teacher I think. If you do something enough it comes back pretty quickly so prep time is minimal. <u>It's that first year or two that is the crucial piece</u>. So if you are going to convince a teacher to use something it is going to have to be good to convince them in the first place and then once they have invested the time to use it, it'll probably keep being used."*

4.10.3 Project Assessment

Project assessment was the third barrier to adoption, which came up in one interview. The following interview excerpt cites a teacher's concern, not just with assessment of the Virtual CVD Laboratory Project, but with any open-ended projects that are ambiguous and require critical and creative thinking:

> *"we are asking the kids really to think about a lot of things and make some decisions…how do you grade the person who does that minimally, minimal effort, with someone who has really thought it through well?… you just find yourself, why you can justify it, there are reasons why you can score things low. It's much harder to justify… And so for this activity, it's very much in that direction where there's going to be some issues and it's going to be obvious when kids aren't trying and you are going to have to defend your decisions and it's, it's uh for that reason teachers could be less inclined to take on, an activity like that. I know it seems silly and I know that as a teacher you should really be trying to, um, give kids the best experience possible, but that, having that, thinking about having to defend*

> *yourself is very much, um, a factor when you are deciding how you are going to do things in a classroom."*

The environment of having to "defend yourself" when giving a student "who does that (the project) minimally, (with) minimal effort" a poor grade can be "a factor when you are deciding how you are deciding how you are going to do things in a classroom," and drive teachers to abandon these type of project-based learning experiences in favor of more directive activities that are more clearly graded. Such a decision would preclude the benefits discussed in the claims above and lead to curricular decisions counter to those advocated in *A Framework for K-12 Science Education*. This concern did not arise in the other teachers' responses, but it was also not directly asked. We believe further investigation is needed.

Despite the barriers to adoption, all high school teachers that provided feedback indicated that they intended to continue using this project in their classes.

4.11 Conclusions

To provide a meaningful learning environment and acknowledge the ideals echoed in Education Standards, students must be given the opportunity to actively engage in problems that are perceived as authentic. Students must be given the opportunity to tackle ill-structured problems (as opposed to typical text-book problems) that not only compel them to seek knowledge and understanding for themselves, but also require *iteration* where knowledge they learn in one attempt can be integrated to improve the next attempt. Often they learn the most when they are not successful and make mistakes, intrinsic pieces of the engineering process. Only by forcing students to perceive such results as opportunities instead of things to be feared, will we truly prepare our students to make meaning of engineering and science in the real world. This work is based on the premise that one of our students' greatest values to our future society will be their ability to contend with open-endedness and ambiguity to provide solutions to the problems they themselves identify.

The Virtual CVD Laboratory Project has been shown to be versatile and promote student motivation, cognition and epistemology. We have also identified three barriers to adoption for this project which include IT infrastructure, preparation time, and project assessment. In this paper, we have illustrated how the Virtual CVD Laboratory Project engages students in ways that are described by the current standards, including engineering design and scientific inquiry, as well as the framework being used to develop Next Generation Science Standards. We believe that other such intentionally-designed, computer-enabled, project-based learning environments can be similarly developed based on authentic, situated projects in order to realize the vision set forth for science and engineering education.

Access to the project (including software and instructional materials) described in this paper is restricted to teachers, but is freely available through a simple authorization process. For more information about the authorization process and the project described in this paper, readers are encouraged to visit http://cbee.oregonstate.edu/education/VirtualCVD/ or contact the corresponding author.

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5. General Conclusion

This dissertation presented three journal articles. Two are submitted, while one is already in print. In the article presented in Chapter 2, four characteristics of feedback are presented: a list and categorization of episode themes, the structure and flow of episodes during the coaching session, the sub-structure present within individual episodes, and the types of feedback present. This article showed how each of these characteristics provides a useful tool to scaffold interaction in project-based learning. It also illustrated similarities and differences between teams and described how the different categories, Student Project Objectives and Coach Objectives are intertwined. This research also showed how feedback on Professional Skills was often embedded within a larger, more technical discussion.

In Chapter 3, a more detailed investigation of Professional Skills was presented. This article illustrates what feedback on Professional Skills looks like through the identification of the Professional Skills addressed in the Virtual CVD Process Development Project. It also identified the following Professional Skills as being attended to in this project: communication, experimental documentation, teamwork, the impact of engineering solutions on the economic and societal context, and project management. This article provided detailed examples of interactions in order to contribute to how these skills are defined in engineering. It also illustrates how feedback on these skills help students become more central participants in a community of practice because of how this feedback alerts students to some of the ways professional skills are part what engineers do and how they are perceived by their peers. For example, one purpose of communication is to express and convey ideas such that another individual can understand. However, another purpose of communication can also be to symbolize legitimate participation in a community of practice, e.g., through demonstrating an understanding of the roles of different community members.

In Chapter 4, the focus shifts slightly to illuminate a different aspect of the Virtual CVD Process Development Project. The focus shifts from investigating the project itself to investigating the spread of the project at the high school level. In this chapter, the Virtual CVD Process Development Project was shown to be versatile and promote student motivation, cognition and epistemology. Three barriers to adoption were also identified for this project, which include IT infrastructure, preparation time, and project assessment.

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APPENDICES

Appendix A - Episodes as a Discourse Analysis Framework to Examine Feedback in an Industrially Situated Virtual Laboratory Project

Gilbuena, D., Sherrett, B., Gummer, E., & Koretsky, M. D.

Proceedings of the 2011 American Society for Engineering Education Annual
Conference & Exposition.
Vancouver, B.C.

Introduction

Feedback has been shown to be one of the most important tools used by faculty to help students close the gap between actual and desired performance. Additionally authentic, situated environments are believed to benefit student learning. Studies of feedback in situated projects are uncommon and needed. This study proposes the use of *episodes* as a discourse analysis framework to investigate feedback in an industrially situated virtual laboratory project. While episodes have been used in other disciplines, they present a new framework for engineering education research.

This paper focuses on a case study of feedback provided to four teams of students as part of an open-ended senior project. The 12 students are drawn from two cohorts in their final year of their undergraduate studies in chemical, biological or environmental engineering at a large public university. Students were organized in teams and placed in the role of semiconductor process engineers, tasked with optimizing a virtual chemical vapor deposition reactor through experimentation, analysis, and iteration. This three week project involved two structured meetings with the instructor who acted in the role of an expert consultant. These meetings are referred to as coaching sessions. The first coaching session for each team is explored in this paper. In that coaching session, termed the *design memo meeting* (DMM), students present their experimental design strategy in hopes of being granted permission to begin experiments. This study is part a larger investigation on student learning in virtual laboratories.

We posit that the presented project is industrially situated and perceived as authentic by students. In this learning environment, the nature of student-instructor interactions is distinctly different than in traditional classroom settings. Feedback during the coaching sessions is intentioned, critical, and catalyzes student learning. Using episodes, the nature of feedback to four different student teams during the DMM is compared. Finally, we argue that the episodes framework provides a potential scaffolding tool for instructors to more effectively provide feedback in this type of learning environment.

Theoretical Framework

Feedback

Feedback is an essential tool used by instructors to close the gap between current performance and desired performance. Feedback in the academic world takes many forms, from interaction in the classroom to interaction during office hours with a teaching assistant or a professor. According to a meta-analysis by Hattie and Timperely, the effect size of feedback is among the top of all educational factors, weighted heavier than such factors as student's prior cognitive ability, socio economic status, and reduction in class size.[1] They describe feedback as a process where teachers identify specific learning goals, help student ascertain where they are relative to reaching those goals, and then assist students in moving their progress forward. Feedback inside the classroom has been found to have a strong connection to student performance.[2] Results, from a study of over 1,500 first year engineering students, “suggest that faculty interacting with and providing constructive feedback to students was significantly and positively related to student gains in several engineering design and professional skills."[3] Similar findings are echoed by others.[4,5] Faculty-student interaction outside of the classroom also often includes feedback. Some studies have targeted improving professor effectiveness in office hours,[6,7] while others cite the importance of office hours as an instructional tool from both the faculty and student perspective.[8,9,10] Student-faculty informal interactions, often including feedback, have been correlated with factors shown to affect learning, such as socialization, academic achievement, satisfaction with college, intellectual and personal development, persistence and attrition, career and educational aspiration, as well as many other concepts.[11] Feedback greatly impacts student learning and performance.

One important aspect of effective feedback is the degree to which it is tailored to individual students. Several models attempting to describe such student dependent instructional techniques have been posed. *Student-centered instruction* describes instructional methods that encourage student learning in individual and small group settings. This is accomplished by instructor coaching on such skills.[12] *Individualized instruction* is characterized by flexible assessment with continuous feedback, students taking an active role in the instructional process, and variation of instructional methods based on individual student abilities and performance.[13] *Dynamic assessment*, another form of tailored feedback, is defined as focusing on student improvements in the cognitive processes related to problem solving by using an assess-intervene-assess instructional framework.[14] Finally, one of the clearest models of tailored instructional methods comes from the literature on K-12 education. *Differentiated Instruction* is explained by C. A. Tomlinson:

> "In differentiated classrooms, teachers provide specific ways for each individual to learn as deeply as possible and as quickly as possible, without assuming one student's road map for learning is identical to anyone else's" [15]

Regardless of the subtle differences in structure of the models listed above, review of the literature clearly points to a consensus in the education community; when instructional methods, including assessment and feedback, can be constructed to address individual student needs, learning increases.

Authentic, Industrially Situated Learning

Learning has also been shown to increase when students engage in authentic projects. The advantages of authentic, situated learning environments have been described by several researchers, some of which are highlighted in the NRC report *How People Learn*,[16] and are interpreted relative to engineering by Prince and Felder:[17]

- New learning involves transfer of information based on previous learning
- Motivation to learn affects the amount of time students are willing to devote to learning. Learners are more motivated when they can see the usefulness of what they are learning and when they can use it to do something that has an impact on others.
- The likelihood that knowledge and skills acquired in and academic setting will transfer to real work settings is a function of the similarity of the two environments.
- Helping students develop metacognition – knowledge of how they learn – improves the likelihood of their transferring information learned in one context to another one.

Industrially situated problems are real with monetary implications and more severe consequences than that of a wrong answer on a contrived test or homework problem. Taken in the context of the report above, there exist several clear benefits of authentic, situated environments for student learning. First, students can potentially increase transfer due to similarities between aspects of the educational project and an industrial project. Second, students may value a situated, authentic project more highly than traditional coursework and thus be more motivated and more willing to invest time and effort into learning.

Establishing and validating authenticity in feedback during such projects is difficult. Feedback in engineering practice is an area in which little research currently exists. In fact, engineering practice itself is an area in which little empirical research exists.[18]

Episodes

This study uses episodes as a framework to examining feedback, especially in the form of the coaching sessions in the situated project. Episodes have been used as a framework for discourse analysis in other educational settings.[19,20,21] The term "episodes" has been used to describe entire situations, such as an entire class period, as well as smaller subsets of discourse. T. A. van Dijk present a broad description of episodes as follows:

> "In this sense an episode is first of all conceived of as a part of a whole, having a beginning and an end, and hence defined in temporal terms. Next, both the part and the whole mostly involve sequences of events or actions. And finally,

> the episode should somehow be 'unified' and have some relative independence: we can identify it and distinguish it from other episodes.” [22]

Mannila et al. described episodes as requiring a “collection of events that occur relatively close to each other in a given partial order.”[23]

Research Design

Participants

This paper focuses on a case study of four teams, a subset of a larger investigation on student learning in virtual laboratories. All students were undergraduates in their 4th or 5th year in a chemical, biological or environmental engineering program and were enrolled in the capstone laboratory course. The four teams studied were self-selected, maintained for the entire course, and comprised of three students each. The teams studied consisted of a total of eight female students and four male students. Two teams each were selected from consecutive years. Approximately 80 students were enrolled in the capstone course each year.

The process for choosing teams to participate in think aloud protocol study addressed several factors, the most fundamental of which was simply schedule; teams were only chosen if a researcher was available during the team’s laboratory section and projected work times. Furthermore, gender distribution also contributed. During the selection of the cohorts presented in this paper, a preference was given to mixed gender teams or all female teams since other alternative gender distributions had been studied previously. The perceived willingness of a team to participate was also a contributing factor to team selection. This includes perceived willingness for both informing the researcher of all team meetings as well as verbalizing thoughts during meetings. A team's perceived willingness was a major criteria for selection because of the limited window of data collection associated with the virtual laboratory project. It should be noted that students' academic performance (e.g. GPA, class standing, test scores) was not a contributing factor to team selection. Also, more than half of the students had previous experience in engineering internships or laboratory research positions.

The faculty member studied in this paper has many years of thin films processing domain experience and has developed several different courses on the subject. This faculty member has performed the role of coach in the virtual laboratory project in this capstone course for several years and has coached multiple teams as they have worked on the project.

Setting and Instructional Design

This paper concentrates on work at a research and degree granting public university located in the Northwest U.S. The 10-week capstone course featured the virtual laboratory project as the second of its three laboratory projects; the other two laboratory projects were traditional physical laboratories. Students had three weeks to complete each laboratory project. During the virtual laboratory portion of the course, students chose between the Virtual BioReactor (VBioR) laboratory and the Virtual Chemical Vapor Deposition (VCVD) laboratory. Students studied in this paper chose the VCVD laboratory as their virtual laboratory project.

The VCVD laboratory was developed to afford students the opportunity to:[24]

1. Promote development of schematic and strategic knowledge[25] in a way that applies core concepts from the curriculum.
2. Engage students in an iterative experimental design approach that is reflective of the approach used by practicing engineers.
3. Provide an authentic context, reflective of the real-life working environment of a practicing engineer, such as working with a team to complete complicated tasks.
4. Promote a learner-centered approach to an open-ended design problem which results in an increase in the student's tolerance for ambiguity.

From an instructional design standpoint, the VCVD laboratory project is very open-ended. Laboratory experiences earlier in the curriculum are often prescribed with clearly defined operating procedures. Strategy in these typical physical laboratory experiences is focused more on how to finish earlier or how to troubleshoot malfunctioning equipment within tight time constraints. In the VCVD laboratory students are required to accomplish an authentic task (maximize reactor performance) with very little procedural or strategic information provided. This increase in cognitive demand in the strategic domain is facilitated by a decrease in demand in the haptic domain. Instead of spending time and cognitive resource setting up equipment and ensuring functionality of instrumentation for a limited experiment, students are able to use the resources previously dedicated to these types of actions on other activities. Students must manage a budget, create and carefully plan the project strategy, and analyze and assimilate the information from multiple experiments that were easily run;

the process of running the reactor once, measuring selected wafers, and exporting the measurement data to excel takes approximately 3 minutes.

The Virtual Chemical Vapor Deposition Project:

The VCVD laboratory project tasks students with the engineering objective of developing an optimal process “recipe” for a low pressure chemical vapor deposition reactor. The project is intended to be situated in the context of the integrated circuits (IC) industry with the reactor being one step of a multi-step process in high volume IC manufacturing. Optimization includes both the uniformity of the deposited silicon nitride (Si_3N_4) film, as well as utilization of the reactant gas while minimizing development cost. Students are charged $5,000 per run and $75 per measurement point. There exists an abundance of literature on low pressure chemical vapor deposition of silicon nitride; however, while general strategies from one reactor can be applied to another reactor, the parameters for optimization are reactor dependent, thus providing a genuine as well as unique challenge. Students are also required to keep a detailed laboratory notebook, similar to those kept in industry, which should contain observations, strategies, analysis, results and logic. This virtual lab is comprised of a 3-D interface available on school computer laboratory computers or for download and installation to a student’s personal computer. Similar in form to the virtual space in many current video games, the students navigate through a virtual 3-D clean room in a microelectronics factory. In order to optimize the process, the students control nine process parameters: reaction time, reactor pressure, flow rate of ammonia, flow rate of dichlorosilane (DCS), and the temperature in five zones in the reactor. After entering and submitting parameters to run, students may implement their measurement strategy in which they choose the number and position of wafers to measure, as well as the number and position of points within each wafer. The results of measurements can be viewed in the program or exported to an excel file where further analysis can take place. Behind the interface, a first principles mathematical model generates the data provided by the virtual reactor. However, the instructor can add measurement and process error so that no two runs or measurements give the same value. More information regarding the VCVD laboratory is available elsewhere.[26]

At the beginning of the VCVD laboratory project, the instructor introduces the faculty member who serves as coach (subject matter expert). The coach presents background technical information, introduces the VCVD laboratory software and presents the project objectives during two, 50 minute class periods. A timeline, list of deliverables, and associated coach-student interaction are shown in Table 7.1.1.

Table 7.1.1. The timeline of the VCVD project.

