AC 2011-1459: ENHANCEMENT OF STUDENT LEARNING IN EXPERIMENTAL DESIGN USING VIRTUAL LABORATORIES - YEAR 3

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Enhancement of Student Learning in Experimental Design using Virtual Laboratories – Year 3

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.[1] In addition to providing students the opportunity to practice engineering, capstone courses facilitate the development of creative and critical thinking, which are crucial in the practice of engineering. By design, these courses are the mechanism by which students apply the core concepts that are critical 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. In the context of providing an effective capstone experience, we have developed two virtual laboratories, the Virtual Chemical Vapor Deposition (CVD) laboratory and the Virtual Bioreactor (BioR) laboratory.[2-5] In a virtual laboratory, simulations based on mathematical models implemented on a computer can replace the physical laboratory. Virtual laboratories have been developed and integrated into engineering curricula.[6-10] However, relative to the work on instructional development, the degree of assessment has been sparse.[11-13]

Our intent is to provide students a capstone experience in which they can apply experimental design in a context similar to that of a practicing engineer in industry. The objectives of this research are to explore the types of cognition and social interactions of student teams as they engage in these virtual laboratories, to determine the role of instructional design in the response of student teams, and to ascertain whether virtual laboratories can effectively promote types of learning that are difficult or impossible to achieve from physical laboratories.

Objectives

The specific objectives of the NSF CCLI Phase 2 project are to:

1. Create the following learning materials and teaching strategies based on virtual laboratories:
   A. Enhance the Virtual CVD laboratory by including interactive reflection tools (e.g., interactive lab notebook, a virtual supervisor), improved treatment of variability and cost, non-radial symmetry, and a new module on statistical process control.
   B. Using an analogous instructional design, develop a virtual laboratory of a bioreactor, the Virtual Bioreactor laboratory, a process in a different industry.
   C. Develop level appropriate assignments to use at the high school and community college levels.
2. Develop faculty expertise and implement the virtual laboratories at the BS and graduate levels by:

A. Delivering the Virtual Bioreactor laboratory and the revised Virtual CVD laboratory in ChE/BioE/EnvE 414, the integrated term of the capstone senior laboratory in the School of Chemical, Biological and Environmental Engineering at Oregon State University.
B. Implementing the Virtual CVD laboratory remotely in the undergraduate ChE program at UC Berkeley and in an accelerated MS graduate program in Semiconductor Processing at the University of Oregon, and implementing the Virtual Bioreactor laboratory at the University of Colorado.

3. Demonstrate the Virtual CVD laboratory is an effective and transportable learning tool that can be tailored to a variety of levels. Develop faculty expertise and then deliver at approximately 10 high schools and 10 community colleges.
4. Assess learning and evaluate the virtual laboratories in the following ways:
   A. Continue to qualitatively and quantitatively study the ways students learn using the Virtual CVD laboratory. Further develop the "talk-aloud" method used in the proof-of-concept stage. Examine how differing discipline specific knowledge combinations that groups of students bring to the execution of the virtual laboratory facilitate or inhibit the development of cognitive processes in experimental design.
   B. Assess student learning using the Virtual Bioreactor laboratory in a similar way. Examine the extent to which the cognitive processes and skills elicited by the innovative approach towards student learning of experimental design demonstrated in the Virtual CVD laboratory also applies to the Virtual Bioreactor laboratory. Use both the Virtual CVD and the Virtual Bioreactor laboratories in the same class to assess the extent to which practice effects influence the approach taken by students (i.e., will they perform in a different manner the second time they go through the design process).
   C. Assess the implementation of the Virtual CVD laboratory at the high school and community college levels.
5. Disseminate results and materials to the professional community, including continued development of a web site, presentations at national meetings and published papers in the engineering education literature.
6. Integrate the laboratory modules into the outreach activities currently in place in the ChE department.

Activities

The following activities are underway:

- SOFTWARE DEVELOPMENT

1. The major effort in software development has expanded interface options for the the Virtual Bioreactor laboratory.[3] The Virtual BioR laboratory is based on an industrial stirred-tank fed-batch bioreactor and can be used for different functions, such as production of a product or degradation of waste. The module allows for a unique set of instructor specified parameters (such as temperature optimum, degree of substrate inhibition, maximum specific growth rate, etc.) for each group in the class. A web-based,

3-D student interface was developed and has been tested; now there are both an HTML and a 3-D interface.

