

## **AC 2007-2251: INSTRUCTIONAL DESIGN AND EVALUATION OF A VIRTUAL LABORATORY IN NANOELECTRONICS PROCESSING**

### **Danielle Amatore, Oregon State University**

Danielle Amatore, a PhD candidate in chemical engineering at Oregon State University, has a research focus on engineering education, with a special interest in applying qualitative research to assess learning in the engineering classroom. In addition, she has developed curriculum built on active learning for nanoelectronics at the graduate and undergraduate levels, as well as for K12 level. She obtained experience in the semiconductor industry while working at Intel and LSI Logic.

### **Edith Gummer, Northwest Regional Educational Laboratory**

Edith Gummer is the Director of the Classroom-Focused Research and Evaluation Program for the Center for Classroom Teaching and Learning at the Northwest Regional Educational Laboratory. She coordinated the structure of the research design and the data collection and analysis processes of the project. She has been faculty in science and mathematics education quantitative and qualitative research design courses at the doctoral level. She has been involved in the development of innovative mathematics curricular activities and formative assessment in mathematics problem solving.

### **Milo Koretsky, Oregon State University**

Milo Koretsky is an Associate Professor of Chemical Engineering at Oregon State University. He currently has research activity in areas related to thin film materials processing and engineering education. He is author of the text Engineering and Chemical Thermodynamics, which includes an integrated, menu driven computer program ThermoSolver. He is interested in integrating technology into effective education practices and in promoting the use of higher level cognitive skills in engineering problem solving. Dr. Koretsky is a six-time Intel Faculty Fellow and has won awards for his work in engineering education at the university and national levels.

# Instructional Design and Evaluation of a Virtual Lab in NanoElectronics Processing

## Abstract

Engineering curricula require effective ways to integrate experimental design into courses and student learning experiences. To address this need, we have developed a virtual laboratory that provides students a capstone experience in which they can apply experimental design in a context similar to that of a practicing engineer in industry. The Virtual CVD laboratory is based on numerical simulation of an industrial-scaled chemical vapor deposition (CVD) process, an important unit operation in the manufacture of nanoelectronic devices. The simulation of the reactor is based on fundamental principles of mass transfer and chemical reaction, obscured by added “noise.” The students specify nine process parameters to perform a “run”; the film thicknesses are then provided to students only at the select wafer locations that they have decided to measure. The software application contains a 3D graphical student interface that simulates a cleanroom environment, a web-based instructor interface with integrated assessment tools, and a database server complete with calculation engine. In this paper, the instructional design and the evaluation of the Virtual CVD laboratory are presented.

Data were collected from the Fall 2006 implementation of the Virtual CVD laboratory in the integrated capstone senior laboratory course. The cornerstone of the data collection utilized the “think-aloud” technique. Twenty groups were assigned the project and three of those groups participated in the “think-aloud.” The qualitative method entailed a detailed task analysis for each group from which a *task map* was developed. Corresponding ratings for the quality of each major task and the group’s tolerance for ambiguity during each session were assigned. A qualitative analysis of the impact that social interactions had on key decision points was completed and the use of reflection tools was evaluated. Of the three groups, the highest performing group demonstrated high quality ratings in each of the major experimental tasks: design, analysis and conclusions. They also exhibited an increasing tolerance for ambiguity as the project evolved and demonstrated effective social interactions, breaking into well defined roles. The contrasting performance of the other two groups is also discussed. The use of reflection tools in the form of experimental journals and design meetings appeared to be effective in keeping students from “video-game” mode. Assessment based improvements of the Virtual CVD laboratory are identified.

## Introduction

Capstone courses in which students have an opportunity to practice engineering are an important aspect of undergraduate engineering curriculum. In the last 20 years, capstone courses have been integrated into engineering curricula nationwide in response to ABET accreditation requirements and feedback from industry. Specific ABET guidelines are the building blocks for the development of many capstone courses; these guidelines focus on the practice of engineering and include requirements for communication, teamwork, creativity, the synthesis of core engineering concepts applied to an open-ended project, incorporation of economic considerations, and inclusion of relevant health, safety, and ethical issues.<sup>1</sup> Industrial needs have also shaped the

development of capstone courses in a variety of ways, from reporting a perceived lack of hands-on-experience in recently graduated engineers to providing mentorship and projects for capstone course.<sup>2</sup> In addition to providing students the opportunity to practice engineering, capstone courses facilitate the development of creative and critical thinking, which are essential in the practice of engineering. By design, capstone courses are the mechanism by which students apply the core concepts that are central to their discipline to solve an open-ended problem; this type of activity should enable students to engage in a deeper level of cognition than experienced earlier in their curriculum, which focuses more on analytical skills. Capstone engineering courses have the challenge of facilitating the development of higher-order thinking in the context of a problem where students need to apply the design approaches of practicing engineers. In this paper, particular attention is paid to the following critical aspects in providing a thought-provoking open-ended problem: the use of reflection tools to promote metacognition, the students' tolerance for ambiguity as they engage in the project, and the sociocognitive interactions of teams. These aspects are examined within the context of a virtual laboratory that is used at Oregon State University to provide a capstone experience.

To help students gain experience in the higher-cognitive domain, reflection tools and opportunities for metacognition have been shown to be effective. Two key aspects of capstone design courses, design meetings, during which a mentor provides input on the project's progress and design notebooks, in which the student reflected on the progress of their project, have been studied in terms of their value as reflection tools.<sup>3</sup> The theoretical framework of the study distinguishes between reflection-on-action, which often occurs when a mentor or coach provides feedback to the student, and reflection-in-action, which occurs when students engage in real-time thought and action experiments.<sup>4</sup> From qualitative analysis of both design meetings and the design notebooks, evidence of both types of reflection was found, with the design meetings consisting mostly of reflection-on-action and the design notebooks showing more evidence of reflection-in-action. Additionally, this study described the significance of the role of coach or mentor in terms of providing the epistemic frame of the engineering profession by teaching the way an engineer thinks and acts.