Timeline	Deliverables	Coach-Student Interaction
Project Introduction		Coach delivers a presentation introducing integrated circuit manufacturing, some engineering science background, the virtual CVD software interface and presents the objectives for the task and the deliverables.
End of Week 1	• Design Memo Meeting (DMM) ○ Initial run parameters ○ Experimental strategy	Student teams meet with the coach to discuss their design strategy. If initial parameters and strategy are acceptable, the coach provides students with username and password to access the Virtual CVD laboratory.
End of Week 2	• Update Memo Meeting ○ Progress to date	Student teams meet with the coach to discuss progress to date, any issues they may have, and the direction they are going.
End of Week 3	• Final Recipe • Final Report • Final Oral Presentation • Laboratory Notebook	Teams deliver a 10-15 minute oral presentation to the coach, 2 other faculty members, and the other students in the laboratory section. The presentation is followed by a 10-15 minute question and answer session.

The Design Memo Meeting (DMM)

The DMM, the first of the coaching sessions, occurs at the end of week one of the project. At this time, the students are asked to propose the first set of experimental run parameters and measurement locations as well as summarize their experimental strategy. This information is presented to the coach in a design memorandum. Logistically, the students bring the memo to a scheduled, 30-minute meeting with the coach, who performs the role of the project supervisor. Usually the meetings utilize the entire allotted time. Additional time is available for students needing more coaching, usually per student request. Once the students have completed the design memo and DMM satisfactorily, access to the 3-D VCVD laboratory interface is granted and they can begin experimentation.

The coaching sessions provide an early checkpoint for the student teams. This early checkpoint prompts students to stay on task regarding the VCVD project, which, as reported by students, is one of the most time demanding projects that they experience in the undergraduate program. Further reinforcing student preparation is the institutional awareness regarding the challenging nature of feedback in these coaching sessions which, among other goals, is intended to promote student preparation for the interaction. This feedback is not intended to “give the students answers” but rather to guide them toward a more desirable solution by the coach asking difficult and thought-provoking questions regarding the key aspects of the project. The early intervention also allows for this challenging, tailored feedback to occur at an early stage in the process affording the students two opportunities to apply feedback given by the coach to a final assessed product (the final report and presentation). Because the feedback is tailored for each student team, it is expected that content, flow and effect of each coaching session would be unique.

Like the project as a whole, the coaching sessions are situated in an industrial setting. Students are told to prepare as if they were presenting to their project supervisor and the coach maintains this role as much as possible while attending to the educational objectives. Additionally, while the students are given a degree of structure regarding what the meeting entails, such as the core requirements for the memo, they are not given a detailed set of requirements, such as memo format and exact structure of the meeting. The meetings instead have the feel of "show your boss what you have been working on." In this way the meetings are scaffolding the students towards what may be expected of them in workplace meetings.

Methods

Data Collection

Data sources for this study include think aloud protocol, semi-structured audio-recorded interviews, and student work products. Think aloud protocol consists of audio recordings of teams as they "think aloud" as they complete the project. These data are supplemented by observation notes from a researcher. Audio recordings are transcribed and the transcripts are used for analysis. Semi-structured interviews with six of the twelve participants have been conducted. A set of interview questions was initially created by the researchers and additional questions were added on a case by case basis. A variety of questions was asked ranging from open-ended questions such as "can you walk me through the project?" to more specific questions such as "what do you think the role of the instructor was in the design memo meeting?" Interviews were conducted 6-9 months after the students had completed the project. Interviews were also audio-recorded and transcribed.

A complete think aloud transcript for one team is 100-200 pages in length. For this study, we primarily focus on the DMM which is 5-10 pages. Two researchers began phrase-by-phrase and word-by-word coding with the goal of connecting teacher objectives to student goals. After reading the four DMM transcripts, it was observed that each DMM followed a similar pattern. Not only were common topics brought up, but there was also a similar pattern in each topic discussion. This pattern was then defined, documented, and revised. The pattern was member checked with the coach and agreed upon by the research team, and defines the episodes framework presented below. Then, two researchers coded the four coaching session transcripts individually, using this framework. They labeled episode components within the transcripts and identified the key topics of each episode. Throughout the coding process, the researchers consulted with each other and the research team regarding less clear sections of discourse. After coding, the researchers compared coded transcripts. During this collaboration, major episode topics were agreed upon almost unanimously. Less critical elements such as the distinction between some of the episode components were not agreed upon unanimously but to a degree that allowed for consensus in all cases.

Results and Discussion

The results and discussion is presented in four sections. First, we report results of student interviews regarding the student perception of the DMM, specifically focusing on the student perception of authenticity and effectiveness. While the intent is to provide an experience that is industrially situated, it is important to validate from the student perspective. Second, the framework of episodes to characterize the student-instructor interactions during the DMM is described. Episodes provided a structure for analysis of discourse and are helping direct ongoing research. Preliminary research results that demonstrate the use of episodes as an analysis tool are presented next. These results are interpreted in terms of the effectiveness of the project and the DMM. Finally, the use of episodes as a tool for instructional scaffolding is briefly discussed.

Student perceptions of the DMM:

Analysis of the student interviews provides some insight into the student perception of the DMM. Follows are some of the common themes among the 6 students interviewed along with student quotes supporting those themes.

- The majority of students expressed that coaching sessions were similar to either their expectation of or experience in industry meetings with a mentor or boss; some students even contrasted this project interaction with typical student-faculty interaction.
  "when it turned into more of like the group meetings [DMM and Update MM], I felt that he was more there in the position of someone like a manager that was like questions like 'what are you doing? Why are you doing this?' and instead of telling us ' here's the process this is great' I found it more helpful 'cause it kind of made us think more about what was going on because he wasn't telling us directly what we needed to do but instead bringing up more questions for us, and more problems to solve."
- All students interviewed found the DMM beneficial to the project.
  "Those meetings gave us direction, he would mention things that we had forgotten and stuff like that, with his way of asking questions about stuff we said."
  "just getting [coach]'s feedback was beneficial. Finding out like if what we came up with on our own was a good idea or if we missed something."
- Students expressed that they appreciated the coach asking difficult questions.
  "I personally like it when [the coach] asks questions that we really don't know the answer to and um cause it really helps us think more about what is going on in the process. I mean it is frustrating while we are there and we look really ridiculous being like 'I don't know' but overall I find that more helpful than being there and just listening and then excusing us to go."
- The students most often identified the coach's primary role as making sure they were on the right track and guiding them toward a better solution. During this process, students recognized that the coach withholds information and

> accept this as part of learning. Interwoven in such responses is an implicit recognition of the value of leading students to their own knowledge integration.
>
> *"I think his role is…to help you get to a place where you can be successful and not be stuck somewhere in your project and help you do that without straight up telling you, helping you realize it."*
>
> *"He will lead you to the answer; he won't ever tell you the answer. It usually ends up being something that you already know…And if you come to the idea then he'll let you know that you got there. But I don't know, it's always annoying at the time but you look back and you're like, that was actually pretty helpful."*

It should be noted that these are not all themes present in interviews; some of the other themes include that the project took too much time, stress, approaches to problems, team dynamics, students liked open-endedness, as well as other themes. The themes presented with quotes above have been echoed in interviews of students not analyzed for this paper and continue to be representative of student interviews. Students, many of which have had internships and research laboratory experiences, expressed that they perceive the DMM as representative of an industrial setting and beneficial student-faculty interaction in providing feedback through asking questions, without providing too much information.

Episodes Description and Development

An episodes framework to reflect student-coach (instructor) dialog in the DMM is shown in Figure 7.1.1. The description of each episode component, along with an example, is given in Table 7.1.2. In the Surveying stage, the coach in the DMM surveys the student team’s understanding by reading the memo and then asking broad questions or simply letting students explain their approach to the project. During this time, the coach attempts to identify potential problem areas in the team’s core knowledge or design strategy. Identification of potential issues leads to the Probing stage where the coach asks probing questions regarding the potential issue in order to assess if it was indeed a problem. The Guiding stage where the coach attempts to guide the students toward a more favorable approach occurs if the coach assesses that a problem is present. Finally, in the Confirmation stage confirming statements (often by both coach and students) conclude the episode and then a new episode begins. As indicated in Figure 7.1.1, the assessment-heavy and feedback-heavy portions of an episode are identified. The definition of episodes for this work fits the description presented by van Dijk,[19] in that they are topic themed and have a clear beginning and ending. Further, a characteristic noted by Mannila et al.,[20] a structure within episodes stood out in the text.

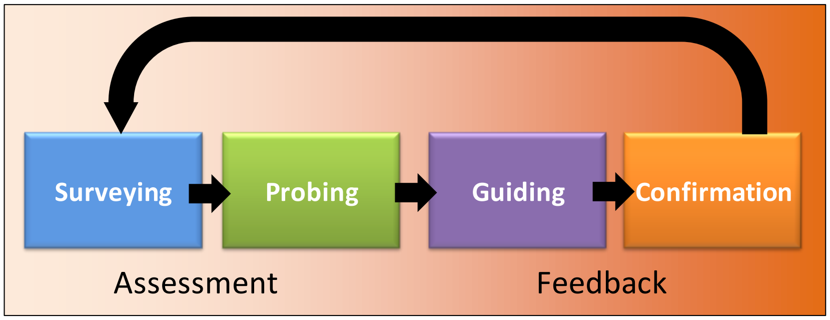

Figure 7.1.2. Episode structure with more assessment present in surveying and probing and more feedback in guiding and confirmation components. The process is iterative and all components are not required for each coaching session.

Table 7.1.2. Descriptions of each of the four parts of episodes. C denotes the coach and S1, S2, and S3 the students.

Episode Stage	Description	Example episode on "intra-group validation" and "situate"
Surveying	This component consists of the instructor becoming familiar with the team and their approach. It also includes the instructor trying to identify potential areas for further discussion and probing, areas in which students have misconceptions or incomplete understanding of important concepts. Surveying is based in part and loosely on an unwritten "check-list" of common student design shortcomings.	C: [upon conclusion of mass balance episode] And are you confident of these numbers? S1: Barely S 2: That's just the minimum to get the deposition so that would require 100% utilization on only the wafers. So that doesn't include the reactors.
Probing	In this part the instructor probes the students by asking directed questions on specific concepts to further understand the students' understanding of those concepts and how they will be used and will impact the design strategy.	C: So, S1, you're confident…So does that mean that you did the calculations? S 1: Yes. C: I see. Did you do the calculations (to S2)? S 2: No. C: And S3? S 3: I didn't work it out by hand.
Guiding	The guiding component occurs after the instructor has identified and confirmed a misconception or shortcoming in the students understanding. This part generally consists of the instructor guiding students either to make them aware of aspects that they do not acknowledge or to guide students toward a better understanding of concepts or a more advanced solution strategy. Most of the time guiding occurs through a series of dialogue with the instructor asking leading questions in order to help students discover or recall a more complete understanding of concepts. Occasionally, the answer will be given directly.	C: All right, so this is something where on your homework, or even more so, if you get a method right you get most of the credit, right? S1,2,3: Yes C: On this thing, if you get a method right, do you get most of the credit. No. S1 is generally very accurate. But what else do you think you can do?
Confirmation	During this part, consensus or acknowledgement of understanding occurs between instructor and students. In some cases, a conclusion is stated by the team and verified by the instructor. In others the instructor confirms the student statement followed by a justification or explanation of the episode. In some cases confirmation merely consists of short statements. This component signifies the end of an episode, after which a new topic is brought up and the cycle repeats with another "episode."	S 2: Have everybody check and do it also. C: Yeah, you could have independent checks on that. I mean, you don't want to spend several thousands of dollars to learn that…Oh, I forgot to carry the zero. I'm not saying it's right or wrong, that's just more of a team strategy.

Key characteristics of episodes include the following:

- Each episode is focused on at least one main theme. Episodes can have multiple main themes, for example an episode may be about flow rates but also be explicitly situating, thus serving two purposes.
- Episodes have a beginning and ending point.
- Each episode has a structure consisting of four episode stages (surveying, probing, guiding and confirmation). However, every episode might not include every stage.
- Episodes may be nested within episodes, for instance an episode on density may be contained within an episode on material balance.

Episodes as a Discourse Analysis Tool

Episodes provide an interesting perspective in the analysis of the DMM. Episodes facilitate the relatively quick and easy parsing and subsequent identification of central topics. While central topics can be discovered through carefully reading of a complete transcript, the use of the episodes as a framework expedites the process because topic-centered episodes are punctuated by easily identifiable confirmation statements, usually by both the coach and the students. A researcher need only scan the text for these confirmation statements, and then assess the theme of the text between confirmations.

Once a transcript has been analyzed via the episodes framework, coaching sessions may be further analyzed on a multitude of different levels. Multiple coaching sessions of a single team and/or coaching sessions of multiple teams can be compared. As an example, the topic flow from Team A is shown in Figure 7.1.2, which can be compared to the topic flows from the other three teams in Appendix 1.

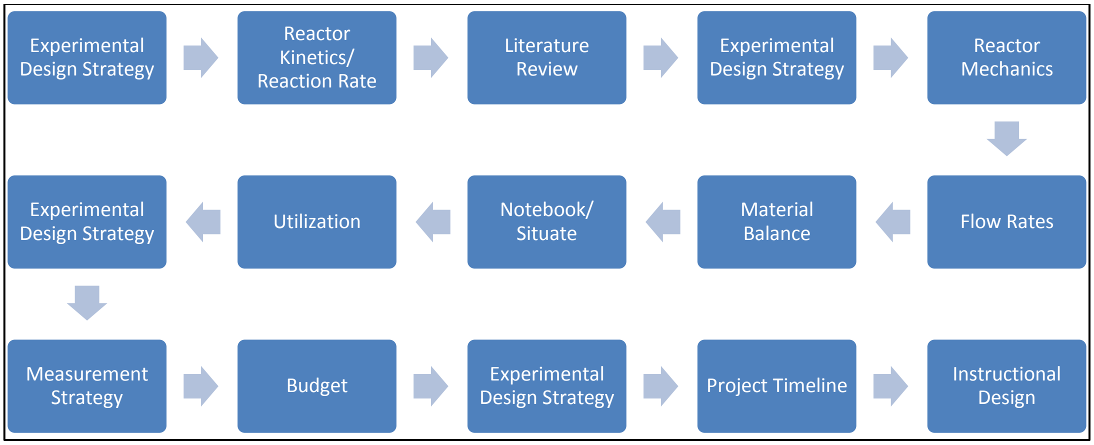

Figure 7.1.3. Team A coaching session episode topic flow.

Major topics of the presented coaching session focus around input parameters, core engineering principles and situated themes such as adequate background research, reasonable budget, well justified experimental design strategy, and manufacturing requirements. The episode topics and words/time spent on topics illustrate feedback that responds to the individual needs of each team. Many team attributes factor into the unfolding of the episode flow sequence, including: the team's general preparedness for the meeting (e.g. having a complete memo), understanding and proper application of prior learned concepts, problem solving skills, and team dynamics. An examination of the topic flows shows that there were more episodes on experimental design strategy in Team A's coaching session than in the other teams' sessions. This may be related to the fact that Team A was the top performing team in its cohort and understood many of the episode procedural and conceptual topics that dominated other teams' sessions, leaving more time and energy to be devoted towards strategy. Investigation is needed into detailed examination of topic flows and time spent on topics. In addition, some episodes are nested within other episodes, which are not adequately described with the depiction in Figure 7.1.2; for example, a material balance episode is actually contained within the discussion on flow rates.

A single episode around a particular topic can also be used as a starting point for more in-depth data analysis; the topic can be used as a keyword to search through transcripts of team work and student work products before and after the coaching session. In the four teams studied, all four had an episode on material balance. While the topic is the same for all four teams, the episodes look quite different in terms of size, content, depth and the amount of guidance provided. Looking at the episode components for these four episodes on material balance allows for further examination of the nature of these episodes and some of the differences. Summary plots of the word counts in each stage for these four episodes are shown in Figure 7.1.3.

