Higher-Order Learning Through Virtual Laboratories in Fluid Mechanics: Lessons Learned

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Abstract

Student achievement of Bloom's higher-order cognitive skills (analysis, evaluation, and synthesis) is recognized as being necessary in engineering education, yet is difficult to achieve in traditional lecture formats. Laboratory components supplement traditional lectures in an effort to emphasize active learning and provide higher-order challenges, but these laboratories are often subject to the constraints of (a) increasing student enrollment, (b) limited funding for operational, maintenance, and instructional expenses and (c) increasing demands on undergraduate student credit requirements. Here, we present results from a pilot project implementing virtual (or online) laboratory experiences as an alternative to a traditional laboratory experience in Fluid Mechanics, a required third year course. Students and faculty were surveyed to identify the topics that were most difficult, and virtual laboratory and design components developed to supplement lecture material. Laboratories were assessed by comparing student ratings of topic difficulty, and student ratings of the virtual laboratory experience. Each assignment was designed to specifically address higher-order cognitive skills, through both laboratory and design modules. The design modules include conflicting project objectives, and require students to apply their engineering skills and explain their reasoning. We focus on lessons learned from development and pilot implementation of these two laboratory modules, providing general guidance for those who seek to develop virtual laboratory modules in any discipline.

Introduction

Engineering education prepares students for careers in application of physical principles to real-world problems. As part of the educational process, engineering education has long recognized the benefits of hands-on laboratories. These laboratory experiments create active-learning environments, allowing students to practice the scientific method by varying experimental conditions and directly observing results. A further benefit of laboratory experiments includes their ability to address higher-order cognitive skills (analysis, synthesis, and evaluation) defined by Bloom's Taxonomy[1]. Problems based on real-world application of theoretical concepts help extend laboratory observations to applied examples that students may face in their future careers.

Despite these recognized benefits, economic and physical space concerns have the potential to adversely impact the quality of the student learning experience. Educational institutions are presented with the dilemma of having to reduce costs while maintaining or increasing educational benefits to students. Further compounding the problem, student schedules are increasingly filled with academic requirements leaving little time for hands-on laboratory experimentation even if labs are available.

Constructivist learning theory purports that knowledge is actively constructed by the learner through hands-on, active experience. However, these active experiences can be mediated through technology, offering an alternative to traditional hands-on methodologies. Technology based theories such as anchored-instruction promoted by Bransford[2] and Pea's[3] work can be helpful when considering the use of multi-media environments. Research surrounding these theories has demonstrated that technology-mediated learning environments can present learners with complex, real-world problem solving opportunities that can support and promote higher order thinking for knowledge construction and transfer. For example, Scanlon,[4] examining current learning models in the learning sciences, systematically presents how technology mediated labs can promote student learning and support conceptual change.

Virtual labs are but one example of technology-mediated learning environments. The labs can take the form of imitations of real experiments, or computer simulations designed to provide students with a comparable learning experience to traditional labs. Virtual labs allow students to "stop the world" and "step outside" of the simulation allowing them to better understand the underpinning concepts, an ability not likely feasible in most physical lab experiments.[5] The work of McAteer[6] and colleagues exemplifies how technology mediated practical work can change lab practice in the life sciences. The authors found that there were no differences between simulated and virtual labs in the way that students talk about experiments or the way that the students engage the instructor and their peers. The value that online labs in engineering may provide is further reflected in a recent literature review by Ma and Nickerson[7] who sought to compare the value of hands-on labs, simulated (or virtual labs), and remote labs. They found that most of the labs discussed in the literature fell into the engineering domain and that each lab type had value while focusing on different learning objectives. The authors did acknowledge that no standard criteria to measure the effectiveness of the lab work has been developed. Several other researchers have demonstrated the effectiveness of virtual labs in the sciences. For example Shin[8] and colleagues found virtual labs in chemical engineering "help students to understand the fundamentals of unit operations…" and had other learning benefits. The authors note, "It is also expected to contribute to increasing students' adaptability by working in real world process plants after graduating." An additional example is the Virtual ChemLab[9] which provides a parallel to this project. The creators of the Virtual ChemLab have had a track record of successful use of virtual laboratory exercises to improve student learning in inorganic chemistry. Virtual ChemLab creators emphasize ease of use and connectivity of theory to application as successful traits in their work.