The open-ended nature of a project in a capstone course should be reflective of real-world engineering projects. To successfully navigate an open-ended problem, the practicing engineer needs to accept some inherent ambiguity. This real-world application of engineering is juxtaposed to the common type of "academic" engineering problems students find in textbooks. William Perry developed an empirical model based on his experiences as Director of Counseling at Harvard that reflects intellectual development of students while at college.<sup>5</sup> The model has nine levels of intellectual growth that can be placed in four major categories: dualism, multiplicity, contextual relativism and commitment within relativism. Growth is reflected in a student who transforms from a dualistic view with blind acceptance of authority (Level 1) to an acceptance of multiple views and a commitment to pursue knowledge in the face of ambiguity (Levels 7-9). Through their college experience, the majority of students from the liberal arts oriented curriculum studied by Perry reached Level 6 or beyond; however, studies of a population of students specifically from science and engineering showed that fewer than one-third even reached Level 5.<sup>6,7</sup> There is a significant group of "rule followers" who believe all problems have known answers and who show little tolerance for ambiguity. These students are the ones that have difficulty with open-ended projects or that may perform poorly on job

interviews despite a very high GPA. Complex, real-world open-ended problems in the engineering curriculum can help students ascend in Perry's levels. Moreover, students' skill in responding to these problems is based on their ability to make reasonable choices in the face of uncertainty and evaluate those decisions and adapt their approach accordingly. This general skill is labeled the "tolerance for ambiguity."

Most capstone courses include a focus on developing teamwork skills because it is important to provide students an opportunity to practice the type of sociocognitive interaction that engineers encounter when working in teams to resolve high-level cognitive tasks. The term sociocognitive interaction refers to both how the social dynamic of the group affects the cognitive activities of the individual, and how the cognitive tasks affect the social dynamic. A recent survey of capstone courses in 360 engineering departments across the country identified teamwork and project managements as the top lecture topics.<sup>8</sup> The increased emphasis on teamwork and project management in capstone courses is largely motivated by industrial feedback. The specific impact of working in teams in capstone courses has been studied and has resulted in a description of common problems encountered by students and best-known-methods for the formulation of teams. A survey was conducted in which over half of engineering students working in teams identified poor communication among members, lack of leadership, failure to compromise and procrastination problems as issues.<sup>9</sup> Research into the construction of engineering teams compared five different methods of forming teams and found that the most effective teams contained students with different GPA but similar interests.<sup>10</sup> Interpretation of these findings suggests that the social interactions amongst team members have a significant impact on project performance and that the nature of the social interactions has an impact on the approach that students take to the project. Moreover, the nature of the respective cognitive tasks drives different types of interaction between team members and this social interaction is an important factor in determining the project direction. In practice, the effective team of engineers collaborates to resolve high level cognitive tasks, such as experimental design, data interpretation, and the iterative process of redesign.

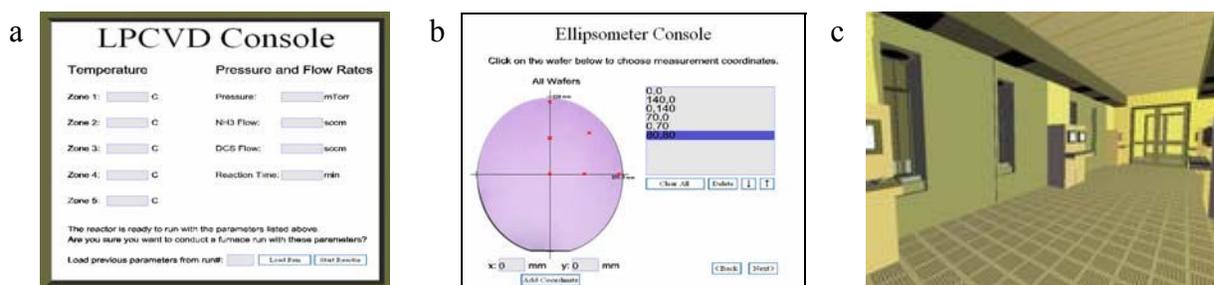
We have reported a capstone project for chemical, biological and environmental engineers at Oregon State University based on a virtual laboratory of an industrial chemical vapor deposition (CVD) process, the Virtual CVD laboratory.<sup>11</sup> In a virtual laboratory, simulations based on mathematical models implemented on a computer are used to replace the physical laboratory. This technology-enabled learning tool has been specifically designed to incorporate critical aspects of capstone courses identified in the engineering literature. This paper describes the instructional design of the Virtual CVD laboratory and presents the results of an evaluation of the students' experimental approach, the use of reflection tools, the students' tolerance for ambiguity, and the nature of the sociocognitive interactions.