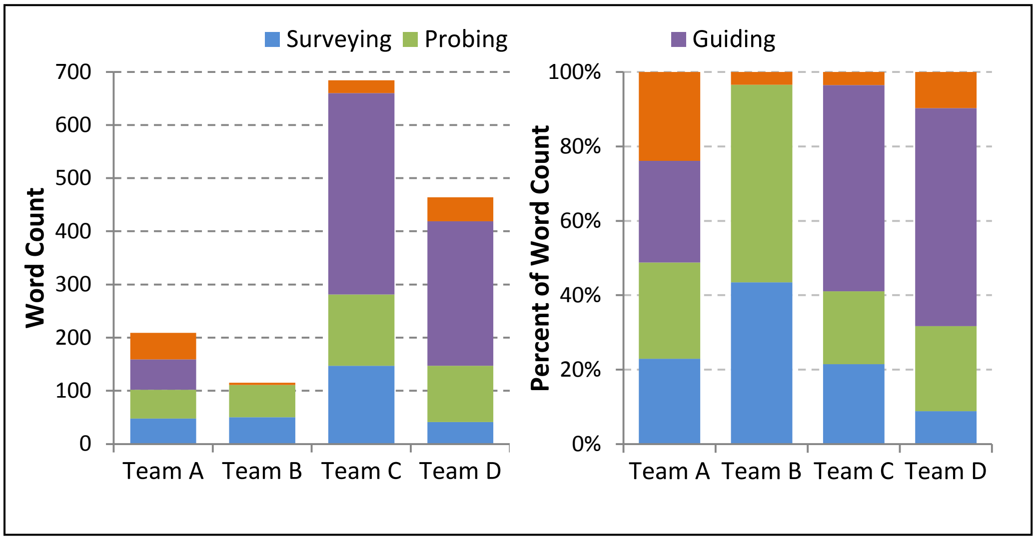

Figure 7.1.4. Comparison of Material Balance episodes: (left) word counts for episode components, (right) word count percentages for episode components

Two of the four teams, (Team C and Team D) had not performed a material balance prior to the DMM. The total word count in Figure 7.1.3 (left) clearly shows that these two teams discussed the guidance of the topic in greater detail than the other two teams; more than twice as many words were allotted to material balance in the teams that had not previously performed one. This is to be expected as a material balance is an important concept in completion of the project. Next if we consider both word count (Figure 3, left) and the relative break down of component parts (Figure 3, right), Team C and Team D experienced more guiding than Team A and Team B. Not only did they spend more discussion on the topic, but also a larger percentage of discussion consisted of guiding from the coach.

It is interesting to juxtapose the context of the Material Balances episode for the four teams studied. In Team A's Material Balance episode, the episode topic was a concept they had thought of and performed calculations on prior to the DMM, but the DMM reinforced the concept. The episode focused on creating a material balance "chunk" as they had already completed the mechanics of the material balance, but hadn't "chunked" the procedures into one unit. This also plays another role in enculturation, as the term "material balance" is commonly referred to and understood in chemical, biological and environmental engineering. Two comments from a team member interview demonstrate the knowledge integration of the material balance concept through this "chunking" process:

> *"so, learned a lot, learned that the key phrase is, uh what should you do, a material balance, which I'm taking design and it's really true cause like in design it's also like oh just do an energy/material balance and see what you can get from that first"*
>
> *"like I said, like the whole material balance concept that, that's like it's something you learn sophomore year and you don't necessarily really keep in mind as you go through, but it's a really essential element of chemical engineering and just gives you like, makes you step back and think about like the big picture of what's going on"*

Team B had written in their memo that they had done a mass balance and as one might expect, the Material Balance episode is very short (115 words). The coach merely surveyed and probed on calculation verification and the reliability of their reference for parameters. As we can see with the data from Team B, not all episode components are present in all episodes; no guiding was necessary as the students had addressed all of the coach's questions. In some cases, no surveying is directly present because surveying information was gained from previous episodes. Another interesting note, regarding the episode component analysis of Team B, is that the surveying and probing components of this team's material balance episode appear to be surprisingly large as a percent of the total, however if we look at the word count it is similar to that of Team A and Team D. The high percentage is simply a result of the lack of a guiding component and the overall low word count of the episode.

Team C presented a special case, which may illuminate some of the limitations of episodes as an analysis framework. Although episodes were parsed and analyzed, it was more difficult than with the other teams. Episodes for Team C were generally longer than those of the other 3 teams and appeared to have less clear confirmations. The length is demonstrated by a Material Balance episode of 684 words, almost twice as many words as the average of the four Material Balance episodes described and more than 6 times larger than the smallest Material Balance episode described. An interesting question that may warrant further investigation is whether there is a correlation between the effectiveness of episodes as characterized by pre- and post-think aloud data, interview data or survey data and clarity of confirmations or length of episodes. One might, for instance, expect that as episodes got longer with less clear confirmations, that they may also become less effective.

Team D was one of the two that had not performed a material balance prior to the DMM. Their material balance episode was preceded by discussion about modeling diffusion in a complex manner and the flow rate ratio between the two reactants. During the episode, the coach probed regarding the value selection. The team had based their flow rate values on a scientific paper. It becomes clear that the students had not accounted for the difference in size between the reactor in the paper and the reactor with which they would be working. The coach guides them towards using a material balance to assess the reasonableness of their values through leading questions. In addition, the coach promotes the students to reflect on the complexity of their approach and to consider things from a more simple perspective. The students come to the realization that they can calculate the number of moles needed in their final film. Near the end the coach states:

"I really think that you need to do a material balance to see if that is a reasonable number."

The students agree, discuss what values they need for that calculation and the episode ends. In their team meeting after the coaching session, students reflect on the episode as follows:

> *S1: So, I don't know why we didn't think of this, mass balance.*
>
> *S3: I know right? We were thinking yesterday that the whole time, what photo should we use, maybe we should do this, this sounds good [referring to deciding on what they should include in the memo prior to the meeting] and it was like wait, it should be reasonable [referring to the revelation in the meeting]. Nope we can't think about anything. [laughs]…*
> *[pause and other discussion]*
>
> *S3: I am currently working on a material balance and I am trying to go backwards. So I am gonna find the surface area of the wafers, multiply that by 400 because it grows on the inside and the backside of the wafer and then I am going to calculate how much silicon nitride, that comes down to work the chemical equation backwards to see how many moles of dichlorosilane that comes out to. And then factor that into what our flow need to be based on how long we're running this which is 60 minutes. And so that will tell us how many SCCMs we need in order to get this much.*

> *And then once I get that flow rate I am going to take that flow rate and say up it by 10% because we're not going to get 100% utilization, especially not on our first run.*

As illustrated by the Material Balance episode, the structure of the coaching sessions allows for effective feedback, specific to each team. Through surveying and probing, instructors assess what competencies and deficiencies a team has relative to knowledge and skills needed to complete the task. As part of this process, students begin to ascertain where they are relative to reaching their goals. Through guiding and confirmation, the instructor then assists them in moving their progress forward. The episodes framework also affords comparisons between coaching sessions on the number and flow of episode topics, depth of specific topics, percent of time or discourse spent on episode components, as well as many other opportunities for analysis.

As the understanding of coaching sessions increases through the use of student interviews and episodes analysis, extending this framework and the information gained beyond research into instructional practice is a logical extension. The next section describes how the episodes framework is of use to instructors using similar situated projects.

Episodes as a Model for Scaffolding Instructor Development

While the topic themed episodes presented in this work provide a framework for analyzing discourse in industrially situated coaching sessions, we propose that scaffolding for instructional improvement is also a useful and powerful extension of this tool. The four part episodes and list of key project components provide a framework that instructors may implement in similar industrially situated learning environments.

Regarding the use of the episodes framework for instructor development, we envision three categories of application. First, and most obviously, this framework may be used by instructors implementing the VCVD curriculum in a similar setting (a senior chemical engineering laboratory course) who also have instructional goals for the project which are aligned with those presented in this paper. This “plug and play” approach may also be useful for instructors who have little time to prepare for the VCVD project or who lack experience or confidence with structuring these types of student/instructor interactions. In this case, the instructor may simply employ the surveying, probing, guiding, and confirmation pattern to investigate and offer feedback on the topics listed in this paper. A list of categorized episode topics for the VCVD laboratory project is presented in Table 7.1.3.

Table 7.1.3. Common episode topics seen in VCVD coaching sessions. Secondary topics are shown in parentheses.

Chemical engineering content episode topics:	**General episode topics:**
• Material balance • Diffusion (pressure/temperature relationship) • Reaction regime • Reaction kinetics (temperature, concentration) • Modeling of reaction • CVD reactor mechanics • Input parameters (pressure, temperature, flow rates/ratio, time) • Objectives (utilization, uniformity)	• Experimental design strategy(DOE) • Measurement strategy • Budget • Literature review (evaluation of sources, citing sources) • Team dynamics (intra-team validation) • Situate VCVD laboratory (project-class comparison) • Encourage meta-cognition • Notebook

Secondly, this model may be useful for instructors implementing the VCVD curriculum but doing so in order to address instructional objectives that are different than those covered by the episode topics listed in Table 7.1.3. In this case, instructors can modify the list shown to develop a new list of topics to be covered using the four part episode framework. During this process two important pieces of information should be considered. First, it should be noted that the list of topics of episodes presented in this paper are based on coaching sessions in the third and fourth year of coaching in this setting (approximately 53 teams). These have been refined based not only on evolving instructional objectives but also on aspects of the project that students have consistently had problems with throughout the years. Furthermore, it should be noted that while an explicit or implicit list of topics is a useful tool to support instructors, the topics and nature of each episode ultimately depend on the team that is being coached. Terms such as “Are there any other questions?” encourage a wide range of topics. Considering these two points, it is important for the instructor to realize that, like the composition of each episode, the episode topics also vary as a function of instructor experience and individual team traits. While a topics list is a useful tool, it is in no way comprehensive in predicting the content of every episode. Finally, the episode framework may be employed in other situated problem-based learning instructional activities. In this case, the instructor may choose to use the surveying, probing, guiding, and confirmation in coaching sessions in a wide variety of projects. Other industrially situated virtual laboratory projects seeking a framework for instructor/student interactions may find the content of this paper especially easy to apply as the framework was developed in such an atmosphere. However, transfer to more traditional physical projects in the realm of problem-based learning in a variety of contexts may also benefit. For example, one of the authors has recently used this four part coaching episodes framework in memo meetings held with his high school physics students. In this situation, the students were presenting a memo outlining their design for mechanics project in their advanced placement physics class. The project was situated in practice by the students being instructed that they were working as undergraduate interns in a research team attempting to develop a device to deliver fragile cargo (i.e. medical supplies) to high risk areas by air drop. In the memo meeting the instructor served the role of the students’ mentor. He used the episodes framework accompanied by reading their memo to survey what they knew regarding the project and look to identify any problem areas. Once a possible lack of understanding was identified, he further probed on the topic in order to fully understand the students' misconception. Next, he guided students' towards a fuller understanding and finally confirmed with the students that they were on the right track. Topics of these episodes were based primarily on elements he deemed essential to the project and secondarily on issues that arose during the meeting. While both the situated, ill-defined nature of the project was similar to the VCVD lab as well as the student's preparation of a memo, many aspects of the project were different. The students were high school seniors, the project involved content focused on mechanics and dynamics, the meetings were substantially shorter (five minutes), and the project in general was much smaller in scope. However, the framework used did provide the instructor (a first year HS teacher) the scaffolding needed to feel confident and well prepared heading into the meetings.

While the framework is presented, it should be noted that the effective planning and execution of such instructor/student interactions is not trivial. As an instructor, the art of performing as both instructor and mock "project supervisor" benefits from both preparation as well as experience. In these areas, our model can only assist with the former.

Conclusions & Future Work

This paper has described the VCVD project and the coaching sessions contained therein. Student perceptions support the situated intent of the VCVD laboratory project as well as the perceived effectiveness of the coaching sessions. In these coaching sessions, a structure of episodes was found which is topic centered and consists of four stages: surveying, probing, guiding and confirmation. Feedback is crucial to student success. Preliminary examination of coaching sessions with the episodes framework supports both effectiveness of the coaching sessions as well as demonstrates the episodes framework as a potentially powerful tool in discourse analysis, especially for feedback. In addition, the topic flows and component structure lend themselves as a tool for scaffolding instructor development. However, further research is necessary to validate these preliminary findings. In addition, other potential research questions which may be explored by coaching session analysis by the episodes framework are given below:

- Which episodes topics are common to all coaching sessions and which are brought up on a team by team basis?
- What is the duration of each of the common episode topics in each team's coaching session?
- How do individual episode components vary between teams? Is there a common length to each component?
- Are there episode topics that typically accompany each other?
- Are episode topics aligned to instructional goals for a given coach?
- Are episode topics aligned to deliverables for the students?
- How does a coach change with time? Do common topics change? Does the composition of episodes change?
- Are particular episode compositions, orders, or qualities more effective than others?
- What degree does the episodes framework transfer to different coaches interacting in different contexts?

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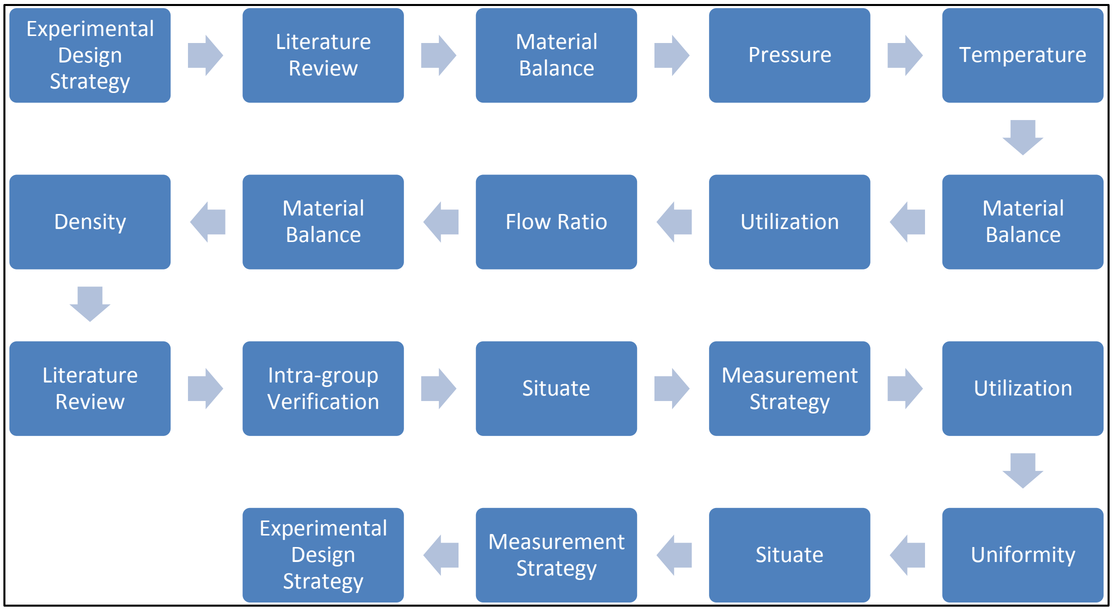
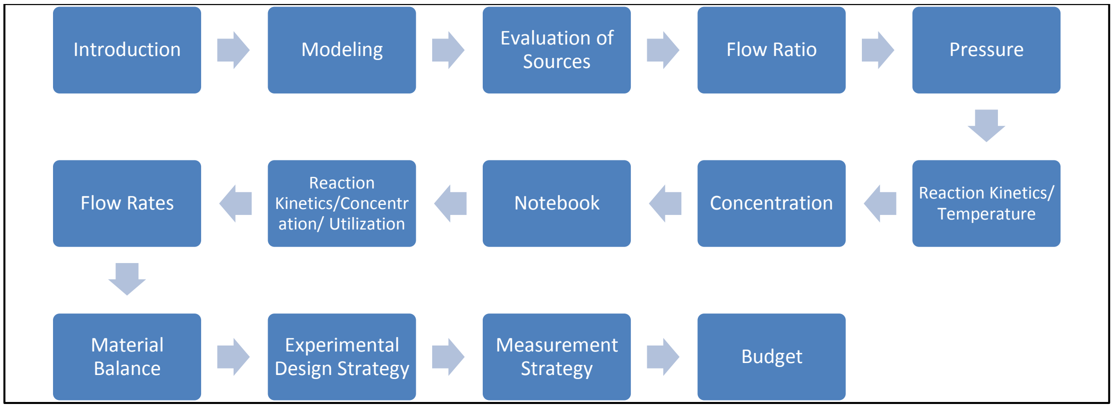
Appendix 1: Team B, C & D Topic Flows