- CURRICULUM DEVELOPMENT

The following learning materials and teaching strategies, based on virtual laboratories, were created:

1. Using an instructional design that was analogous to the Virtual Chemical Vapor Deposition laboratory, university level curricular materials for the Virtual Bioreactor laboratory have been made available for use at other institutions. The target is for a capstone process laboratory design project in the senior year where students are instructed to find operating conditions that maximize volumetric productivity in the bioreactor. Additional faculty expertise was developed in the Bioengineering program at Oregon State University; a second faculty member was integrated into the project delivery team.
2. A second set of curricular materials have been made available for use at other institutions that are developmentally appropriate for use in chemistry and pre-engineering classes at the high school level.[14] These materials scaffold the complex content in the college level course materials.
3. A supplemental operations manual was developed to describe the Virtual CVD laboratory, as a reference for student and faculty use.

- IMPLEMENTATION

1. Research has begun into the scale-up or adoption of the Virtual CVD laboratory and the Virtual BioReactor laboratory. Preliminary results are presented elsewhere.[15] To-date the Virtual Laboratory Project has been appropriately adapted to high school, community college and other university settings and implemented in a total 15 institutions and 59 cumulative classes. Nine of the 15 institutions have also used the virtual laboratory more than once. Student and faculty interviews and surveys were analyzed by identifying common themes. Some of the virtual laboratory's perceived "sources of effectiveness"[16] 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. Modifications of the virtual laboratory were made to accommodate different educational levels; Based on student and faculty perceptions, some degree of effectiveness was maintained through the adaptation process. Preliminary data suggests that this learning environment may have the potential for more widespread adoption and adaptation; additional research is in progress to further evaluate this potential.
2. The delivery of Virtual Laboratories at Oregon State University is shown in Table 1. The Virtual CVD laboratory (VCVD) has been used since Winter 2005 (W05). The Virtual Bioreactor laboratory (VBioR) was used for the first time in Fall 2007 (F07) in ChE/BioE/EnvE 414, the integrated term of the capstone senior laboratory in the School of Chemical, Biological and Environmental Engineering.

Table 1. Summary of experimental activity of the Virtual Laboratories at Oregon State University
*Virtual cost refers to the virtual expenditures the team used to reach their solution.

Class	Term	Students	Groups	Runs	Measurements	Virtual Cost
ChE 444	W 05	24	8	97	2,672	$685,400
ChE 444	W 06	28	8	122	2,241	$778,075
SESEY	Su 06	4	4	146	6,413	$1,210,975
ChE 414						
Project 1	F 06	52	23	384	5,293	$2,316,975
Project 2 (SPC)				572	33,136	$5,345,200
ChE 444	W 07	12	4	60	1,915	$443,625
CBEE 414	F07	15	7	93	1,722	$594,150
VBioR		37	14	237	7,449	$2,894,815
ChE 444	W08	12	4	45	611	$270,825
SESEY	Su 08	2	1	10	387	$79,025
CBEE 414	F08	41	14	290	8,250	$2,068,750
VBioR		39	13	243	8,748	$3,540,897
ChE 444	W09	6	2	22	469	$145,175
CBEE 414	F09	45	15	256	7,155	$1,816,625
VBioR		36	12	277	10,461	$2,624,155
ChE 444	W10	6	2	41	916	$273,700
CBEE 414	F10	38	13	284	5,805	$1,855,375
VBioR		38	13	300	6,804	$2,825,650
Total		**383**	**157**	**3479**	**110,447**	**$29,769,392**

3. A major objective of this project is to facilitate the implementation of the Virtual Laboratories at a number of universities beyond Oregon State University to develop evidence of the portability and generalizable use of the virtual laboratory instructional materials. Table 2 lists the institutions that have used the Virtual CVD laboratory remotely.