Here, we present results from a pilot study performed in Fluid Mechanics, a required third-year course in Civil and Environmental Engineering at a large mid-Atlantic research university. Our pilot study included the development and implementation of two virtual labs in a class of 78 students. Virtual labs were delivered via ANGEL, an interactive online course management system similar to Blackboard. The goals of this project were (1) to enhance student understanding of difficult course topics through inclusion of virtual labs, and (2) to enhance student achievement of higher-order cognitive skills through virtual labs and design exercises. In this manuscript we highlight our lab development strategy, discuss student perceptions of virtual labs, provide evidence of effectiveness of virtual labs, and summarize our experience as lessons learned for virtual lab design.

Methodology

Based on available resources, we first determined a reasonable format for our virtual labs. Labs would be implemented via web-based software and delivered to students through Penn State University's ANGEL Course Management Software. Each lab would consist of photographs and video clips of experiments being completed, and would require students to collect data for analysis (Figures 1-3 provide screenshots of the labs as delivered to students). Finally, each lab would include a design exercise to simulate real-world application of the theory and require students to justify their decisions in an environment with competing objectives.

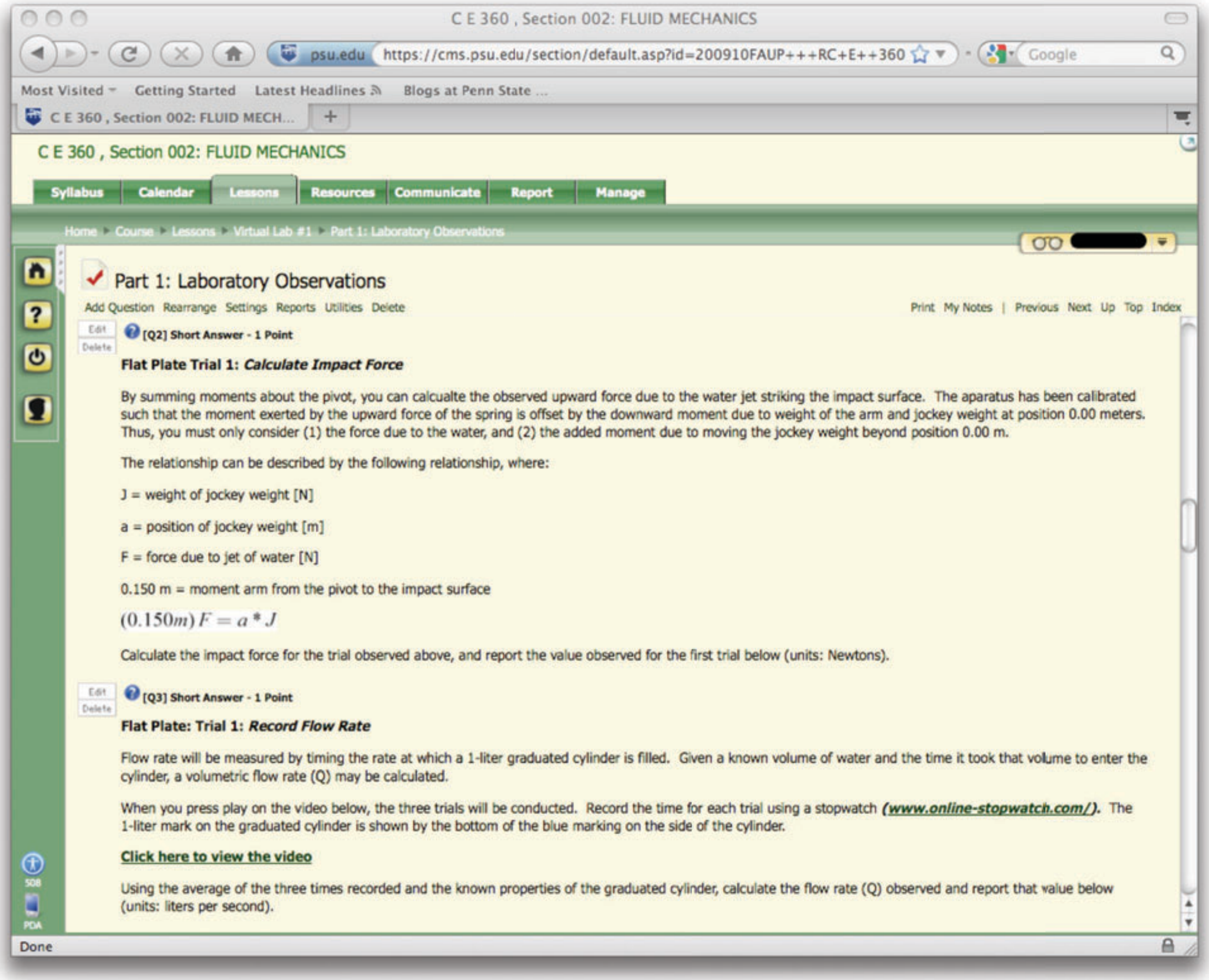
We began development of the virtual labs by conducting a survey of both course instructors and alumni to identify the most difficult topics in the class. A total of 12 instructors and teaching assistants, and 96 course alumni were surveyed to rank the fourteen major course topics using a rating scale ranging from "very easy" to "very difficult". Based on synthesis of instructor and student results, we identified two topics (conservation of momentum, dimensional analysis) as being the most difficult topics, and thus would serve as the focus of our virtual labs. For each topic, we identified appropriate laboratory experiment. In development of the lab, we considered the need to have laboratory procedures captured by photography and video for use in the online laboratories. In summary, each virtual lab required students to make measurements and observations, formulate and test hypotheses, and then apply theoretical concepts to a more open-ended real-world problem.