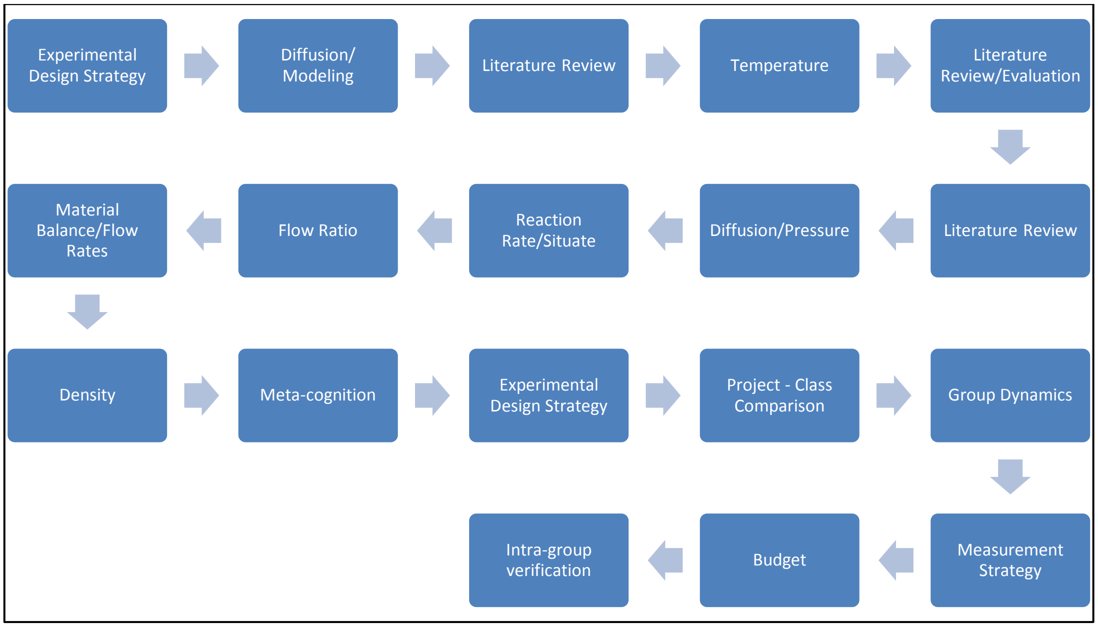
Team B



Team C



Team D


Experimental Design Strategy
Diffusion/ Modeling
Literature Review
Temperature
Literature Review/Evaluation
Literature Review
Diffusion/Pressure
Reaction Rate/Situate
Flow Ratio
Material Balance/Flow Rates
Density
Meta-cognition
Experimental Design Strategy
Project - Class Comparison
Group Dynamics
Measurement Strategy
Budget
Intra-group verification

Appendix B – Understanding Feedback in an Authentic, Ill-Structured Project through Discourse Analysis: Interaction between Student and Instructor Objectives

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Abstract

This paper presents a case study of feedback in an authentic engineering project in which the primary objectives of the students and the instructor are different but complementary. Students focus on completion of the authentic task. The instructors' intent is to promote knowledge integration of core engineering science concepts. These perspectives are bridged by the project's authentic, situated context. Using an episodes framework to examine a feedback session, we investigate how the student objectives, the instructor objectives, and project contextualization are addressed and how these three elements interact. They are found to be interwoven generally initiating with student objective focused discussion, incorporating instructor objectives, as appropriate, as tools to help students achieve their objectives. Project contextualization reinforces the authenticity and contributes to validating the utility of core content and concepts.

Context

Feedback has been shown to be one of the most important tools used by instructors to help students close the gap between actual and desired performance. According to a meta-analysis by Hattie and Timperely (2007) the effect size of feedback is among the highest of all educational factors, weighted heavier than such factors as students' prior cognitive ability, socioeconomic status, and reduction in class size. While feedback has been shown to strongly influence student performance and learning, explicit research on the effect of feedback in engineering education is sparse. Findings from studies of first-year engineering students (Bjorklund, Parente, & Sathianathan, 2002; Moreno, Reisslein, & Ozogul, 2009) show that feedback is positively related to learning gains. These results are consistent with studies in other disciplines (Kuh & Hu, 2001). However, there is no general agreement on what characterizes “effective” feedback. Additionally authentic, situated environments are believed to benefit student learning. Studies of feedback in authentic projects are uncommon and needed. This study extends our group's use of *episodes* as a discourse analysis framework to investigate feedback in the industrially situated Virtual Chemical Vapor Deposition (CVD) Laboratory Project.

Over the last seven years, we have developed, implemented, and been assessing the authentic, industrially situated Virtual CVD Laboratory Project (Koretsky, Amatore, Barnes, & Kimura, 2008). This project provides opportunities for student teams to develop and refine solutions to an authentic engineering task through experimentation, analysis, and iteration. While the phrase “student objectives” can be interpreted in many ways, in this study the student objectives encompass the explicit project objectives: develop an optimal 'recipe' for industrially-sized, Chemical Vapor Deposition (CVD) reactors which deposit thin films on polished silicon wafers, maximize utilization of the expensive and hazardous reactant (referred to as DCS), and minimize the development and manufacturing costs. To achieve these objectives, student teams must find suitable reactor input variable values (temperatures along the reactor, flow rates for two reactants, pressure, and reaction time) that result in films of uniform thickness at the desired target value. The instructor’s learning objectives focus on professional development skills (e.g., working in teams, communication) and integration of core engineering science concepts (e.g., material balances, reaction kinetics, statistics).

A typical student team devotes a substantial 15 - 25 hours to this complex, three-week project. A summary of key project milestones and corresponding opportunities for feedback is shown in Table 1. The feedback analysed in this paper occurs during the *initial coaching session,* shaded in blue. In this 20-30-minute meeting, students must deliver to the coach a memorandum that specifies the values for their first run variables, a strategy for subsequent runs and experimental data evaluation, and a budget (in virtual dollars) for the entire project. This assignment places an unusual responsibility on the students, requiring them to formulate and solve a problem that requires integration of prior knowledge from previous courses. In the initial coaching session, the coach acts as a mentor or boss would in industry. The coach asks questions to guide the students in further developing their strategy, initial variable values, and budget. Feedback is carefully tailored to engage students in identifying gaps in their current design and directing attention to methods for addressing those gaps.

Table 1: Timeline and opportunities for feedback in the Virtual CVD Laboratory Project.

Timeline	Key Project Milestones	Student-Coach Opportunity for Feedback
Project Begins	• Goals of the task are introduced • Criteria for success are indicated • Provided with laboratory notebook	Instructor (coach) delivers introductory presentation on integrated circuit manufacturing, some engineering science background, the Virtual CVD software interface. Also presented are project objectives and deliverables. Feedback is limited to questions and in-class interaction.
End of Week 1	• Initial coaching session ○ Variable values for first run ○ Experimental strategy	Feedback takes the form of a 20-minute coaching session in which coach and students ask questions and discuss the students' design strategy and initial variable values. If initial variable values and strategy are acceptable, they are granted access the Virtual CVD laboratory.
End of Week 2	• Update coaching session ○ Progress to date	Another opportunity for feedback is this second meeting between student teams and coach. Discussion includes progress to date, issues students may have, and the direction they are going.
End of Week 3	• Final Recipe • Final Report • Final Oral Presentation • Laboratory Notebook	Teams deliver a 10-15 min oral presentation to the coach, two other instructors, and the other students, followed by a 10-15 minute question and answer session that affords additional feedback. Final project feedback consists of grades and written comments on final deliverables.

Research Questions

Using the episodes framework, what evidence is there that the semi-structured feedback sessions in the Virtual CVD Laboratory Project address the: student perspective of task completion, instructor intent of knowledge integration, and authentic, industrial context of the project? Ultimately, we are interested in understanding how these elements interact with one another to contribute to student learning.

Theoretical Framework

Hattie and Timperley (2007) describe feedback as a process in which instructors make learning objectives clear to students, assist students in ascertaining where they are relative to those objectives, and then help students move their progress forward.

Researchers have advocated that feedback works best when it directs student attention to appropriate goals and actions (Kluger & DeNisi, 1996), or encourages student reflection (Bangert-Drowns, Kulik, & Morgan, 1991). Research also suggests that appropriate feedback is specific to the learning context of the student and/or task (Shute, 2008). Prince and Felder (2006) discuss the trade-off between directive projects, which can be crafted to specifically address learning objectives, and ill-structured projects that require students to formulate the project and develop appropriate strategies. Ill-structured projects are generally more authentic and have been shown to increase student motivation; however, it is more difficult to guarantee that specific learning objectives, or what we term "instructor objectives," are met.

We propose that authentic projects motivate students and allow them to integrate prior knowledge in part because the student objectives can differ from the instructor objectives. We wish to study these contrasting, but complementary, perspectives in the Virtual CVD Laboratory Project. The intent of feedback in this project is to help students close the gap between their present performance and the desired performance; however, it takes a slightly different form than described by Hattie and Timperley. The instructors make student objectives explicit, and then through feedback assist students in integrating and then addressing the instructor objectives. We posit that this relationship between student objectives and instructor objectives is present in many project-based learning experiences and that intentioned feedback based on these juxtaposing objectives can be more effective in helping students close the performance gap. This study forms a foundation to explore this conjecture.

We use the analytical framework of *episodes* to examine the feedback. This framework has been used for discourse analysis in several fields such as linguistics (Korolija & Linell, 2011) and medicine (Cordella, 2004). Our definition of the episodes framework is described in more detail elsewhere (Gilbuena, Sherrett, & Koretsky, 2011) and is partly adapted from van Dijk (1981): each episode addresses a specific topic, labelled the episode 'theme;' each episode has a clear beginning and ending point; and each episode has a sub-structure that includes up to four 'stages.' Smaller episodes may also be nested within larger episodes, as illustrated in the Findings & Conclusions section of this paper.

Our *episode stages* include: Surveying, Probing, Guiding, and Confirmation. In the *Surveying stage*, the coach assesses the student team’s current understanding by reading their memorandum, asking broad questions, or listening to students explain their strategy; the coach attempts to identify potential problem areas in the team’s core knowledge or design strategy. Identification of a potential issue initiates the *Probing stage* where the coach asks probing questions in order to assess if there is indeed a problem. The *Guiding stage*, where the coach attempts to guide the team toward a more favourable approach or a deeper understanding, occurs if the coach assesses that a problem is present; this stage may include leading questions. Finally, in the *Confirmation stage* confirming statements such as “ok” and “alright” (often by both coach and students) conclude the episode. Episodes must contain at least two stages. The stages, while central to our episodes framework, are not the focus of this investigation.

Methods

This paper presents a case study of one team, a subset of a larger investigation of student learning in virtual laboratories. The undergraduate students were in the 4th or 5th year of a chemical, biological or environmental engineering program and enrolled in a capstone laboratory course of approximately 80 total students. The team, of two female students and one male student, was self-selected and maintained for the entire course. Team selection criteria for this research are described elsewhere (Gilbuena, Sherrett, & Koretsky, 2011). One faculty member, the coach, participated in this study and has coached over 60 teams in the same capstone course over several years. The faculty member also has many years of thin films processing experience and has developed several courses on the subject.

The primary data source for this study uses the think aloud protocol, and is comprised of audio recordings of the team as they “think aloud” while completing the project. Transcripts of the audio recordings were analysed. For this study, we focus on the initial coaching session transcript. Two researchers examined the transcript to investigate the connection between student and instructor objectives by coding the coaching session transcript; each researcher coded the transcript individually by identifying episodes within the transcript and labelling the key theme of each episode. After coding, the researchers compared the coded transcript; major episode topics were agreed upon almost unanimously and discrepancies were easily resolved.

Episode themes were categorized as follows:

1. ***Student Objectives -*** *Inputs variables and performance metrics* focuses on one of the reactor input parameters (reactor temperature, pressure, or input flow rates) or

one of the project performance metrics (wafer uniformity, gas utilization, or project budget).

2. ***Instructor Objectives -*** *Core content and concepts* refers to topics from previous courses (e.g., material balance, reaction kinetics, statistics, project management, writing).
3. *Project contextualization* emphasizes the authentic context of the project which situates it in industrial practice. For example, an episode in this category might contain discussion of the typical discussion between engineers with operators in a processing facility.

Themes in the second category were member checked with the coach. A graphical representation of coaching session episodes' length and chronological order was prepared based on this categorization.

Findings & Conclusions

For the team studied, the coaching session contained twenty-five distinct episodes; nine addressed student objectives of inputs and performance metrics, thirteen attended to instructor objectives of core content and concepts, and two provided project contextualization. Figure 7.2.1 shows the chronological order of episodes within the coaching session. The 20-minute coaching session consisted of approximately 2200 words and the length of the box representing each episode is scaled to the word count. Inputs and performance metrics episodes are denoted with a white box, core content and concepts episodes are shown as a box with a grid pattern and project contextualization episodes are denoted with a shaded box. Each episode is labelled with its particular theme.

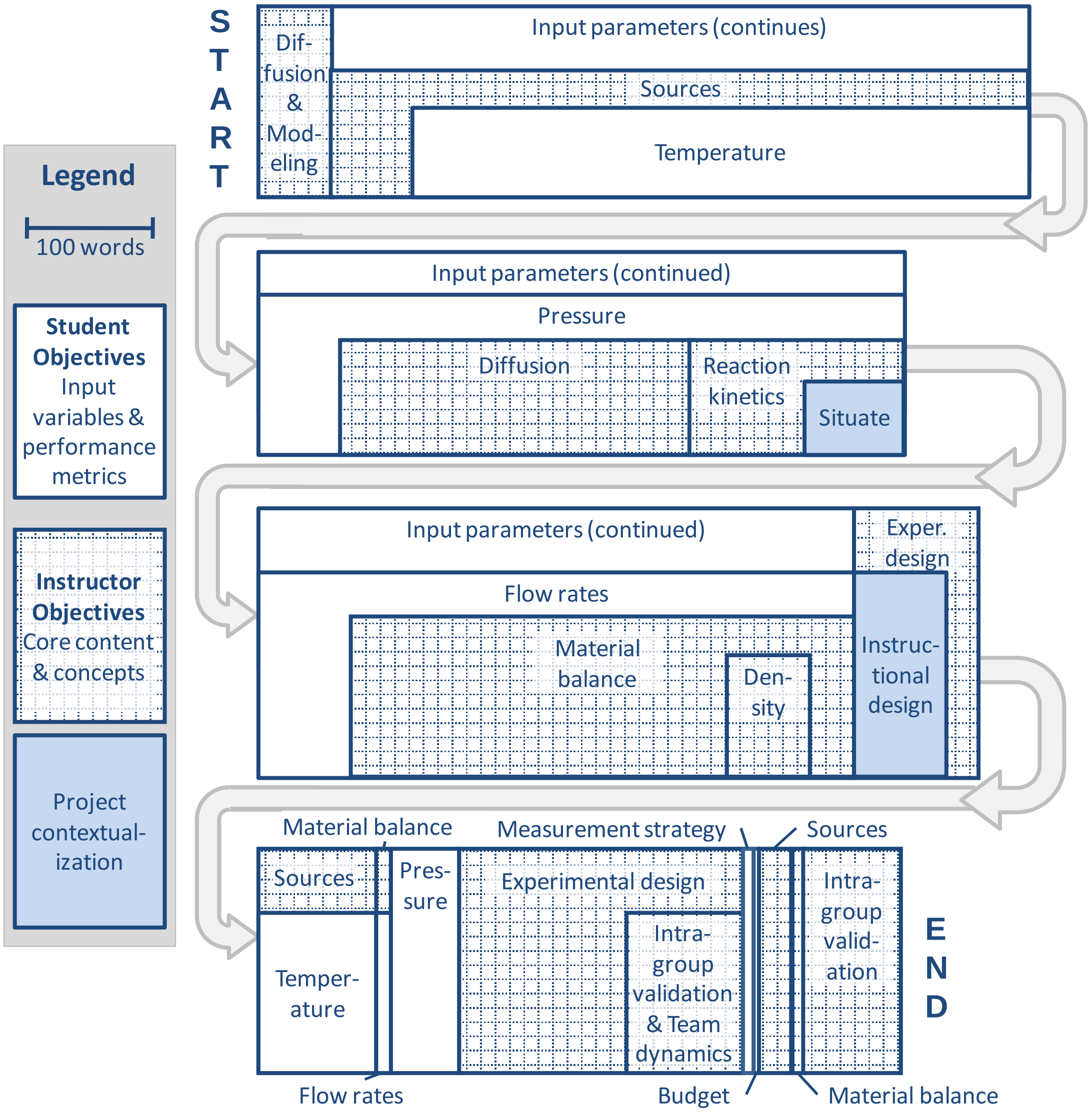

Figure 7.2.1: Chronological representation of episodes in a coaching session.

Figure 1illustrates the approximate proportion of discourse allotted to each of the discussion themes. The themes discussed here are similar to those reported for other teams (Gilbuena, Sherrett, & Koretsky, 2011). The pattern of discussion begins to illuminate the interaction between student objectives and instructor objectives. Throughout the coaching session we see smaller episodes relating to instructor objectives nested within the context of larger episodes relating to student objectives.