Table 2. Summary of experimental activity of the Virtual CVD Laboratories outside Oregon State University

Class	Term	Students	Groups	Runs	Measurements	Virtual Cost
U Oregon	Su 06	11	3	40	538	$240,350
U Oregon	Su 07	10	3	57	610	$330,750
UC Berkeley	S 07	25	25	96	8,980	$1,153,500
CVHS Chemistry	S 08	210	92	1,100	53,971	$9,547,825
CVHS Engineering	S 08	53	31	424	10,899	$2,937,425
U Oregon	Su 08	16	4	50	1,137	$460,275
Workshop	Su 08	15	7	165	5,014	$1,201,050
Workshop	F08	17	17	98	3,220	$731,500
North Dakota State	F 08	20	7	60	557	$341,775
UC Berkeley	S 09	32	32	563	31,619	$5,186,425

U Montana	S09	44	17	337	9,399	$21,549,500
Hudsen Valley CC	S 09	20	11	66	1,340	$430,500
Wilkes University	S 09	14	7	48	1,139	$325,425
North Seattle CC	S 09	6	6	53	1,213	$355,975
North Eugene HS	S 09	67	33	279	6,813	$1,905,975
Nyssa HS	S 09	26	14	315	10,727	$2,379,525
CVHS	S 09	183	74	1,638	64,913	$13,058,475
Cascade HS	S 09	22	10	69	1,593	$464,475
Workshop	S09	8	5	6	145	$40,875
U Oregon	Su 09	11	5	43	679	$265,925
Workshop	Su 09	31	31	259	6575	$1,788,125
North Eugene HS	F 09	24	6	59	1,641	$418,075
North Seattle CC	W10	4	4	30	877	$215,775
CVHS	S 10	49	20	289	7,449	$2,003,675
Hudsen Valley CC	S10	22	11	230	23,028	$2,877,100
Ontario HS	Sp10	4	10	37	785	$243,875
Total		**944**	**485**	**6,411**	**254,861**	**$70,454,150**

- ASSESSMENT AND EVALUATION

A major activity is the development of an assessment system to evaluate the effectiveness of this tool in promoting the development of complex knowledge structures and integration of higher order thinking skills. The evaluation model that best fits the *Virtual Laboratories* is one that closely integrates assessment results to improve their design and implementation. Evidence of the development of the cognitive capacity of students requires the design and interpretation of an assessment system that mirrors the ways in which knowledge is developed and applied in the working environment of engineers. The development of an assessment system tied through backwards design to the educational objectives that frame the content and processes of the courses is viewed to be one of the products of this project. In addition, the evaluation plan measures the transportability of the Virtual CVD laboratory to support its use in a variety of engineering and science courses.

Four research questions have been addressed:

1. What is the nature of the experimental design process that students apply in the virtual laboratories?
2. How does students' tolerance for ambiguity change while completing the virtual laboratories?
3. In what ways do students perceive the virtual laboratories as an authentic experience that is reflective of real-life engineering? How do the ways that students perceive virtual laboratories compare to physical laboratories?

4. What types of knowledge structures and cognitions are demonstrated by students when engaging with the virtual laboratories?

Four measurement tools are being used to collect data for analysis in this project:

1. **Talk -Aloud Protocol:** The cornerstone of the data collection utilizes the "talk-aloud" technique, in which students' performances are observed and recorded while they verbalize their thought processes. This technique has been shown to give insight to their cognitive processes, especially in situations where complex knowledge structures are evoked and higher order critical thinking ability is needed.[17] During data collection, students are instructed to merely verbalize their thoughts and discouraged from describing or explaining their thoughts as part of the "talk aloud." In order to more effectively study the development of knowledge structures, especially schematic knowledge, we have added the use of free stream video software such as Cam Studio or Camtasia to record the team's progress in some cases. This software video records the display of the computer monitor and can be synced to the audio record. The digital audio files are used for further analysis. Transcripts have been completed for a subset of audio files. Over the span of five years, complete data sets have been audio recorded from 20 student teams as they have completed the virtual laboratory project (14 CVD and 6 BioR).