### **The Virtual CVD Laboratory**

The Virtual CVD laboratory is based on an industrial scaled chemical vapor deposition (CVD) vertical reactor, an important unit process used to grow thin films in the manufacture of integrated circuits and other devices.<sup>12</sup> The software incorporates a simulation of thin film growth which is based on fundamental principles of mass transfer and chemical reaction,

obscured by added “noise.” The Virtual CVD software application is designed as a number of independent components. The three main components are the three-dimensional (3D) student graphical interface, the instructor web interface, and the data server. A complete discussion of the software design is discussed elsewhere.<sup>11</sup>

Students use the virtual reactor in the same context as they would use a reactor in industry. They are tasked with optimizing reactor performance based on experimentation. From the 3D student interface the students can make Virtual CVD reactor runs, take thin film thickness measurements that they specify, get output data and determine the cost of their experiments. Figure 1 displays screen-shots of this interface. The student must typically specify 9 operating parameters to make a reactor run; the reactor input screen is shown in Figure 1a. After the student has run a batch of wafers through the virtual reactor with a given set of input values, he/she has access to a virtual ellipsometer to measure the film thicknesses. Figure 1b displays a view of the selected measurement points for a specific wafer. To apply a realistic cost constraint, the students are charged virtual money for each run and for each measurement. Since the simulation uses a model based on first principles, the reactor outputs are reflective of the chemical and physical phenomena occurring within the system masked by the variation seen in real processes and measurements. Thus those students who integrate their fundamental engineering science knowledge should be more efficient with the experimental designs.



**Figure 1.** Screen shots of the Virtual CVD 3D Student Client a. Virtual CVD reactor parameter inputs: these parameters must be input by the student to run the reactor b. selection of measurement points on a wafer c. CVD reactor bay in the virtual factory.

Real-time assessment has been identified as a critical, but lacking, aspect of most virtual and physical laboratory learning experiences.<sup>13</sup> To meet this need, the Virtual CVD laboratory instructor web interface has been designed to allow formative assessment of student’s performance and to provide summative assessment by compiling a summary of final student performance. Through this web interface, the instructor has access to the students’ interactions with the learning tool. All of the student’s virtual experimental activity, including the data for student runs and measurements, is captured in a database and can be utilized as an assessment tool. Summative assessment, or assessment of each group’s achievement, is automatically generated by the learning tool upon student completion of the assignment. Details are presented elsewhere.<sup>11</sup>

## Instructional and Evaluation Design

The Virtual CVD laboratory has been designed to elicit the following learning outcomes:

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.

In Fall 2006, the Virtual CVD laboratory was the first project in the year long capstone laboratory sequence for chemical, biological and environmental engineers at Oregon State University and was completed by 20 teams of two to three members. These teams were specifically formulated according to grade point average (GPA) such that each team contained a student with a high GPA and a student with a low GPA. Since there were six laboratory sections, team formulation was further constrained by assuring all members attended the same section. No effort was made to match student interest. A formative evaluation of the Virtual CVD laboratory was utilized to assess learning of students using an approach that specifically measured the achievement of the intended learning outcomes. A major outcome of the evaluation was to identify potential enhancements to the Virtual CVD laboratory software and to discover ways to enhance student learning in a capstone laboratory course.

The cornerstone of the data collection utilized the “think-aloud” technique. Previous research has shown the value of observing people while they “think aloud” to give insight to their cognitive process, especially in situations where higher order critical thinking ability is needed.<sup>14,15</sup> Analysis of the “think-aloud” data can elucidate the cognitive processes and the effect that the group dynamics has on the project direction. Three groups from the Fall 2006 class participated in a “think-aloud” study of the Virtual CVD laboratory; the GPA of each student in these groups is detailed in Table 1. Groups A and C were mixed with two different disciplines represented while Group B contained students all from within the same discipline. The researcher observed and audio recorded the groups at all times they worked on the project, which was an average of three, two-hour sessions. The digital audio files were used for further analysis, and specific passages were transcribed as needed. The qualitative method entailed a detailed task analysis with corresponding evaluation of the quality of each task, a rating of the group's tolerance for ambiguity, and an analysis of the impact that social interactions had on key decision points.

**Table 1.** Grade point averages (GPA) of students in the three groups participating in the “think-aloud” study

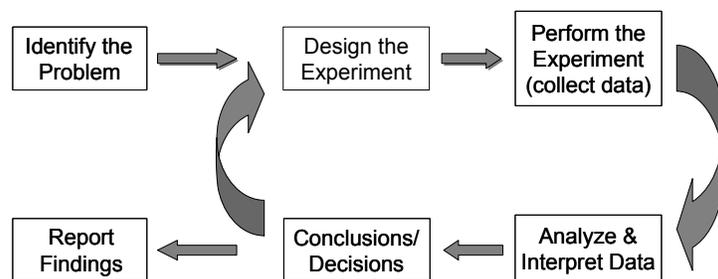
	Group A	Group B	Group C
Student 1	3.7	3.7	4.0
Student 2	3.3	3.4	3.4
Student 3	2.6	3.2	2.9
<b>Average</b>	3.2	3.4	3.4

### Students' Experimental Approach

A schema representing the experimental approach of practicing engineers is shown in Figure 2. The iterative nature of this process is a key element. The result of a designed set of experiments often does not lead to an answer of the problem being posed. In such a case, the engineer needs to identify the next set of experiments based on what he/she has learned, as illustrated by the recursive arrow in the figure; in an iterative manner, he/she converges on a suitable solution. The student at the university does not typically have the opportunity to experience this iterative process with physical laboratories. The Virtual CVD laboratory provides such an opportunity by providing instructional scaffolding that places a different emphasis on the experimental design process. Instructional scaffolding is an instructional tool that provides support, extends the range of the learner, and permits the completion of tasks not otherwise possible.<sup>16</sup> Since the operation of the process and metrology equipment is performed virtually by the simulation, student effort can be focused on the experimental design, the analysis and interpretation of the data, and drawing conclusions. Most importantly, they have time to iterate on their experimental solution. The task analysis of the "think-aloud" data consists of chunking sets of observed actions into one of four categories of tasks, Design, Experiment, Analysis, or Conclusion. These types of tasks are elicited by the Virtual CVD laboratory and have a natural alignment with the tasks that are completed by a practicing engineer when solving a real-world engineering problem, as shown in Figure 2. A *task map* is developed which shows the sequential flow of tasks that have been chunked into the appropriate category. Additionally, the quality of each of these tasks is assessed on a four-level scale. The coding matrix used to assess the quality of the tasks completed by the students is depicted in Table 2.