For example if we look at the second row of discourse in Figure 7.2.1, discussions of diffusion and reaction kinetics are nested within the larger context of pressure. The students must select a value for pressure in order to proceed with their experiments; the discussion initiates specifically addressing this need. The instructor then connects the core concepts of diffusion and reaction kinetics as a way for the student team to *think* about their objective. We next unpack this interaction.

The pressure episode begins after the temperature and sources episodes conclude; the coach starts by directly asking the students how they determined the starting variable value for pressure. They respond citing a literature reference, and state that they didn't think the pressure was as important as the other variables. The transition from strictly focusing on the input parameter of pressure, a student objective, to diffusion as a focus is illustrated in the following excerpt. It occurs with a question posed by the coach regarding what affects pressure and the team's answer of 'diffusion:'

> *Coach: So what do you think affects pressure?*
> *Student: Diffusion*
> *Coach: So pressure is diffusion. In terms of diffusion where do you want the pressure to be?*

They discuss the core concept of diffusion, an instructor objective, for 275 words within the context of its impact on the student objective, pressure. With probing, it appears the team has a misunderstanding about the role of diffusion and the impact of pressure on the performance metrics. The team is guided to conclude that diffusion is not the only way pressure affects their performance objectives. A discussion of the concept of reaction kinetics, another instructor objective, follows. The students are guided to relate pressure to concentration and recognize its impact on reaction kinetics. The transcript excerpt below shows the transition beginning with revisiting a previous question; the coach asks what other thoughts the students have about why the pressure should not be set too low. Students respond relating pressure loosely to reaction rate, after which the coach guides the students with a leading question that focuses discussion on the contribution of pressure to reaction rates.

> *Coach: Any other thoughts?*
> *S1: That makes it, basically you are limiting, the thing that's limiting what's happening would be how they hit and so you'd have to model basically the reaction rate based on how they hit instead of*
> *Coach: You talked about reaction rates, what are reaction rates a function…*
> *S1: Temperature*
> *Coach: Temperature, what else?*
> *S1: Concentration*
> *Coach: Concentration, so what happens to concentration as pressure goes down?*
> *S3: Concentration goes down*
> *Coach: Concentration goes down*
> *S3: If the pressure goes down too much it will limit how concentrated*
> *S1: And the reaction rate goes down, concentration goes down*

The students then recognize that pressure determines the concentration which in turn impacts the reaction rate; this illustrates the strong link between a student objective (what value will we pick?) and the instructor objective (integrating the concept of reaction kinetics into this authentic task). An example of project contextualization is illustrated at the conclusion of the reaction kinetics episode with a small episode focused on situating the project in the industrial context, shown below. This situating episode links the concept of reaction kinetics to its impact on high-volume manufacturing.

> *Coach: Alright, and what's the problem with that in high volume manufacturing facilities?*
> *S1: You have waste*

> *S3: You can't get things done very fast*
> *Coach: You can't get things done very fast and so you*
> *S1: Okay*
> *S3: It will still get deposited or it will still get there, it will take a lot longer and it's not*
> *Coach: You're making less product than your competitor.*
> *S3: It might be uniform, you might have high utilization but oh we take 4 hours. Wait 4 hours? Why are you taking 4 hours?*

The last row illustrated in Figure 7.2.1 represents approximately the final quarter of discourse and consists of the meeting wrap-up discussion. During this time, students may ask final questions regarding aspects they are unclear about. In addition, many topics previously explored in depth are touched upon as a reminder of what aspects of the student's design strategy merit attention. During this portion of the meeting, for example, pressure is revisited in a student initiated discussion where one student asks the coach if there is more to consider with pressure and another student responds that their pressure is fine. The coach leaves that input variable for the students to explore, without adding additional insight.

In conclusion, the three theme categories are interwoven as the students and instructor discuss the experimental design strategy of the team. Episodes in the core content and concepts and project contextualization categories were found to be nested within episodes in the inputs and performance metrics category. This feedback, perceived as effective by students (Gilbuena, Sherrett, & Koretsky, 2011; Koretsky, Kelly, & Gummer, 2011), starts primarily focused on student objectives of inputs and performance metrics. Core content and concepts are tools incorporated, as appropriate, to help students understand and achieve their objectives. Project contextualization validates the utility of core content and concepts and increases student motivation through the reinforced authenticity of the project.

Recommendations & Future Research Plans

More intentioned research investigating feedback in engineering education is needed. Of particular interest are the investigations of feedback in authentic projects and projects in which the student objectives differ from the instructor objectives. We propose that the episodes framework may be used to explore a variety of projects, characterize the nature of feedback, and examine the extent to which each participant's objectives are being addressed.

We plan to extend this investigation to include five additional student teams from three cohorts, to further explore the presented findings. Episode stages analysis is also planned to provide additional information as to the nature of feedback in these coaching sessions. To establish the effectiveness of feedback present in coaching sessions, we plan to analyse think aloud transcripts from team meetings that occurred before and after the coaching session. Analysis of pre coaching session transcripts is expected to provide indications of the team's understanding of content and concepts before feedback was provided; the analysis of post coaching session transcripts is expected to provide evidence of the impact of the feedback given in the coaching session on later discourse and actions of the team.

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Appendix C – The Effect of Feedback on Modeling in an Authentic Process Development Project

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Abstract— Developing and using models is an important skill employed by practicing engineers that is difficult to cultivate in students. One way to help students develop modeling capability is through feedback. Feedback has been shown to be effective in helping students close the gap between actual and desired performance. This case study investigates the effect of feedback on student teams' use of models in a three-week, open-ended, process development project in which students conducted experiments using a virtual laboratory. Feedback took place during meetings with an expert coach, termed coaching sessions. Coaching sessions of four teams were found to include a substantial amount of model-related feedback. In addition, an in-depth exploration of a single team provides insight into the impact of both directive and facilitative feedback on student modeling behavior.

Keywords-feedback; model development; virtual laboratory; engineering education; qualitative research

Introduction

While studies on the actual activities of practicing engineers are sparse, the development and usage of models is believed to be an important skill when completing open-ended, illstructured projects. For example, studies have found that practicing engineers develop and use models to better understand and predict the behavior of phenomena [1], [2]. The perception of engineering educators and students reflects this finding by emphasizing that problem-solving is central to engineering and modeling is a key part of problem solving [3]. While modeling is an important element in engineering practice, it is difficult to develop in students One way to help students develop modeling capability is to provide them with timely feedback. Feedback has been shown to be one of the most important tools used by instructors to help students close the gap between actual and desired performance [4].

This paper reports findings from a study of feedback in the Virtual Chemical Vapor Deposition (CVD) Laboratory Project. This authentic, industrially situated project requires student teams to optimize an industrial process within economic constraints. It has been shown to engage student teams in iterative experimental design, analysis and interpretation, and redesign [5]. Throughout the project, teams have opportunities to receive feedback on their strategy, experimental design, and performance. We believe the iterative process, combined with the feedback they receive, helps teams develop and enhance pertinent models to use in their solution process. In this study we begin to understand how feedback given to student teams in this project helps them develop and use models. Specifically, we ask the following research questions:

1) To what degree does feedback given to students in the Virtual CVD Laboratory Project directly pertain to modeling? What aspects of this feedback are directive or facilitative?
2) What is the effect of this feedback on student teams' subsequent use of models?

Theoretical Framework

Modeling

While many definitions of a model have been proposed, for brevity we limit our discussion to the definition adopted from Schwarz et al., who define a model as "a representation that abstracts and simplifies a system by focusing on key features to explain and predict scientific phenomena" [6, p663]. We focus on the qualitative and quantitative, syntactic mathematical models that students develop and use to explain and predict the CVD reactor behavior. Modeling theories describing science, mathematics and engineering professionals in practice contend that models are constructed from prior knowledge and newly gathered information and that they are refined in an iterative cycle of creation, use, evaluation, and revision. One study examined the evolution of models of chemical engineering undergraduates placed in the role of plant operators, as they performed troubleshooting in a simulated chemical plant [7]. In another study, protocol analysis was used to examine how instructional design experts used prior knowledge and experience to solve ill-structured problems [8]. This study investigates student model development and usage with respect to feedback.

Feedback

Feedback can be broadly defined as “information provided by an agent (e.g., teacher, peer, book, parent, self, experience) regarding aspects of one’s performance or understanding” [4, p81]. Based on an assessment of hundreds of meta-analyses from 180,000 studies, Hattie concluded that “the most powerful single moderator that enhances achievement is feedback” [9, p13]. While feedback has been shown to strongly influence student performance and learning, explicit research on the effect of feedback in engineering education is sparse. Findings from studies of first-year engineering students [10], [11] show that feedback is positively related to learning gains. These results are consistent with studies in other disciplines [12].

In general, there is limited agreement on what characterizes “effective” feedback, especially in ill-structured, open-ended projects. Hattie and Timperley [4] suggest that feedback is more effective when the feedback is related to the achievement of and progress towards specific goals and that less complex feedback may be more effective than more complex feedback. They also suggest that feedback focused on the individual rather than the task and goal is not effective. Elaborated feedback, feedback in which an explanation is provided rather than a simple “right” or “wrong,” may be more effective than a simple mark or grade. Shute contributed a literature review on formative feedback which supports these suggestions and provides tabulated lists of “things to do,” “things to avoid,” timing related issues, and learner characteristics to consider when providing feedback [13]. Feedback has previously been grouped as either reinforcing feedback or corrective feedback [14]. Reinforcing feedback, which we call affirmative feedback [15], acknowledges a correct response and may include praise. Corrective feedback has been described by Black and Wiliam to have two main functions: (1) to direct, and (2) to facilitate. Directive feedback tells the recipient what must be corrected whereas facilitative feedback, which may be more effective, provides suggestions to guide the recipient toward his/her own revisions [16]. In this study we classify episodes of discourse that contain feedback using one of these three descriptions: affirmative, directive, or facilitative. We then extend our group's use of episodes as a discourse analysis framework [19], described in the methods section of this paper, to investigate directive and facilitative feedback, and its impact on modeling, in the industrially situated Virtual CVD Laboratory Project.

Project Description

The Virtual CVD Laboratory Project provides opportunities for student teams to develop and refine solutions to an authentic engineering task through experimentation, analysis, and iteration. For this project, students were placed in the role of semiconductor process engineers. Student teams were tasked with the objective of optimizing an industrially sized virtual CVD reactor, which deposits thin films on polished silicon wafers. Performance metrics include high film uniformity at the target thickness, high utilization of an expensive and hazardous reactant, and minimization of development and manufacturing costs. If one performance metric is optimized, it is generally at the cost of another. To achieve their objective, teams must find suitable reactor input variable values (temperatures along the reactor, flow rates for two reactants, pressure, and reaction time). Their final "recipe," one of the final deliverables, consists of a set of values for these input variables that yields the best results with respect to the performance metrics. To optimize the reactor, they must integrate prior knowledge from previous courses. The desired learning objectives for the project include both development of professional skills (e.g., working in teams, communication) and integration of core engineering science concepts (e.g., material balances, reaction kinetics, diffusion).

A typical student team devotes 15 - 25 hours to this complex, three-week project. Key project milestones and corresponding opportunities for feedback are summarized in Table 7.3.1.

Table 7.3.1. Timeline and Opportunities for Feedback in the Virtual CVD Laboratory Project

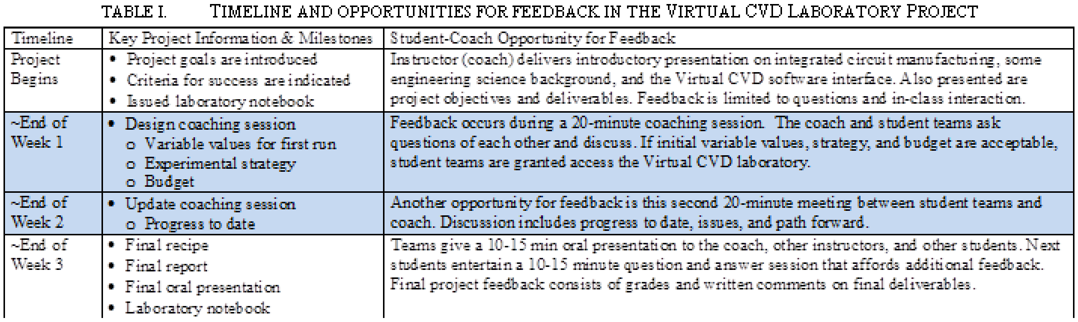

TABLE I. TIMELINE AND OPPORTUNITIES FOR FEEDBACK IN THE VIRTUAL CVD LABORATORY PROJECT

Timeline	Key Project Information & Milestones	Student-Coach Opportunity for Feedback
Project Begins	• Project goals are introduced • Criteria for success are indicated • Issued laboratory notebook	Instructor (coach) delivers introductory presentation on integrated circuit manufacturing, some engineering science background, and the Virtual CVD software interface. Also presented are project objectives and deliverables. Feedback is limited to questions and in-class interaction.
~End of Week 1	• Design coaching session o Variable values for first run o Experimental strategy o Budget	Feedback occurs during a 20-minute coaching session. The coach and student teams ask questions of each other and discuss. If initial variable values, strategy, and budget are acceptable, student teams are granted access the Virtual CVD laboratory.
~End of Week 2	• Update coaching session o Progress to date	Another opportunity for feedback is this second 20-minute meeting between student teams and coach. Discussion includes progress to date, issues, and path forward.
~End of Week 3	• Final recipe • Final report • Final oral presentation • Laboratory notebook	Teams give a 10-15 min oral presentation to the coach, other instructors, and other students. Next students entertain a 10-15 minute question and answer session that affords additional feedback. Final project feedback consists of grades and written comments on final deliverables.

The feedback analyzed in this paper occurred during two 20-30 minute meetings, referred to as coaching sessions and shaded in blue in Table 7.3.1, between the student teams and a faculty member, who we call the coach. During the coaching sessions the coach acts as a mentor or boss would in industry. In the design coaching session, students must deliver a memorandum that details values for their first run variables, a strategy for subsequent runs and experimental data evaluation, and an entire project budget (in virtual dollars). In the update coaching session students must deliver another memorandum with an update on their progress. The coach asks questions to guide students to further develop their experimental strategy, models, and understanding of core content and concepts, initial variable values, and budget. Feedback is tailored to engage students in identifying gaps in their current design and directing attention to methods for addressing those gaps.

Methodology

Participants & Setting

The twelve student participants were drawn from two cohorts in the final year of an undergraduate chemical, biological or environmental engineering program at a large public university. The project described in this paper took place as the second of three laboratory projects in a capstone laboratory course. Students were organized into teams of three and maintained their team composition throughout the course. One coach provided feedback to all student teams. This coach has coached over 60 teams in the same capstone course over several years and has many years of thin films processing experience. The coach has also published research papers and developed courses on the subject. This study is part of a larger study on student learning in virtual laboratories.

Data Collection & Analysis

Data sources include think-aloud protocol, student work products, and the Virtual CVD database logs. The think-aloud protocol [18], consists of transcribed audio recordings of the four student teams (Team A, Team B, Team C, and Team D) as they worked throughout the entire project. Student work products include the following items: laboratory notebooks in which students were instructed to detail their thoughts, calculations, and work throughout the project; all memos; final reports; final presentations; and electronic files, such as spreadsheets in which students developed mathematical models. Virtual CVD database logs record the chosen variables, measurements, and timing of all experimental runs.

Episodes analysis was performed on transcripts of the design coaching session for all four teams in order to investigate the first research question. In episodes analysis, feedback in the coaching sessions is characterized by parsing transcripts into a series of episodes. Each episode in this work has a central theme that has been found to fit into one of three general categories [19], a clear beginning and end, and contains up to four stages: surveying, probing, guiding and confirmation. Some smaller episodes have also been found to be nested within larger episodes, i.e., one themed discussion takes place in the context of a larger themed discussion. Episodes were classified as either model-related or not model-related. Model-related episodes were classified as either affirmative or corrective, with corrective episodes designated as either directive or facilitative. Episodes were designated as directive if the coach explicitly requested action and facilitative if guiding took place without an explicit request for action.

To explore the impact of feedback on student modeling behavior, we chose to examine one team in depth. Because Team A had the highest number of episodes that included corrective feedback on modeling, this team was chosen for a more detailed analysis. In addition to the design coaching session, episodes analysis was also performed on the update coaching session for this team. This team’s entire transcript consisted of nearly 67,000 words in 226 pages. We used an iterative approach to relate the feedback in the coaching sessions to the team’s modeling activity throughout this extensive project. First, two techniques were considered simultaneously: episodes analysis, described above, and Model Maps. A Model Map, described in [20], presents a chronological, visual inventory of the solution path that a team followed. A Model Map is created through analyzing work products and think-aloud protocol transcripts. The Model Map used in this study identified transcript page numbers corresponding to each instance of modeling activity. Initial analysis was performed by comparing the model-related episodes with Team A’s Model Map, focusing on modeling activity after the coaching session, in order to identify commonalities. Commonalities were further investigated by carefully examining the corresponding sections of the transcripts. A list of keywords was developed from both the coaching session episodes and the other sections of the transcripts that were identified by Model Maps. Keywords were then used to search the entire transcript for evidence of feedback related to modeling activity.