   Because of the situated nature of the virtual laboratories, completion of the project itself results in the development of evidence about students' performances on an articulated set of component tasks. Therefore, a task analysis of the students' approach to the project is an essential aspect of the virtual laboratory assessment. In the case of the virtual laboratory projects in this study, the solution by any student group or, in contrast, by any "expert" is only one of numerous possible solutions. We are seeking to compare a set of solutions characteristic of the student teams to that of an expert. Comparing the nature of the respective solution paths allows elucidation of the difference between how expert and novice "see" this project. Additionally, the "talk aloud" studies have revealed certain developmental changes during the course of the project. Thus, there are specific changes on a time-scale much shorter of that of development from novice to expert. One such change that has been demonstrated is the growth in tolerance for ambiguity. In summary, the qualitative method has evolved to entail 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. We are presently focusing our analysis on the aspects of instruction and feedback during the design memo meeting.

2. **Episodes Framework:** 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 design memo meeting (DMM) was compared. The episodes framework consists of four components: surveying, probing, guiding, and confirmation. 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. Preliminary examination of DMMs with the episodes framework also supports effectiveness and demonstrates the episodes framework as a potentially powerful tool in discourse analysis. The episodes framework also provides a potential scaffolding tool for instructors to more effectively provide feedback in this type of learning environment.[18]

3. **Model Development and Usage Representations:** In order to capture the model construction and higher cognition and to characterize the schematic and strategic knowledge invoked by the Virtual Laboratory Project, we have developed Model Development and Usage Representations (Model Representations) as an analysis tool. The Model Representations are generated from student work products, such as journals/laboratory notebooks, written reports, and memorandums, and from the instructor interface, which records all groups' run parameters and results. They are a visual and chronological coding tool used to identify and characterize student knowledge structures and cognition as students perform the Virtual Laboratory Project. The Model Representations can be used to identify the ways students use their schematic knowledge to build models and use their strategic knowledge to integrate these models into their project solutions. This approach uses a cognitive historical analysis, i.e., it examines historical records with the specific objective of understanding cognition as opposed providing a historical account.[19]

   A coding system was developed to show a visual representation of teams' modeling progression with regards to the types of model components employed (quantitative, qualitative, experience-based), whether they are operationalized, their correctness, and the experimental runs to which they are relevant. Model components are placed on a time line along with experimental runs, emotional responses and instructor interaction to show context. Student journals serve as the primary source of information since they are intended to contain all ideas and notes over the course of the project. Models components are drawn from the student journals chronologically and are then supplemented with other materials such as reports and memoranda which serve to confirm, explain or expand upon the journal content. Student researchers first dissect the work products to construct the initial model development representation. Consensus is then obtained by a group of two students and two faculty. One faculty member, the domain expert in the appropriate field, examines the source material and evaluates the accuracy and context of the model development representation. A summary statement is then written. In order to assure reliability, the other student and faculty who work in the other domain, participate to assure consistency between the representations of the two virtual laboratories. The method development and preliminary results are described elsewhere.[5, 20]

4. **Student Survey:** Finally, a student survey has been developed to describe the differing student perceptions of the learning that they were to take away from the three different laboratory experiences, two physical laboratories and the virtual laboratory. A set of survey questions was provided to the students in ChE/BioE/EnvE 414 senior laboratory class in Fall 2007 and Fall 2008 as an assignment. The survey questions were asked after the students had completed each of the three laboratories. The survey was implemented, in general, as soon as possible after the final laboratory report for that given laboratory had been turned in. There were, in some cases, overlap in that the content for the next laboratory had commenced. Students' perceptions of what they were intended to learn provide a lens into their metacognitive processes. Research in metacognition in engineering education has demonstrated the efficacy of providing students with learning environments that enhance students' reflection upon and regulation of their own learning. This research seeks to identify the ways that student knowledge and awareness of their own learning might evolve as they move through three structured laboratory experiences. A methodology for analysis has been developed including coding protocol and analysis for three of the questions and analysis development to improve inter-rater reliability and to check if there is a bias in the analysis. This activity is described in more detail elsewhere.[21,22]

- WORKSHOPS

  Four workshops for college and high school faculty have been delivered at Oregon State University and at ASEE's 6th Annual Workshop on K-12 Engineering Education. The intent is to demonstrate the utility of the Virtual CVD laboratory as a learning platform at different curricular levels and to develop faculty expertise. This activity is described in more detail elsewhere.[14]

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