**Table 2.** Task quality matrix for "think-aloud" analysis

Quality Rating	Design	Analysis	Conclusion
4 Correct and appropriate completion of task	Deliberate experimental design that is founded on knowledge of the process and/or incorporates findings from previous experimental runs.	Completion of one or both of the following as appropriate: 1. Plot and/or model trends. 2. Proper application of statistical methods.	Decision is based on correct interpretation of the data with application of fundamental processes.
3 Correct, appropriate completion of task; however, with some poor choice stemming from inexperience	Deliberate experimental design; however with a clear poor choice (inaccurate understanding of process, poor choice of reactor parameters).	Completion of one or both of the following as appropriate; however, with some error or misapplication: 1. Plot and/or model trends. 2. Proper application of statistical methods.	Decision is based on valid interpretation of the data.
2 Improper, completion of task	Pursuing a specific experimental design even though previous data suggests other modifications.	Survey of raw data, observation of trends, rough estimates of important responses (uniformity, average thickness)	Decision is based on incorrect interpretation of the data, or is made with incorrect application of the data analysis.
1 Impulsive, illogical completion of task	Not purposeful or well thought-out change of experimental design.	Cursory look at raw data. Incomplete, without noting important features of the data.	Decision is illogical and not based on the data or physical understanding of the process.



**Figure 2.** Schema depicting the experimental approach of practicing engineers.

### *Reflection Tools*

Reflection tools were provided through completion of an experimental journal and project meetings with the instructor. The experimental journal promotes reflection-in-action by requiring students to write out their experimental approach and decisions stemming from data analysis. Before being granted access to the reactor, each team was required to write a “Preliminary Design Strategy” which was reviewed by the team and the instructor. The design strategy process ensured that the groups had thought through their approach before making runs, and reduced the probability that they would draw-on prior experience with popular computer and video games, which tend to elicit more intuitive, lower-order cognitions. This “video-game” mode is a common concern with technology-enabled learning tools because although the student seems engaged, learning is not necessarily occurring. The Virtual CVD laboratory helps avoid this “video-game” mode through integration of reflection tools to stimulate higher order cognition. For example, the initial design strategy began the process of eliciting higher-order cognitive thought. In order to determine their initial reactor parameters, the students needed to apply concepts learned in core chemical engineering classes to this open-ended problem. This task is a direct indication of their cognitive ability to synthesize. In addition, the students needed to review the course textbook and other references to determine realistic operating conditions; this task gives insight into their critical evaluation skills. An intermediate update meeting was conducted half way through the project in which the team reviewed their experimental journals and received guidance.

### *Tolerance for Ambiguity*

Due to the open-ended nature of the Virtual CVD laboratory project, students’ tolerance for ambiguity was revealed. Perry’s scale was used to quantify the tolerance for ambiguity for the three groups that participated in the “think-aloud” study. A coding matrix, depicted in Table 3, was used to assign a Perry’s level for each Virtual CVD work session; the task scale was too small to provide a meaningful Perry’s level assignment.

### *Sociocognitive Interactions*

While there are clearly many benefits of integrating team work into engineering education, the sociocognitive interactions among a team of practicing engineers can be distinctively different than among students in a physical laboratory at the university. In most cases, the effective team of engineers collaborates to resolve high level cognitive tasks, such as experimental design, data interpretation, and the iterative process of redesign shown in Figure 2. On the other hand, when student teams operate a physical laboratory, it is the haptic skills in collecting data and the verbal

skills of communicating results where collaboration inevitably occurs. The nature of the respective cognitive tasks drives different types of interaction between team members. Since the Virtual CVD laboratory emphasizes the high level cognitive tasks of design, analysis and evaluation, it promotes the type of socio-cognitive interactions found in teams of practicing engineers. Key decision points that were influenced by sociocognitive interactions were identified from the “think-aloud” sessions and, therefore, elucidate the impact of these interactions on the project direction.

**Table 3.** Coding matrix used to quantify the tolerance for ambiguity by applying Perry’s levels

Perry’s Level	Perry Category	Application to VCVD
1	<b>blind acceptance of authority</b> a dualistic view of the world, in which all intellectual and moral questions have unique correct answers, authorities know what those answers are, and the students’ task is to accept the authorities’ answers without question and to repeat those answers on tests	Direct application of DOE as presented in lecture.
2		Direct application of DOE with some modification stemming from a direct student experience.
3	<b>multiplicity of views</b> vision of a world as essentially relativistic and context-bound; a withdrawal from reliance on the word of authorities and the growth of the perspective that individuals are an active maker of meaning.	Realization that direct application of DOE is not the only path. Attempt to use data to better understand the system in order to determine appropriate experimental path.
4		Construction of a unique experimental approach that applies information learned from previous runs; however, student is unsure if this is an appropriate approach.
5	<b>contextual relativism</b> characterized by a belief there are no absolute answers nor reliable authorities; all knowledge and values are seen as contingent and contextual	Construction of a unique experimental approach that applies information learned from previous runs. Confidence that this approach is appropriate and a reasonable path forward.
6-9	<b>commitment within relativism</b> awareness of the necessity for commitment in the face of uncertainty and the undertaking of such commitments and coming to terms with their implications	Not observed