Results & Discussion

Feedback Related to Modeling: A Survey of Four Teams

Examination of the first coaching session for each of four teams suggests that some episode themes are present in most design coaching sessions (e.g., citing or evaluating sources, and performing a material balance), which is consistent with previous findings [17]. While some themes are common, each coaching session is unique and carefully tailored to each team's particular strategy. It was also clear that the design coaching session often involves episodes and feedback on themes that do not pertain to modeling, such as social dynamics, instructional design, input parameters, core content and concepts, and professional skills. In this study we focus on only the model-related episodes. To examine the degree to which feedback given to students in this project pertains to modeling (Research Question 1), episodes were grouped. Initially episodes were assessed as either model-related or not model-related. Next, the subset of model-related episodes was further divided into three groups: facilitative, directive, and affirmative. The results of this grouping are illustrated in Figure 7.3.1. Teams on average had 23 total episodes. An average of 10 of these related to modeling. The distribution of the type of feedback given in these model-related episodes varied from team to team. The model-related feedback that Team A received was fairly balanced between facilitative and directive and only included two affirmative episodes. Team B had come to the meeting with common model-related episode themes adequately addressed. This preparation appears to have prepared them well for the coaching session, since with regards to model-related episodes, minimal corrective feedback was given and no directive feedback was given. By contrast, Team C had come to the meeting late, and appearing unprepared. There was even an episode near the beginning of the meeting in which the coach asked the team if they wanted to postpone the meeting until the team was more prepared. They declined. In their coaching session, they had a few long, model-related episodes and, likely due to their lack of preparedness, many shorter episodes that focused more heavily on professional skills. The model-related episodes of Team D were distributed pretty evenly between the three types of feedback investigated here. Considering all four teams, it is evident that different types of model-related feedback are given in these coaching sessions to varying degrees depending heavily on the teams.

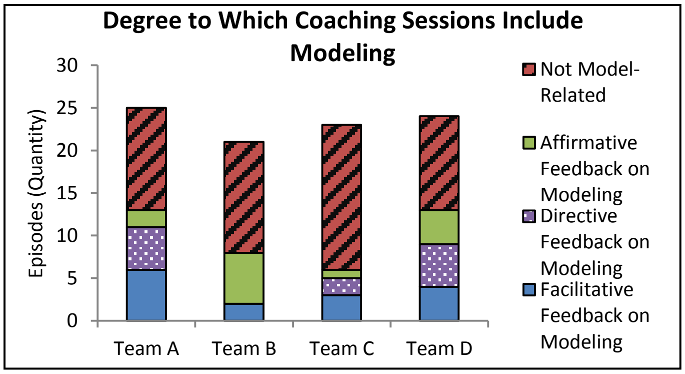

Figure 6.3.1: Episode grouping for four teams.

Impact of Feedback on Modeling: A Detailed Description of Team A

In the design coaching session of Team A, two of the model-related episodes were primarily affirmations, either acknowledging or confirming student responses with no guiding or correction. Five model-related episodes contained primarily directive feedback. These five directive episodes had a central, unifying topic: choosing a method to determine flow rate values. Two were substantially longer than the other three. They guided students to realize that material balance was an appropriate method to find initial flow rate values and ended with a statement in which the coach directed the students to do so. The other three directive episodes were very brief and occurred later in the coaching session, simply reiterating the directive statement given earlier. Six episodes in the design coaching session contained primarily facilitative feedback. One was nested within the context of the two larger directive episodes discussed above. The other five facilitative episodes were centered on the topic of the impact of pressure. Within the context of pressure there are two sub-episodes: one is themed around diffusion, the other has a reaction kinetics theme. The reaction kinetics episode provides the context for a sub-episode relating the impact of reaction kinetics to industrial practice.

The update coaching session was much shorter than the design coaching session, containing approximately half as many words and only eleven episodes. In the update coaching session, all corrective feedback was facilitative, with no explicit request for action from the coach. This coaching session contained a brief episode on maintaining their laboratory notebook, multiple episodes on modeling and their experimental strategy, and concluded with discussion about the final deliverables. Two episodes were model-related, facilitative episodes corresponding to the central topics of determining activation energy and identifying the distribution of wafers in the reactor. The four central topics are elaborated upon in the following sections.

Choosing A Method to Determine Flow Rate Values – Directive Feedback:

For the design coaching session, students are required to choose flow rate values for their initial run(s). Use of a material balance has previously been identified as a common method suggested by the coach to estimate or verify flow rate values in the design coaching sessions [17].

After identifying commonalities between episodes and Model Maps, and creating a list of keywords (i.e., material, mass, balance, flow, rate), the entire transcript of this team was explored in depth to look for indications of their activities prior to feedback and to examine their activities after feedback. At a team meeting the day before their design coaching session, the students expressed uncertainty in their values for flow rates. They proceeded to review literature and base one of their flow rate values on a journal article, while fixing the ratio between the two flow rate values. During a flow rate episode in the design coaching session, the coach probed the students regarding how they had selected their flow rates. They referenced a journal paper. However, the students had not accounted for the difference in size between the reactor in the paper and the reactor in the project. The coach guided them with leading questions towards using a material balance to assess the reasonableness of their values. The students confirmed that they were able to do so. Near the end of the material balance episode the coach gave a directive statement: *"I really think that you need to do a material balance to see if that is a reasonable number."*

The students agreed. The students and coach discussed what values were needed for the calculation, specifically density, and how to acquire those values. The episode then ended. The coach reiterated the directive statement in three very brief episodes later in the design coaching session. After the coach directed the students to perform a material balance, this directive feedback was almost immediately taken up by the students; it was required before they could proceed with the project. In their team meeting directly following the design coaching session, students reflected as follows:

> *S1: So, I don't know why we didn't think of this, mass balance.*
> *S3: I know right?*

S3 immediately performed the calculation. Later in the meeting, another student did the calculation independently, so that they could be confident in their values. After calculating, the students expressed appreciation for the result:

> *S3: Okay awesome stuff. When we get these numbers it's going to rock. I'm happy that we got these. For one I am really confused that we didn't figure this first. For two I am happy that we don't have this haphazard number no more. All*

> *the other ones are based off of things we looked up and yesterday we were just like sccms that's a good number. And we got pretty close considering we kind of guessed*
> *S1: Oh no, it wasn't a randomly picked number*
> *S3: Yeah it wasn't completely random but it still wasn't exactly for our process*
> *S1: But it does show the fact that we were so close because if you don't account for the excess it is even closer right? It does show that these references that we are looking at have somewhat of an idea on what they're doing. I guess they are about the same size reactor*

The team was required to revise their memorandum before receiving approval to begin experimentation. They presented a revised memorandum to the coach just over an hour after the first meeting concluded. The coach checked the directive items and gave authorization. Later in the project this team used the concept of a material balance in another way; they incorporated it into their mathematical reactor model to calculate the depletion of reactant gas as it flows through the reactor.

The Impact of Pressure – Complex, Facilitative Feedback:

The impact of pressure, as a central topic, was investigated similarly, with the following keywords: pressure, diffusion, and concentration. Like flow rate values, students must also choose an initial value for pressure before they can proceed with their experiments. Analysis of the think-aloud transcript before the design coaching session revealed that students had surveyed a variety of references to find an initial value for pressure. They had also identified models of diffusion. In these early meetings the team focused on diffusion as a key to achieve one of their performance metrics, uniform film thickness. They even stated that the system was diffusion controlled and expressed a desire to develop models of diffusion. While preparing for the design coaching session, they emphasized that they wanted to convey to the coach that they have put effort into investigating diffusion, illustrated by the following excerpt:

> *S1: I don’t know. But when we talk to him we can say that we had that, I don’t know, but I want him to know we’ve been thinking a lot about diffusion*

While pressure was not included in many of their diffusion discussions, the students explicitly related two aspects of diffusion directly to pressure. Discussions of these two aspects resulted in incorrect conclusions regarding both. Later, as the team wrote their initial memorandum they noted that they wanted to keep pressure low and that their initial pressure value was based on estimation.

During the design coaching session there was a group of facilitative episodes on this topic. An episode themed around pressure provided the context for two sub-episodes, one with the theme of diffusion and the other with the theme of reaction kinetics. A smaller episode, themed around situating the project in industry, was contained within the reaction kinetics episode. The coach began the pressure episode by directly asking the students how they determined the starting value for the pressure variable. The students cited a literature reference, and stated that they didn’t think the pressure was as important as the other variables. Within the context of pressure, the team and coach discussed diffusion. During this sub-episode on diffusion, students stated that pressure should be low. The coach then asked why it would be problematic to use an incredibly low value for pressure. This prompted a discussion about the two aspects the students had previously considered, incorrectly, relating pressure and diffusion. It appears the team had a misunderstanding or incomplete understanding about the role of diffusion and the impact of pressure on the performance metrics. The team was guided to conclude that diffusion is not the only way pressure affects their performance metrics, which led to the second sub-episode.

This second sub-episode, on the concept of reaction kinetics, began with revisiting a previous question; the coach asked what other thoughts the students had about why the pressure should not be set too low. Students related pressure loosely to reaction rate. The coach focused discussion with a leading question regarding the contribution of pressure to reaction rates. The students were then guided to recognize that pressure plays a role in the concentration which in turn has an impact on the reaction rate. Within the reaction kinetics episode is another sub-episode which situated the project in the industrial context and linked the concept of reaction kinetics to its impact on high-volume manufacturing. At the end of this group of episodes, students acknowledged that if the reaction rate is slow, product will be made at a slower rate, which may pose a problem in high volume manufacturing.

Following the coaching session, the team discussed their previous understanding of pressure as it relates to diffusion and stated that they needed more information to better understand how diffusion relates to pressure. As they progressed through the project, it is clear from their discourse that they still lack a firm conceptual basis for determining pressure values. They continued to primarily reference diffusion when discussing pressure until one student, S3, created a mathematical model.

Approximately one week after the design coaching session, S3 came to a team meeting with a mathematical model of the entire reactor. S3 then began to emphasize the impact of pressure on concentration and reaction kinetics, the same emphasis the coach had given in the design coaching session. This sentiment was reiterated several times throughout the meeting both in the context of trying to convey the information to the other two team members as well as trying to phrase it properly for inclusion in their update memorandum. However, S1 and S2 appear to maintain their understanding that pressure only impacts diffusion. The very last reference to the impact of pressure occurred in the team's last meeting; again S1 and S2 referenced decreasing pressure to increase diffusion, with no mention of reaction kinetics or reaction rate.

Determining Activation Energy –Facilitative Feedback:

In this example, we show how feedback resulted in a change in a mathematical model parameter value. Prior to the second coaching session, S1 and S3 had a debate in which they discussed two options to acquire a value for one of their model parameters, activation energy: S1 wanted to calculate it from their experimental data, while S3 wanted to get it from a literature search. They chose to search for it because S3 commented that the team should keep things simple. This statement appears to reference an episode in the design coaching session on team dynamics in which the coach noted that S1 had a tendency to make things complex. S3 was also the student who was performing the bulk of the mathematical modeling and would be directly integrating the value into the model. S3 spent time independently finding model parameters, and expressed that activation energy had take "a really long time" to find. The keywords used to explore this topic include: activation, energy, Ea, reaction, and rate.

In the update coaching session, while discussing the team's experimental strategy, an episode directly addressed activation energy. The episode started with a student expressing uncertainty in their mathematical model parameters. The coach asked what value they used for activation energy and further probed to identify the source of their activation energy. After discovering that they had found the value at a website, the coach guided the students towards the other option they had previously debated, calculating a value from their experimental data. After this feedback, the students explicitly performed experimental runs in order to determine the activation energy experimentally with S3, the student previously opposed to this option, taking the lead and personally performing the calculations to experimentally determine the activation energy.

Identifying the Distribution of Wafers in the Reactor - Student-Initiated, Facilitative Feedback:

Our final example is of straight-forward, student-initiated feedback. To explore this topic, keywords include: wafer, and zone. In this case, students noted a need to know the distribution of wafers in the reactor while working on their mathematical model. The reactor has 5, independently controlled temperature zones in which the wafers are distributed. In a team meeting, prior to the update coaching session, students said "we really need to know how many wafers are in each zone." They even cited that lack of information on the topic was impeding their modeling progress. They made an estimate about the distribution of wafers based on an image of the reactor; however, they also decided to ask the coach during the update coaching session. In the update coaching session, they asked and the coach provided them with the information. After the update coaching session, they immediately integrated it into their mathematical model. While this feedback was briefer than others, the students clearly had a need for the information and initiated the discussion. They were ready to receive the information and apparently perceived it as something that would help them towards their end goal.

Conclusions & Future Work

Feedback on modeling is present to varying degrees in all coaching sessions that were examined. When exploring one team in depth, coaching was found to have a significant impact on the progress of the team. The first two general topics brought up concepts that hadn’t been fully explored by the team previously. One included primarily directive feedback, to which the students responded with the requested action, and later incorporated the same concept in a very different way into their project. The second included primarily facilitative feedback. The topic of the impact of pressure was complex and appears to have been incorporated by each student differently. The student who had created the mathematical model integrated it fully. The concept was required in order to develop the mathematical model. The remaining two students appear to have maintained their prior understanding more than integrating the feedback from the coach. It is possible, that because they were less involved in the creation of the mathematical model, that they did not need to further investigate the topic to proceed with the project and they did not have to reconcile what they understood with the complex interactions in the mathematical model. The final two topics were facilitative and had both been discussed explicitly by the team prior to the coaching session in which they received feedback. Feedback regarding both of these topics was fully integrated into the model development of the team. While not discussed in depth in this paper, it appears that episodes focused on team dynamics and other themes not specifically model-related, may have had an influence on the team's modeling activity. This warrants further investigation. In addition, modeling activity is not the only aspect of engineering practice that is elicited in this project. It has been argued that professional skills are an aspect of engineering practice that are underrepresented in engineering education and engineering education research [2]. With a similar approach to that used in this paper, we plan to investigate the development of professional skills in relation to feedback.

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Appendix D - Adaption of a Virtual Laboratory Curriculum: A Preliminary Study of Implementation at Other Institutions

Gilbuena, D., Sherrett, B., & Koretsky, M. D.

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Abstract

This paper describes the adaption and implementation of the Virtual Laboratory Project from its home university to other institutions. In the Virtual Laboratory Project students do not interact with real equipment to obtain data, but rather with computer simulations of laboratory equipment, obscured by noise. This innovation was developed with the intent of complimenting physical laboratory experiences by allowing future engineers to practice designing experiments, analyzing and interpreting data and making informed choices based on their analysis, skills they will need in industry. The idea of using virtual laboratories to facilitate project based learning is compelling since, once the software has been developed, the cost to transport a virtual laboratory to a new institution is relatively small, consisting mostly of developing teacher expertise.

Understanding and planning for the transportability of educational interventions is being emphasized by funding agencies at the national level. The aspects of transportability specifically studied in this paper include usage history and current adoption information, the Virtual Laboratory Project's perceived sources of effectiveness, barriers to implementation and adaptations made during the implementation process. This paper is a subset of a larger investigation on student learning in virtual laboratories. Artifacts of implementation and teacher and student perceptions were the primary data sources for this investigation.

Thus far, the Virtual Laboratory Project has been adapted to high school, community college and other university settings and implemented in a total 15 institutions and 59 cumulative classes. Some of its perceived sources of effectiveness include the industrially situated context which is reinforced by the budget, and the components that afford students the ability to quickly and easily collect authentic data. This preliminary report suggests that this learning environment may have the potential for widespread adoption and adaptation; however, additional research is needed.

Introduction

Transportability is a widespread goal of education research and curriculum development. If an intervention is effective in one environment, many developers want to share the intervention with other teachers and institutions to have a larger impact and improve the educational process as a whole. Often developers of curricular interventions provide suggestions for implementation, curricular materials, and support; however, one aspect commonly missing is more reflective and evidence-based description of the implementation process as technical and pedagogical innovations move from the institution at which they were developed to other institutions with different faculty, different students and a different culture.

The need for more systematic understanding has recently been emphasized at the national level. The President’s Committee of Advisors on Science and Technology Panel on Education Technology reported in 1997 that significant investment needed to be made in understanding learning and supporting the development of best practices. In supporting best practices, the report emphasized the need for large-scale studies to determine best practices and provide information on generalizability.[1] The Interagency Education Research Initiative, formed in response to that report, was created to support research and develop a knowledge base to "support the development, testing, and implementation of scalable and sustainable interventions to improve teaching and learning, particularly through the use of technology."[2] Additionally, funding agencies like the National Science Foundation (NSF) require a "broader impact" component in all grant proposals.[3] Transportability is specifically emphasized in the new Transforming Undergraduate Education, in Science, Technology, Engineering and Mathematics (TUES) Program, which requires transportability as a main component for funding of proposals.[4] The Institute of Education Sciences (IES) specifically listed "Scale-up Evaluation" as a research project goal in the most recent Request for Applications and approximately two percent of IES funded projects since 2004 had the goal of researching scale-up evaluations.[5]

This paper describes the adaptation of a virtual laboratory curriculum from its home university to other institutions. The Virtual Laboratory Project developed at Oregon State University is very early in the scaling or diffusion process. This innovation's eventual fate is unknown, but investigation of the process at multiple stages is useful for informing future work, both within this project as well as for others. This paper presents preliminary results intended to assess the current adoption, investigate sources of the innovation’s effectiveness and examine issues and adaptations of this industrially situated Virtual Laboratory Project during implementation in various settings.

Transportability and Scale-up

Transportability is a broad topic that is difficult to research and assess. The ultimate question in this type of research is what works, with whom, where and in what conditions? It is concerned with both the overall diffusion of an innovation as well as the details of that process in assessing changes and effectiveness.

Diffusion of innovations is a theory put forth by E.M. Rogers in his first book on the topic in 1962.[6] Diffusion of innovations has been used as a theoretical framework for decades and has accounted for more than 5,000 publications in the field. According to Rogers “diffusion is the process in which an innovation is communicated through certain channels over time among the members of a social system.” [6] Characteristics that contribute to the rate at which an innovation is adopted include relative advantage, compatibility, complexity, triability, and observability. The innovation-decision process used by an individual in consideration of adopting an innovation consists of five stages “(1) from first knowledge of an innovation, (2) to forming an attitude toward the innovation, (3) to a decision to adopt or reject, (4) to implementation of the new idea, and to (5) confirmation of this decision.”[7]

Assessment of implementation is emphasized in the literature because of the major role it plays in evaluating the effectiveness of interventions. Implementation of an educational intervention may be performed with fidelity or adaption. *Implementation fidelity*, also known as integrity or adherence, is defined as "the degree to which teachers and other program providers implement programs as intended by the program developers."[8] Implementation fidelity has been used to assess interventions and training in parenting, suicide prevention, drug abuse prevention, violence prevention and many other programs. However, recreating the original implementation as intended by the developers is challenging in practice. *Implementation adaption*, also known as adaptation, reinvention, or flexibility, allows for modifications to an intervention in order to suit the needs of the individual teachers and program providers. The acceptability of adaptation has been in debate since the 1980s,[8] and has recently turned to a closer examination of what kinds of adaptations are acceptable.[9]

Coburn pointed out that there was tension between the viewpoints of *scaling-up* via implementation fidelity versus scaling-up via implementation adaptation and further argued that scaling-up was more than just the use of an intervention in multiple settings, but included other factors.[10] Coburn proposed a conceptualization of scale that includes dimensions of depth, sustainability, spread, and shift. Dede added to Coburn's conceptualization of scale with a dimension of evolution.[11] From a design perspective, innovation development within those five, interrelated dimensions might necessitate certain activities[12]:

- *Depth*: conducting evaluation and research to understand and enhance causes of effectiveness;
- *Sustainability*: adapting to inhospitable contexts via developing hybrids tailored to adverse conditions;
- *Spread*: modifying to retain effectiveness while reducing the level of resources and expertise required;
- *Shift*: moving beyond "brand" to support user ownership as co-evaluators, co-designers, and co-scalers; and
- *Evolution*: learning from users' adaptations to rethink the innovation's design model.

McDonald emphasizes the importance of the context in which an intervention is implemented, a point of view that supports careful and evidence based adaptation of an intervention to suit different contexts.[13] Dede also emphasized the adaptation of innovations and summarized scale-up as "adapting an innovation that is successful in one setting to be effectively used in a wide range of contexts."[11]

This paper integrates perspectives from both the diffusion of innovation theory and the scale-up framework. We use the diffusion of innovation theory particularly to track the metrics of the adoption process while scale-up provides a beneficial framework to characterize the important and unique attributes of the innovation.

Research Design

The research design is presented loosely in the form of the diffusion of innovations framework while incorporating Dede's scale-up and innovation development framework. The timeline is presented first, to provide context. Next, the innovation is described along with evolution of the innovation at the home institution. This description includes the authors' expected sources of effectiveness. Communication channels are expressed in two parts, the selection of initial institutions for adaptation and implementation, and the widespread dissemination of the Virtual Laboratory Project via additional diffusion mechanisms. The social system, while complex is partially described with participants in the Methods section, and further explored in the Results and Discussion section.

Timeline

The development, implementation and scaling of the Virtual Laboratory Project has thus far consisted of four phases:

1. Initial development, implementation and revision of the innovation at the home institution.
2. Careful adaptation and implementation of the innovation at three additional institutions.
3. Workshop development based on student learning assessment and scaling information from Phases 1 and 2.
4. Workshop delivery and open use with developer approval.

The timeline for these four phases is described in Figure 7.4.1.

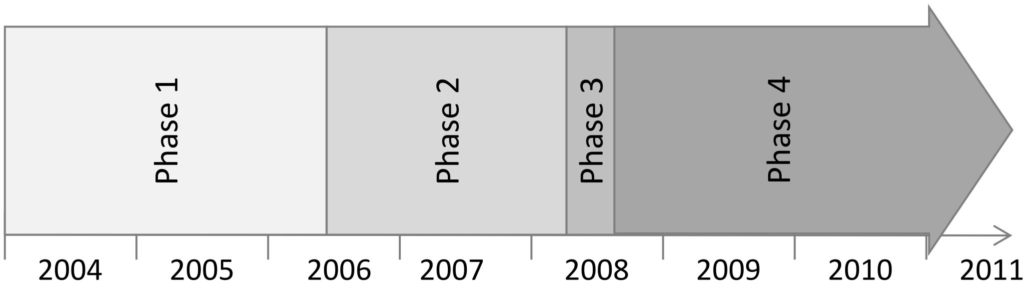

Figure 7.4.1. Timeline of the development, implementation and scaling of the Virtual Laboratory Project

The Innovation – Industrially Situated Virtual Laboratory Project

Over the past seven years two industrially situated virtual laboratories have been developed, implemented, assessed and disseminated. While they differ in topic, they are similar in other aspects and are both referred to as the Virtual Laboratory Project because of their similarities. Both virtual laboratories are based on engineering principles and use detailed mathematical models. Both also give the teacher the option to incorporate process and measurement error. In the Virtual Laboratory Project, learning occurs not by direct interaction with the software, but rather through interaction with team members, teachers and other resources that is mediated by the software. The Virtual Laboratory Project is not intended as a replacement for physical laboratories. We believe hands-on physical laboratories are essential to learning engineering. The Virtual Laboratory Project, however, was intended to compliment the experience of physical laboratories by minimizing the difficulty in performing experiments and allowing students to focus efforts on strategically designing their experiments, analyzing and interpreting data and making informed choices based on their analysis. In this way, this innovation scaffolds problem solving that students would not have the time or resources to accomplish otherwise.[14]

The Virtual Laboratory Project was initiated based on four learning objectives[15]:

1. Promote development of creative and critical thinking in a way that applies core concepts from the curriculum.
2. Engage students in an iterative experimental design approach that is reflective of the approach used by practicing engineers.

3. Provide an authentic context, reflective of the real-life working environment of a practicing engineer, such as working with a team to complete complicated tasks.
4. Promote a learner-centered approach to an open-ended design problem which results in an increase in the student's tolerance for ambiguity.

The delivery of the project at the home institution lasts for three weeks. In the beginning of the first week of the Virtual Laboratory Project, the laboratory instructor introduces the faculty member who serves as the subject matter expert. The expert presents background technical information, introduces the virtual laboratory software and presents the objectives of the project during two, 50 minute class periods. A timeline, list of deliverables, and description are shown in Table 7.4.1. The expert also meets with student teams at schedule times during the project to provide feedback.

Table 7.4.1. The timeline and description of the Virtual Laboratory Project.

Timeline	Deliverables	Description
Project Introduction		Expert presents introductory manufacturing context, engineering science background, the Virtual Laboratory Project software, and project objectives and deliverables.
End of Week 1	• Design Memo Meeting (DMM) ○ Initial run parameters ○ Experimental strategy	Student teams meet with the expert to discuss design strategy. Upon approval of strategy and parameters, students are given a username and password to access the Virtual Laboratory Project.
End of Week 2	• Update Memo Meeting ○ Progress to date	Student teams meet with expert to discuss progress, issues, and receive feedback.
End of Week 3	• Final Recipe • Final Report • Final Oral Presentation • Laboratory Notebook	Teams deliver a 10-15 minute oral presentation to the expert, 2 other faculty members, and the other students in the laboratory section. The presentation is followed by a 10-15 minute question and answer session.

The Virtual Laboratory Project as delivered at the home institution is very open-ended, unlike laboratory experiences earlier in the curriculum. Many physical laboratories are described as confirmation experiments, with clearly defined operating procedures where strategic focus is on finishing on time or troubleshooting malfunctioning equipment within tight time constraints. In the Virtual Laboratory Project, students must optimize reactor performance with very little procedural or strategic information provided. The increase in cognitive demand in the strategic domain is balanced by the decrease in demand in the haptic domain. Instead of spending time and cognitive resources assembling equipment, and initiating and maintaining functionality of instrumentation, students are able to use their resources to manage a budget, create and carefully plan the project strategy, and analyze and assimilate the information from multiple experiments that were easily run. The process of running the reactor once, taking measurements, and exporting the measurement data to excel takes approximately 3 minutes.

Virtual Chemical Vapor Deposition Laboratory

The first industrially situated virtual laboratory discussed in this work, the Virtual Chemical Vapor Deposition (VCVD) laboratory, was designed and developed in 2004 and first implemented at the home institution in one course in 2005. The original Virtual Laboratory Project consisted of three elements: the student interface (originally HTML) which facilitated data acquisition, the instructor interface that allowed for control and assessment of student results, and the instructional design which wrapped the project in an industrial context and set forth student objectives and deliverables. In 2005, after the initial implementation a 3-D interface was constructed, that closely resembles a microelectronics industry cleanroom, as a potential replacement for the HTML interface. The HTML interface was maintained however, for institutions that could not accommodate the 3-D interface.

The VCVD laboratory project tasks students with the development of a process "recipe" for a low pressure chemical vapor deposition reactor in high volume manufacturing. Optimization includes both the uniformity of the deposited silicon nitride (Si_3N_4) film, as well as utilization of the reactant gas while minimizing development cost. Students are charged per run and per measurement point. This project is situated in the context of the integrated circuits industry. Students are required to keep a detailed laboratory notebook, similar to those kept in industry, which should contain observations, strategies, analysis, results and logic. In order to optimize the process, the students control nine process parameters: reaction time, reactor pressure, flow rate of ammonia, flow rate of dichlorosilane (DCS), and the temperature in five zones in the reactor. After entering and submitting parameters to run, students may implement their measurement strategy in which they choose the number and position of wafers to measure, as well as the number and position of points within each wafer. The results of measurements can be viewed in the program or exported to an excel file where further analysis can take place.

Virtual BioReactor Laboratory

In 2007 a second virtual laboratory was added, the Virtual BioReactor (VBioR) laboratory. This second virtual laboratory was added to appeal to bioengineering and environmental engineering students. While the scientific content was based on a different subject, the VBioR laboratory shared the same learning objectives, a similar theory-based model with error, a similar type of instructor interface and an HTML student interface. In 2010, a web-based 3-D interface was developed for the VBioR. In the VBioR laboratory students are tasked with optimizing volumetric productivity by controlling temperature, substrate concentrations, cultivation times (both batch and fed batch), and feed flow rate. Students also choose when and what to measure. Every run and every measurement costs virtual money. The project is situated in the context of either production of a recombinant protein (as might be found in the pharmaceutical industry) or waste degradation (typical of waste water treatment plants). Additional details of implementation and student learning in the VCVD laboratory and the VBioR laboratory have been previously published.[16,17]

Characteristics and Sources of Effectiveness

Characteristics of the Virtual Laboratory Project that, according to the diffusion of innovations theory, influence the diffusion process include compatibility, complexity, triability, observability, and relative advantages. In the Virtual Laboratory Project, learning outcomes are compatible with those of many teachers; however, as discussed in the Results and Discussion section, IT infrastructure may pose a different kind of compatibility issue. The Virtual Laboratory Project may be perceived as complex due to the topic and the technology requirements. The Virtual Laboratory Project is free to use, and teachers need only contact the developers for access. It is also observable primarily via publications. As budgets are tightened and class sizes increase and the option of a free, effective educational intervention becomes more of a relative advantage.

For a more detailed assessment of the characteristics of the Virtual Laboratory Project, it is useful to frame it in terms of "sources of effectiveness," an important component of the scale-up framework. Identified sources of effectiveness as assessed by student learning investigations and developer perception are presented in Table 7.4.2 along with the affordances these sources of effectiveness provide.

Diffusion Mechanisms

As with most new innovations, the Virtual Laboratory Project environment described in this paper first required development, implementation, assessment and revision at the originating institution. During this time, assessment included examination and improvement of the project environment and scientific study of student learning, results of which were disseminated via primarily conference publications.

Table 7.4.2. Sources of effectiveness and affordances of the Virtual Laboratory Project.

Sources of Effectiveness		Affordances
Instructional Design	Project Objectives	Multiple design objectives emphasize design strategy and integration of appropriate domain knowledge. These also link to the situated nature of the project, along with the budget and industrial context. The students value the project because the objectives are real - high quality product at low price (both development and production).
	Budget	Cost constraint makes students value runs which emphasizes planning and discourages "video game" mode. The budget reinforces the authentic nature of the project.
	Coaching	Feedback from teacher facilitates integration of prior knowledge and reinforces the industrially situated nature of the project.
	Worksheets	Used at the high school and community colleges, worksheets provide level-appropriate scaffolding to allow access at all levels.
	Formal Communication	Induces student reflection and organization of thoughts, including team negotiation. Provides opportunity for instructor feedback
	Teams or Individuals	Structuring student groups promotes peer instruction, team negotiation, collaboration and project management.
	Industrial context	This affords student to value the project. They take ownership of the project because they feel it is helping to prepare them for careers and ties to the real world. They feel the skills that they are using to solve the problem are tools that they will use in the workplace. The budget plays a role in supporting the industrial context.
Student Interface	3-D	Represents the authentic environment of an authentic IC factory. Reinforces the sequence of procedures to obtain experimental data. Students also enjoy this aspect as a "fun" part of the project.
	HTML	Allows Institutions that are technology challenged to use the project.
	Reactors and measurement tools	Allow students quick and easy data acquisition which allows for iterative design.
	Data display and export	Allows students to integrate engineering science knowledge and apply statistical methods to analyze results from an experiment.
	Cost tracking	Reinforces budget and industrial context, allows for easy budget tracking.
	Theoretical Model	The rigorous model reinforces the authentic nature of the problem. Students believe the results could be obtained in a real IC factory. Including measurement and process error is critical to the authentic nature of the problem. An over simplified model would make the experience much less real.
Teacher Interface	Student account setup	Allows teachers to assess individuals or groups of students in terms of budget, progress and performance and use that information to provide feedback. This also allows the teacher to restrict usage until students have formulated a plan.
	Student progress	Allows teachers to incorporate dynamic assessment of student progress and performance into feedback.
	Reactor customization	Allows task characteristics to be changed from year to year which can be used to combat "institutional knowledge."
	Instructional materials	Provides resources for new teachers to learn about the technology and materials for implementation.
	Class history	Allows comparison of performance from previous years.

Phase 2 of the Virtual Laboratory Project scaling proceeded over the next three years (2006, 2007, and 2008). A series of careful implementations of the innovation were performed at two universities and one high school (one per year with the high school being the last). In all cases, a graduate student from the home institution was paired with the teacher in order to facilitate implementation. All teachers in this stage of implementation had chemical engineering experience and in the first two cases the teachers had project specific expertise. In two cases, the graduate student assisted in actual presentation of the implementation. For the high school, the instructional design was modified in order to suit the needs of the teacher and the lower educational level of the students. Scaffolding was developed and took the form of a homework worksheet prior to presentation of the project, two walk-through worksheets intended to introduce students to the environment and assist in the first exploration of variables and an optimization assignment. A more detailed description of the first implementation of the Virtual Laboratory Project at the high school level in an Introduction to Engineering class and Chemistry classes is available elsewhere.[18]

In Phase 3, the information gained from the careful implementation efforts was combined into materials for a workshop on the Virtual Laboratory Project. Materials included project assignments, presentations, curricular schedules, and student learning information. A workshop binder was created as a resource for workshop participants to reference; it included all workshop presentations and curricular materials as well as background information on the Virtual Laboratory Project topic and software installation instructions. These materials were also made available to instructors via the password protected instructor interface website.