## Results and Discussion

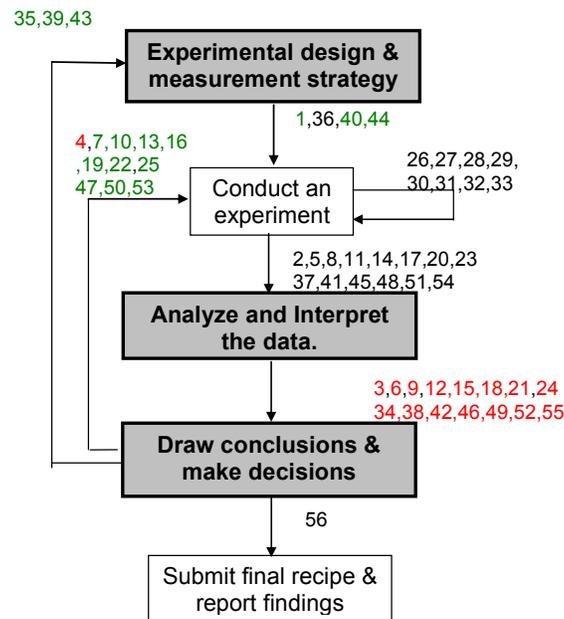
Qualitative analysis of the three student teams that participated in the “think-aloud” study can provide insight into the effectiveness of the Virtual CVD laboratory with respect to its intended learning outcomes. Specifically, the students’ experimental approach, the use of reflection tools, the students’ tolerance for ambiguity and the teams’ sociocognitive interactions are examined.

### *Students’ Experimental Approach*

A *task map* from the task analysis from one of the student teams (Group C) is depicted in Figure 3. The sequence of tasks completed by the group is indicated numerically in the schemas. The color of the task number relates to the assigned quality of that task, with red indicating poor quality (1 and 2 on the quality scale), green indicating a high quality (level 3 or 4), and black indicating tasks that are automated by the Virtual CVD laboratory simulation (the task of

performing experiments). *Task maps* for the other two teams were also generated and showed similar patterns. A sample data analysis sheet is shown in Appendix I. These data analysis sheets were compiled from observation of “think-aloud” sessions during which student groups interacted with the Virtual CVD laboratory.

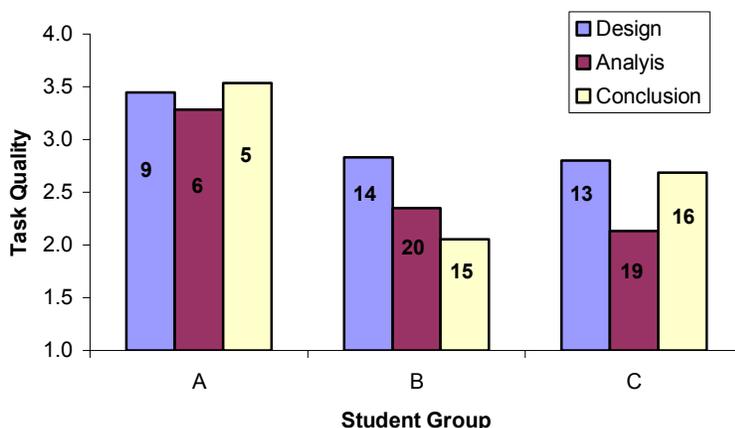
The team shown in Figure 3 started the project with an experimental design based on a 2-level, 3-factor, full factorial design array in an almost direct application of recent lecture materials on design of experiments (DOE) (task 1). After completing the first run in the array (task 2), they analyzed the data (task 3) and concluded that they would continue their DOE without modification (task 4). However, proper inspection of the data from this run would have suggested that their DOE should be modified since the wafers at the exit of the reactor had no film growth. Their inaction demonstrated the rule-following nature of this team. The team continued to conduct all the experiments prescribed by their DOE (tasks 5-25), then proceeded to complete a duplicate set of runs (tasks 26-33). Next, the team completed an ANOVA analysis of their DOE data and developed a model from this analysis (task 34). They used the model to determine reactor parameters for their next run (tasks 35-36). Next, the team calculated the statistics appropriately (task 38), but were very surprised by the results since they expected their model to result in perfect run conditions. The next decision was challenging for them and they demonstrated noticeable discomfort in the face of uncertainty, indicative of a low tolerance for ambiguity. Eventually, they resorted to making small, one-factor at a time changes to their run parameters until they felt their process recipe was optimized.



**Figure 3.** Task analysis of one team that participated in the “think-aloud” study

Task quality analysis was completed in which each task (Design, Analysis, and Conclusion) completed by the three student groups participating in the “think-aloud” study was assigned a rating of 1 (poor) to 4 (excellent) by application of the task quality matrix. For each group, the number of times each task (Design, Analysis, and Conclusion) is engaged and the average quality that this task is executed is shown in Figure 4. Group A, completed the project using

fewer tasks while demonstrating the highest overall quality of task performance with each type of task being completed with similar quality, with values from 3.3 - 3.5. Both Group B and Group C took more tasks to complete the project and demonstrated lower levels of quality than group A. Groups B and C each has their highest quality on the “Design” task, each with a value of 2.8. Group B showed poor ability to draw conclusions (quality rating of 2.1) and Group C poor quality in analysis (2.1). The quality of the performance of the groups in this project is measurably different even though their GPAs are essentially the same (see Table 1).



**Figure 4.** Task quality assessment showing results from the “think-aloud” study

### *Reflection Tools*

Inspection of the experimental journals indicates that they provide an opportunity for reflection. An excerpt from one team’s experimental journal which shows evidence of reflection is depicted in Figure 5. This journal entry was from the first laboratory session in which the design strategy meetings were conducted. It shows part of a mass balance calculation that the students were performing to estimate appropriate reactant gas flow rates to input into the Virtual CVD reactor. No specific instructions were provided to the students to aid in selecting input parameters; students needed to create their own method. This creative process inherently elicits synthesis, a high-order cognitive process. For example, the journal entry shown in Figure 5 demonstrates evidence of synthesis in that the students apply the ideal gas law, a fundamental concept covered earlier in the engineering curriculum, to relate the gas flow rate to a mass balance. Evidence of reflection is also demonstrated by the journal entry depicted in Figure 5. The ammonia ( $\text{NH}_3$ ) flow rate was initially determined to be “537.591 scm”; however, this value is crossed out in the experimental journal, replaced with “1075.18” and annotated with a comment stating, “2 sides of wafer.” During this team’s design strategy meeting, the instructor reviewed the team’s initial mass balance calculation and discovered that the team was only considering film deposition on the top side of the wafer; in actuality, film is deposited on both sides of the wafer. The student’s error in the calculation revealed that they had an inaccurate visual image of the deposition process stemming from a misunderstanding of how the wafers were physically positioned in the reactor. This excerpt from the experimental journal coupled with the discussion of the calculation in the design strategy meeting show evidence of both reflection-in-action and

reflection-on-action. In hindsight, both the design strategy and intermediate update meetings provided rich opportunities for reflection-on-action which resulted in improvements to the experimental approach and promoted a deeper understanding of the process. Due to the significant impact of these meetings, they will be studied more rigorously in future implementations of the Virtual CVD laboratory.

Another benefit of the experimental journal is that by forcing students to reflect on their analyses and decisions in writing, it prevents students from going into "video-game" mode when interacting in the Virtual CVD laboratory. Degenerating to the "video-game" mode is a unique concern with virtual laboratories that is not encountered with physical laboratories. The experimental journal is intended to reduce the likelihood that this mode occurs by promoting reflection and requiring that the students rationalize their decisions when completing the Virtual CVD laboratory. Evidence from the "think-aloud" study confirms that the act of completing the experimental journal helped facilitate the students to take a thoughtful approach. For example, during their first session in the virtual laboratory, one team had a team member assigned as the "recorder" to capture their activity in their experimental journal, while another team member was "driving" the computer and entering run conditions. During this session, the recorder asked the driver to stop before entering every new run and explain the reasons why they choose those parameter values. This reflection may not have happened if there were not a requirement that they complete an experimental journal.

Assume ideal (low pressure)

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$$PV = nRT \rightarrow V = \frac{nRT}{P} = \frac{0.36 \text{ mol} \cdot 0.08206 \frac{\text{L} \cdot \text{atm}}{\text{mol} \cdot \text{K}} \cdot 273 \text{ K}}{1 \text{ atm}}$$


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$$V = 8.06387 \text{ L} = 8063.87 \text{ cm}^3$$


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$\text{NH}_3$ : Min. time = 537.591 sccm = 1075.18 (2 sides of water)

Max time = 70.12 sccm = 140.24

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DCS: 322.555, sccm

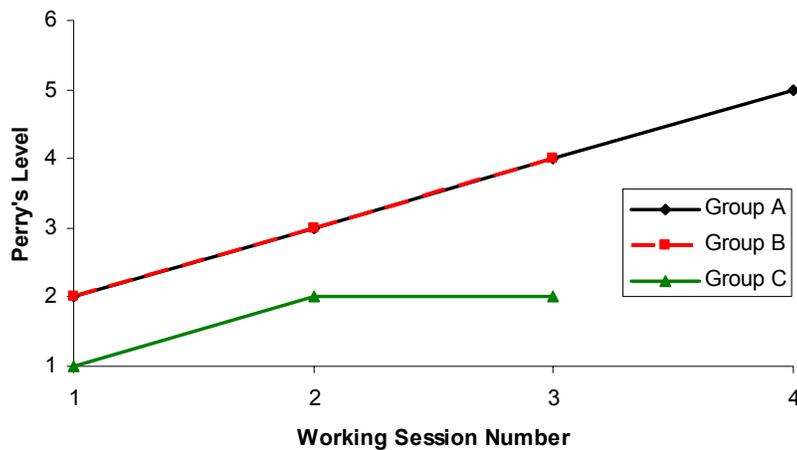
42.07, sccm

Figure 5. Excerpt from a student team's experimental journal that shows evidence of reflection

### Tolerance for Ambiguity

The modified Perry's-levels were applied to quantify the team's tolerance for ambiguity. The results for the three groups are plotted vs. working session number in Figure 6. The Perry's level assigned to Group A and Group B linearly increased with each working session while Group C reached a plateau at a Perry's level of 2. Although all three groups started the project by directly applying the recent lecture on DOE, blindly accepting that it was the optimal experimental approach, the first two groups were able to adapt and become more comfortable with the open-ended nature of the project, and began ascending Perry's levels. By the end of the project, Group A had developed a completely unique approach to the project by creating a model based on mass balances and results from previous experimental runs. Furthermore, the group was confident that

their approach was accurate and that developing a unique experimental design was the intent of the project. This approach corresponded to a Perry's level of 5. In contrast, Group C remained at the rule-following level for the duration of the virtual laboratory, executing a DOE from start to finish in a manner that directly mirrored the lecture material, and did not surpass a Perry's level of 2. When the DOE analysis yielded unexpected results, they had difficulty determining their next step, and never reevaluated their experimental approach. As Table 1 shows, Group A had the lowest average GPA but demonstrate the greatest tolerance for ambiguity. In contrast, the highest individual performer in the class (GPA = 4.0) was in Group C. Success in the academic curriculum and tolerance for ambiguity are apparently not correlated.