Phase 4 consisted of holding workshops based on the workshop materials and open dissemination of the Virtual Laboratory Project. Workshop participants were solicited via word of mouth, personal promotion by the developers and collaborators, flyers posted on the home institution website, and an advertisement in a teacher association publication. In order to use the Virtual Laboratory Project in classes, a teacher need only contact the developers for a teacher account. There is no charge for use of the Virtual Laboratory Project; however, users were requested to provide documentation in order to satisfy grant requirements. Technical support is offered to users as requested, with no charge. A detailed description along with assessment of two of the workshops is described elsewhere.[18] A summary of diffusion activities is shown in Figure 7.4.2.

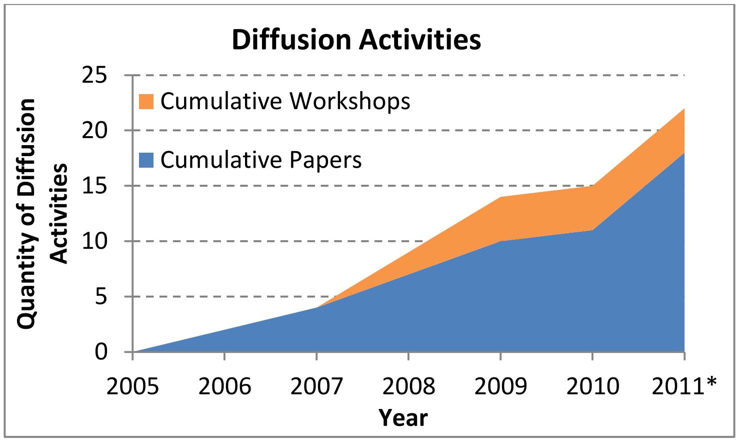

Figure 7.4.2. Summary of diffusion activities, growing from zero in 2005 to the current total of 18 published or accepted papers and 4 workshops. *values for 2011 include the current number of accepted papers and zero additional workshops.

Methods

Participants

Participants consist of individuals from 12 institutions total, five of which were universities (offering undergraduate and graduate degrees), two were community colleges, and five were high schools. This research was approved by the institutional review board and all participants signed informed consent forms.

Students from the home institution and three other institutions were interviewed and/or surveyed. Students surveyed at the home institution consisted of all students that participated in the project. Interviews were conducted with students in two cohorts at the home institution; selection of these students was based on their participation in a larger research study on student learning in virtual laboratories. The process for choosing these students addressed several factors including schedule, gender distribution, and perceived willingness to comply with research study requirements. Students' academic performance (e.g. GPA, class standing, test scores) was not a contributing factor in selection at the home institution. Students surveyed and interviewed at the remaining three institutions were selected by the teachers at those institutions and represent three cohorts and four classes in which the Virtual Laboratory Project was implemented.

Teachers were either surveyed or interviewed. The teachers surveyed consisted of individuals that had been participants at workshops on the Virtual Laboratory Project.

One post-implementation survey was completed after the teacher had implemented the Virtual Laboratory Project in their class. A small stipend was offered to some workshop participants (multiple workshops were presented with a stipend only offered at a fraction of them) for attending workshops, with a subsequent stipend offered if participants implemented the Virtual Laboratory Project and submitted the post-implementation survey with required documentation. Interviewed teachers included workshop participants and non-workshop participants, all of which had implemented the Virtual Laboratory Project in their curriculum.

Data Collection & Analysis

Data sources included three broad categories: (i) history of Virtual Laboratory Project usage (e.g., number of users, number of classes, number of institutions over time), (ii) artifacts of implementation (e.g., lesson plans, project assignments and summaries of student information), and (iii) participant perceptions (e.g., student and faculty questionnaire responses and audio recordings, transcripts, and notes of semi-structured interviews).

The Virtual Laboratory Project history of usage was analyzed for adoption rate and cumulative adoption and usage. Project implementation timelines and artifacts were compared directly and used to assess adaptations made in the different settings. Surveys and interviews were examined for common themes, a subset of which was tied to either sources of effectiveness of the innovation or barriers to adoption.

Teacher perceptions and student perceptions were used as indicators of the sources of effectiveness.

Results and Discussion

Current Adoption

To date a cumulative total of 15 institutions have implemented the Virtual Laboratory Project in a cumulative total of 59 classes (a class in which the Virtual Laboratory Project was used multiple years is counted for each year). Adoption of the Virtual Laboratory Project over time is shown in Figure 7.4.3.

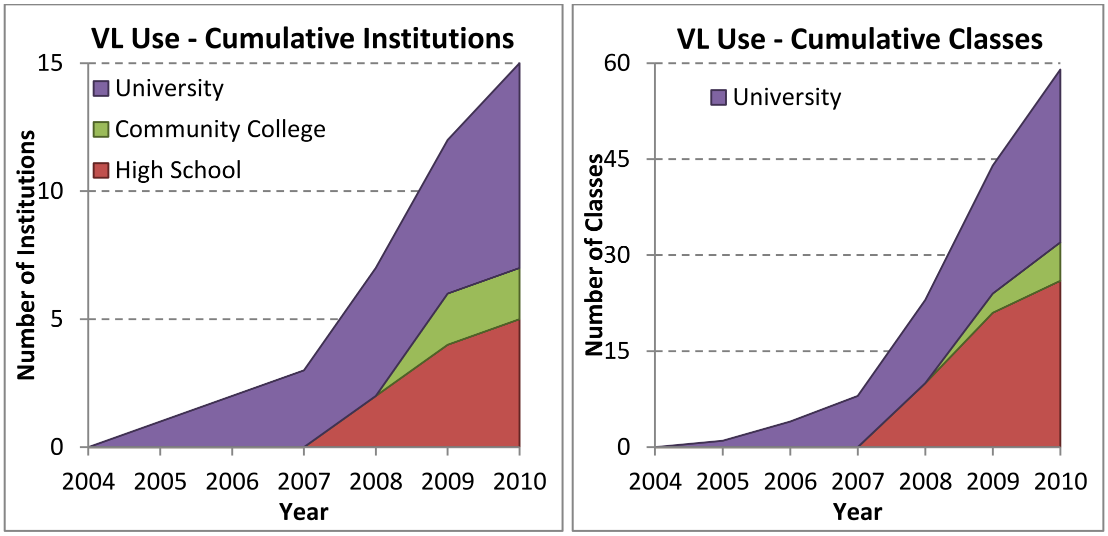

Figure 7.4.3. Virtual Laboratory Project cumulative use over time with number of institutions (left) and number of classes (right)

In 2008 and 2009 high school adoption of the Virtual Laboratory Project contributed greatly to the overall adoption. This corresponds to the workshops that were delivered, two in 2008 and two in 2009. The majority of high school teachers that have implemented the Virtual Laboratory Project in one of their classes attended one of the workshops prior to implementation, the only exception being the initial high school implementation. In addition, both community college teachers that have used this innovation attended one of the workshops. By contrast, more than half of the universities, other than the home institution, were introduced to the innovation through one-on-one interaction with one of the developers.

Considering the usage information of the Virtual Laboratory Project, some institutions have continued use every year since initial implementation, others use it in a course offered every other year, and still others have scaled down use or ceased to use the Virtual Laboratory Project. Nine of the 15 institutions that have used the Virtual Laboratory Project have used the innovation for more than one year, and three institutions used it for the first time in 2010. Of the six teachers that completed post-implementation surveys, 100% stated that they intended to use the Virtual Laboratory Project again. The majority of those interviewed also expressed interest in using the Virtual Laboratory Project in subsequent years.

Sources of Effectiveness

In this preliminary report of findings, some of the authors' expected sources of effectiveness were found to be reinforced by both teachers and students interviewed and surveyed. One of these sources was the situated, industrial context of the instructional design. Three questions on the post-implementation survey elicited responses consistent with this source of effectiveness:

- What need in your teaching did the laboratory address?
- What specific content, concepts, and/or set of cognitive skills were you able to address with this virtual laboratory?
- What is the value added in the use of the virtual laboratory?

Five of six teacher participants that completed post-implementation surveys expressed that the Virtual Laboratory Project provided a realistic experience for students in either an engineering or scientist position. Participants further commented on the benefits of the workplace scenario. In addition, the same questions were asked of students at one of the universities and more than 41% of the 60 students either explicitly referred to the "real world" scenario or heavily eluded to the "real world" context. The following student responses reinforce this point:

> *"It allowed us to do some of the real problem solving that we might have to do in our careers."*
>
> *"It allowed us to apply knowledge to real life situations."*

Interviews of teachers were also consistent with the surveys on this point:

> *"this [the virtual laboratory project] is one way that we are definitely doing it, allowing them to act like real scientists and real engineers"*
>
> *"the CVD is one of the only examples we have to give them where they get a glimpse of what it might be like to take this little thing and scale it" [referring to scaling it to an industrial size and manufacturing setting]*

Interviews with students were also consistent, with many students emphasizing the "real world" aspect of the project.

At the university level, the budget, another perceived source of effectiveness, was noted to reinforce the situated nature of the project by both teachers and students. Furthermore, one institution placed little emphasis on the budget and the project appeared to be less successful. However, drawing conclusions is difficult as there are several factors that affect the success or effectiveness of the project. Further investigation of what conditions make the budget a significant source of effectiveness is needed.

Other sources of effectiveness that were reinforced by teachers and students were the theoretical model and the reactors and measurement tools, which combined to allow students to easily and reliably collect authentic data. This feature affords students the ability to perform iterative experimental design and analysis. An interview with one of the teachers illustrates this well:

> *"the pros of the virtual lab are that they do get it to work and they get lots of data and so there's a much greater opportunity to look back to theory. Um, so it's as if they've spent six months in the lab, you know, at the end of six months they might actually have their [experiments] working well enough that they can connect back to theory and so that certainly is really helpful."*

The majority of students interviewed expressed that they appreciated that they could gather data easily without worrying about equipment troubles.

> *"I found it to be one of our more helpful projects because I felt that we got to go more in depth with it than some of our other labs because some of our other labs have so many things that go wrong because we have like cheap [equipment] and stuff like that. So it was nice that we didn't really have to deal with that at all."*

> *"for the virtual lab, the lab equipment worked. Ha ha huh, 'cause like with many of the other labs they're like 'ok this kinda works.' And you know, it's like ok take this reading and this part of the equipment doesn't quite work and so it's just kind of like work arounds. And like oh look the hoses you know and now it broke off and it's squirting water all over. You know, so it was nice to have…a lab that we could access any time and it would function"*

Preliminary data support the budget, reactors and measurement tools, theoretical model and industrial context as sources of effectiveness. The remaining sources of effectiveness require investigation into how they align with teacher and student perceptions and in what ways the current list warrants revision.

Barriers to Adoption

Two potential disadvantages regarding the Virtual Laboratory Project are information technology and preparation time. Two of the six teachers that completed post-implementation surveys commented on issues with the IT infrastructure and could not install the 3-D interface. One of these teachers also noted that they had spent preparation time attempting to install the 3-D interface, but ended up using only the HTML interface. In fact, two teachers noted that they spent time attempting to obtain permissions to install the 3-D interface, something that was also emphasized as an issue in two interviews. Other technology based interventions also have faced challenges.[19]

Of the seven teachers that specified preparation time needed for this project, the shortest amount of time was two hours and the longest was 30 hours. The average was approximately 12.5 hours (rounding to the nearest half hour). In general, teachers with more domain expertise would be expected to require less preparation time; that seems consistent with findings thus far, but additional factors most likely contribute to required preparation time. One teacher that was interviewed had attempted to get colleagues at the institution to implement the Virtual Laboratory Project as well. This individual stated that the biggest barrier for colleagues was:

> *"for them to take the time to meet with me to learn it, to understand it, and then to work it into their curriculum."*

While preparation time may be a barrier for some teachers, one of the teachers compared the preparation time for the Virtual Laboratory Project to physical laboratories they had implemented and expressed a contrary point:

> *"So the effort for me was, I mean, basically nothing compared to the other labs. You know, I mean I did spend probably 15-20 hours going through stuff but, um I didn't have to…deal with all of the frustrations, with ordering different things, equipment. And, um, when I started some of the other labs I had to do a literature search and you know, really try things in lab by myself. So I'd say it was a lot easier than some of those other labs."*

Disadvantages or barriers for teachers to implement the Virtual Laboratory Project need further investigation to assess them more thoroughly. However, based on this preliminary data, software improvements may be considered (e.g. a web-based 3-D interface) in order to integrate more easily with existing IT infrastructure. Additional teacher scaffolding in the form of a "getting started" packet or short video tutorials may also be options to consider.

Adaptations

Several adaptations were made to the Virtual Laboratory Project as it was implemented in various settings. Two adaptations that illustrate the differences in The Virtual Laboratory Project across educational levels include the level of scaffolding provided to students and the time allotted to the project. As expected, the amount of scaffolding required for the various student educational levels decreased with increasing educational level. A greater amount of scaffolding was deemed necessary for high school students than for community college students and even less scaffolding was presented for university students. High school students were provided with more background information, additional homework, and walk-through worksheets in order to help them familiarize themselves with the virtual laboratory background, software and context. In some cases the high school curriculum consisted of as many as five background homework assignments, walk-through worksheets, or problem statement assignments which were intended to scaffold the student approach. This contrasts to university cases, in which students were given as little as one problem statement regarding the project. In all cases, however, student-teacher interaction, either in class, office hours, small group discussions, or scheduled meetings was incorporated into the project.

In addition, supervised, in-class time devoted to the project varied widely between the different levels, with high schools and community colleges devoting the most supervised, in-class time. However, students at the university level were often given unsupervised lab time to complete the project. Total time spent on the project by students was reported to be highest, at the community college and university levels, with an average total of approximately 24 hours and students reporting as many as 50 hours spent on the project. High school students were estimated to have spent only an average of approximately 12.5 hours total on the project.

Some of the other adaptations include method of project presentation, specific project assignment, and presented project context (e.g., one teacher presented the Virtual CVD Laboratory Project in the context of biochip manufacturing as opposed to the typical context of traditional integrated circuit manufacturing). While many adaptations were made during project implementation, future investigation is needed to fully characterize these adaptations and their impact on effectiveness.

Conclusions and Future Work

Dissemination activities of the Virtual Laboratory Project include four workshops and 18 publications. This innovation has been implemented in a total of 59 classes, at 15 different institutions. Confirmation of two perceived sources of effectiveness of the innovation has been found in student and faculty feedback. Students perceive the innovation, as delivered in at least three of the institutions, as being situated in an industrial setting which is reinforced by both the industrial context of the software, delivery, presentation materials, and the budget. Teachers reinforce this perspective. Some data suggests that the project may be less successful or effective when there is little or no emphasis on the budget and industrial context; this aspect requires further investigation. In addition, the theoretical model and reactors and measurement tools and the affordance they provide in allowing for easy collection of authentic data were reinforced as a source of effectiveness. During implementation, IT infrastructure poses a potential disadvantage for this innovation. Many adaptations were made during the implementation process which included varying the degree of scaffolding based on the educational level of the students, and varied time allotted by teachers and students for the project. These and other adaptations require further investigation to assess their impact on effectiveness of the Virtual Laboratory Project in different contexts. This work is preliminary and while it suggests that this learning environment may have the potential for widespread adoption and adaptation, it generates more questions than it answers. Some of the research questions that are of interest for further investigation include the following:

- What evidence is present to support the other perceived sources of effectiveness and how do these change with teacher objectives and different implementation conditions?
- How do teacher objectives map onto perceived sources of effectiveness?
- To what degree do teachers utilize the existing instructional materials and what modifications are most common? How do the instructional materials tie to objectives and impact effectiveness?
- Based on analysis of student work, how do the adaptations impact the effectiveness of the Virtual Laboratory Project?
- How can the Virtual Laboratory Project be modified to make it more robust in adverse conditions?
- How does the effectiveness of the Virtual Laboratory Project change with the expertise and resources of the teacher?
- What other potential factors influence the scalability of the Virtual Laboratory Project (e.g. adopting site characteristics, teacher characteristics, student characteristics, technology resources, etc.)?

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