**Figure 6.** Assessment of Tolerance for Ambiguity from the “think-aloud” study.

### *Sociocognitive Interactions*

Although the focus on teamwork in capstone courses is prevalent, there is little research that rigorously assesses how team dynamics affects learning in these courses. In the analysis of the “think-aloud” sessions, the impact that the social interactions within the group had on the shared cognitive process and approach to the project was recorded. Such analysis can be used to assess the nature and effectiveness of collaborative learning in this project. Upon inspection of these “think-aloud” sessions, certain themes in the social interactions in all groups emerged, while other unique aspects were found. In Group A and Group B, one group member was identified as the analysis expert, however, for very different reasons. During the first virtual laboratory session, “Bob” in Group A was quiet and not the natural leader of the team. During the second session, Bob discussed an analysis method that he had developed for the project with the team, but was unable to convince the rest of the team to implement his idea. However, after the first experimental run, the other team members were unsure how to proceed, and again, Bob suggested his idea. At this point, the team decided to pursue Bob’s idea. The experimental runs that followed were successful, which resulted in the other team members giving control of the analysis method to Bob. In contrast, Group B also ended up with one team member completing the core analysis, but for a very different reason. During the first two sessions, there was a power struggle in the group over project direction, with one group member, “Mark,” apparently using a rational approach and one group member challenging his ideas, but with no apparent method to his approach. There was considerable debate before every experimental run, as

demonstrated by a low number of runs completed during first two sessions (about 5 per day), compared to during the third session (8 runs). During session three, two of the team members became disengaged with the project, stopped challenging Mark and relinquished decision making power. Mark then proceeded to implement a unique experimental approach. The impact of these juxtaposing social dynamics is reflected in the increase in task quality of each group. Once the functional Group A stratified into roles, the average task quality increased 1.2. In contrast the task quality in Group B remained about constant after the dysfunctional role stratification (increase in average quality of 0.3). In contrast to both Group A and Group B, there was very little social interaction demonstrated by Group C. This point is made more interesting considering this group also demonstrated a low tolerance for ambiguity. Instructors often form teams assuming functionality; however results from two out of the three groups who participated in the “think-aloud” process showed otherwise.

### **Assessment-Based Improvement Plan**

Analysis of the evaluation results identified several possible enhancements to the Virtual CVD laboratory.

An important feature of the Virtual CVD laboratory is the use of reflection tools to provide students an opportunity for metacognition and coaching, or reflection-in-action and reflection-on-action. The Virtual CVD laboratory 3D user interface will be upgraded to include two reflection tools that are integrated into the software, an experimental journal and a virtual supervisor. The experimental journal will prompt students to reflect on the reasons for their design decisions. It will be implemented by adding a data entry screen for student’s to capture their results from analysis and reasons for making changes to their experimental design. Additionally, a report will be automatically generated for the students that will display the parameter values, measurement data and experimental journal entry for each experimental run. In certain identified circumstances, the virtual supervisor will provide coaching by appearing in the software to probe students to apply their knowledge of the fundamental processes. For example, if the students completed an experimental run that results in no film growth on the wafers at the exit of the reactor, then the virtual supervisor would appear and ask the students for a physical explanation of the data. In addition to the reflection tools that will be integrated into the software, the implementation of the project will continue to include design strategy meetings with the instructor to provide coaching.

Inspection of the performance data available from the instructor web interface highlighted two ways to make the project more reflective of the experience of practicing engineers. Being aware of variation stemming from both process and measurement equipment is essential to the practicing engineer. The Virtual CVD laboratory presently includes one source of random noise; the measurement variation is not distinguished from process variation. Thus, students who perform duplicate measurements on the same process run see the same variation as students who perform two different runs under the same process conditions. Realistically, the latter would have greater variation. This level of fidelity would be noticed by some students but not others as reflected in the following data. Of 20 groups completing the Virtual CVD laboratory, 14 groups (70%) made no attempt to determine variation while six groups (30%) used experimentation to

determine variation; of these six, five groups completed a duplicate measurement set to determine the error in the measurement tool, while one group actually performed different reactor runs. By modifying how the simulation treats noise, aware student groups will be able to distinguish the two sources of variation. Therefore, the next version of the Virtual CVD laboratory will include two sources of variation; error added to the students' measured film thicknesses via a normal distribution with standard deviation,  $\sigma$ , and a temperature bias randomizer and drift to represent process error.

Another way to make the Virtual CVD laboratory experience more authentic is to make the non-uniform film growth more reflective of reality. Currently, the grown film has radial symmetry; however, in some real thin film processes, maintaining radial symmetry is a challenge and is never assumed to exist. When completing the Virtual CVD laboratory, only 7 out of 20 student groups (35%) verified radial symmetry, while 13 groups assumed symmetrical film growth. Therefore, to make the experience more authentic, a method to skew the temperature horizontally across the reactor will be implemented so that non-radial film growth can be incorporated, if desired by the instructor.

Feedback from students identified another enhancement; to make the cost modeling more dynamic. Currently, there is a flat cost that can be modified from the instructor interface, to make a reactor run. A more realistic cost basis would be dynamic and based on the amount of reactant gas used and time that the reactor is run. This would reward students that attempt to maximize the utilization of the reactant gases. Additionally, it would enable a strategy of optimizing film uniformity then scaling reaction time to achieve the target thickness. Both actions are reflective of the approach that would be used by a practicing engineer.

## **Conclusion**

In alignment with the intent of capstone courses and incorporating the best-known-methods discussed in the engineering education literature, several key components of the capstone experience have been identified: promoting reflection, increasing tolerance for ambiguity and providing an authentic context. The Virtual CVD laboratory was developed to specifically realize these educational outcomes and an evaluation of the learning tool was conducted to measure its effectiveness and identify opportunities for improvement. Specifically, an authentic context was created by having students work in teams to solve a problem using an iterative experimental approach; navigating such an open-ended problem allows a student to become more comfortable with the ambiguous nature of most real-world engineering problems. Additionally, opportunities for coaching were provided by project meetings with the instructor and reflection-on-action was promoted by having the students keep an experimental journal. The evaluation of this learning tool, of which a large aspect was qualitative analysis of “think-aloud” sessions, demonstrated that students engaged in an iterative experimental approach to complete the Virtual CVD laboratory. Evidence of reflection was found in the experimental journals and project meetings with the instructor. To further promote reflection in future uses of this technology-enabled learning tool, an electronic experimental journal and virtual supervisor will be added to the virtual laboratory. Evaluation results elucidating tolerance for ambiguity indicates that by completing this open-ended problem most students evolve past “blind

acceptance of authority” and become aware of a “multiplicity of views”; however, while some students continued to climb Perry’s levels, eventually becoming comfortable with the idea of “contextual relativism”, other students did not. An interesting parallel to these differences is found in the nature of the sociocognitive interactions found in the different student teams; these interactions seem to be able to either promote the desired learning, or they can be detrimental to the intended learning outcomes. Further research into the impact of reflection and sociocognitive interactions is planned to address these issues more fully.

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## Appendix 1: Sample “think-aloud” session data summary sheet

A sample summary data sheet composed from an individual “think-aloud” session is shown in Figure A1. The data sheet was specifically design to align with the qualitative analysis methods in several ways. The right side of the data sheet contains a table where observed tasks are chunked into Design, Experiment, Analysis, and Conclusion tasks and the quality is evaluated (shown in the grey bar) according to the rubric presented in Table 2. Significant sociocognitive interactions (SI) that impact the completion of the task are noted, as shown with task 8. On the left side of the data sheet a task map visually depict the flow of tasks. The “tolerance for ambiguity” demonstrated by the team during the session, as rated corresponding to Table 3, is indicated in the lower left corner.

ChE414 Fall 2006 Think Aloud Data Sheet

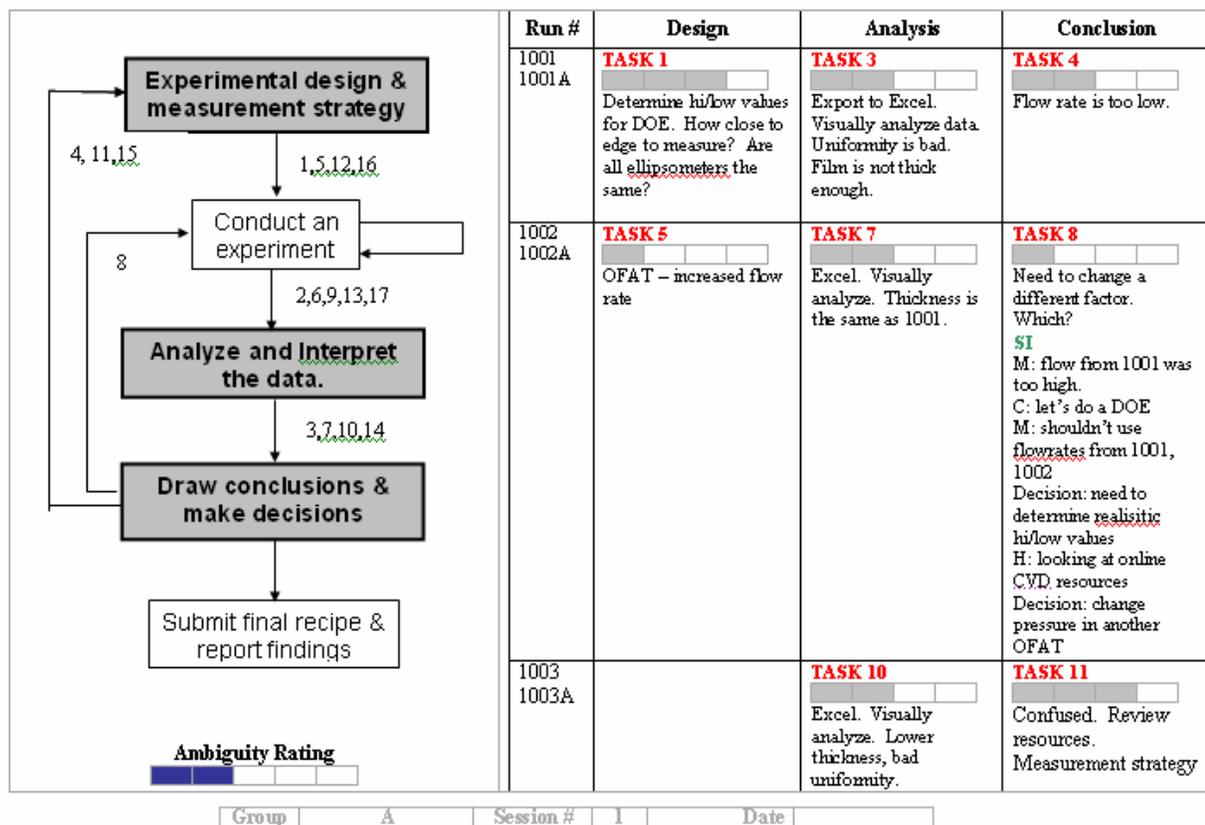


Figure A1. “Think-aloud” Data Entry Sheet