After lab development and internal review, the first lab was administered to a sample of 78 students in a fluid mechanics course. Students evaluated their experience after completion of the lab, responding to both Likert scale items and free response questions. Results from the first lab were used formatively to guide the development of the second lab. Content of the second lab had already been determined based on student and faculty surveys; modifying the delivery and structure of the lab was the primary use for student feedback. The second lab was administered to the same sample population and the same evaluation form used to collect student feedback. Finally, the survey of course topic difficulty and the importance of learning tools was administered to the students as a way to measure effectiveness of the virtual labs in improvement of student understanding of difficult topics.

Virtual Lab #1: Conservation of Momentum

The first exercise explores conservation of linear momentum, using both a laboratory apparatus (Figure 4) and an applied example (design of a sluice gate). The goal of the laboratory is to demonstrate the principles of conservation of momentum, specifically the need to consider the direction of inflows and outflows from a control volume. The laboratory is divided into the following modules, delivered online:

Module 1: Laboratory Observation. Students are briefly introduced to the laboratory apparatus. The strategy of summation of moments about a hinge to determine an unknown force is introduced. Students use a video clip to calculate the flow rate for one trial using a flat-plate deflector (Figure 5A). After calculating the impact force of the water jet, students hypothesize the behavior of similar flow-rates applied to a



Part 1: Laboratory Observations

[Q2] Short Answer - 1 Point

Flat Plate Trial 1: *Calculate Impact Force*

By summing moments about the pivot, you can calcualte the observed upward force due to the water jet striking the impact surface. The aparatus has been calibrated such that the moment exerted by the upward force of the spring is offset by the downward moment due to weight of the arm and jockey weight at position 0.00 meters. Thus, you must only consider (1) the force due to the water, and (2) the added moment due to moving the jockey weight beyond position 0.00 m.

The relationship can be described by the following relationship, where:

J = weight of jockey weight [N]

a = position of jockey weight [m]

F = force due to jet of water [N]

0.150 m = moment arm from the pivot to the impact surface

$$(0.150m)\,F = a * J$$

Calculate the impact force for the trial observed above, and report the value observed for the first trial below (units: Newtons).

[Q3] Short Answer - 1 Point

Flat Plate: Trial 1: *Record Flow Rate*

Flow rate will be measured by timing the rate at which a 1-liter graduated cylinder is filled. Given a known volume of water and the time it took that volume to enter the cylinder, a volumetric flow rate (Q) may be calculated.

When you press play on the video below, the three trials will be conducted. Record the time for each trial using a stopwatch ***(www.online-stopwatch.com/)***. The 1-liter mark on the graduated cylinder is shown by the bottom of the blue marking on the side of the cylinder.

Click here to view the video

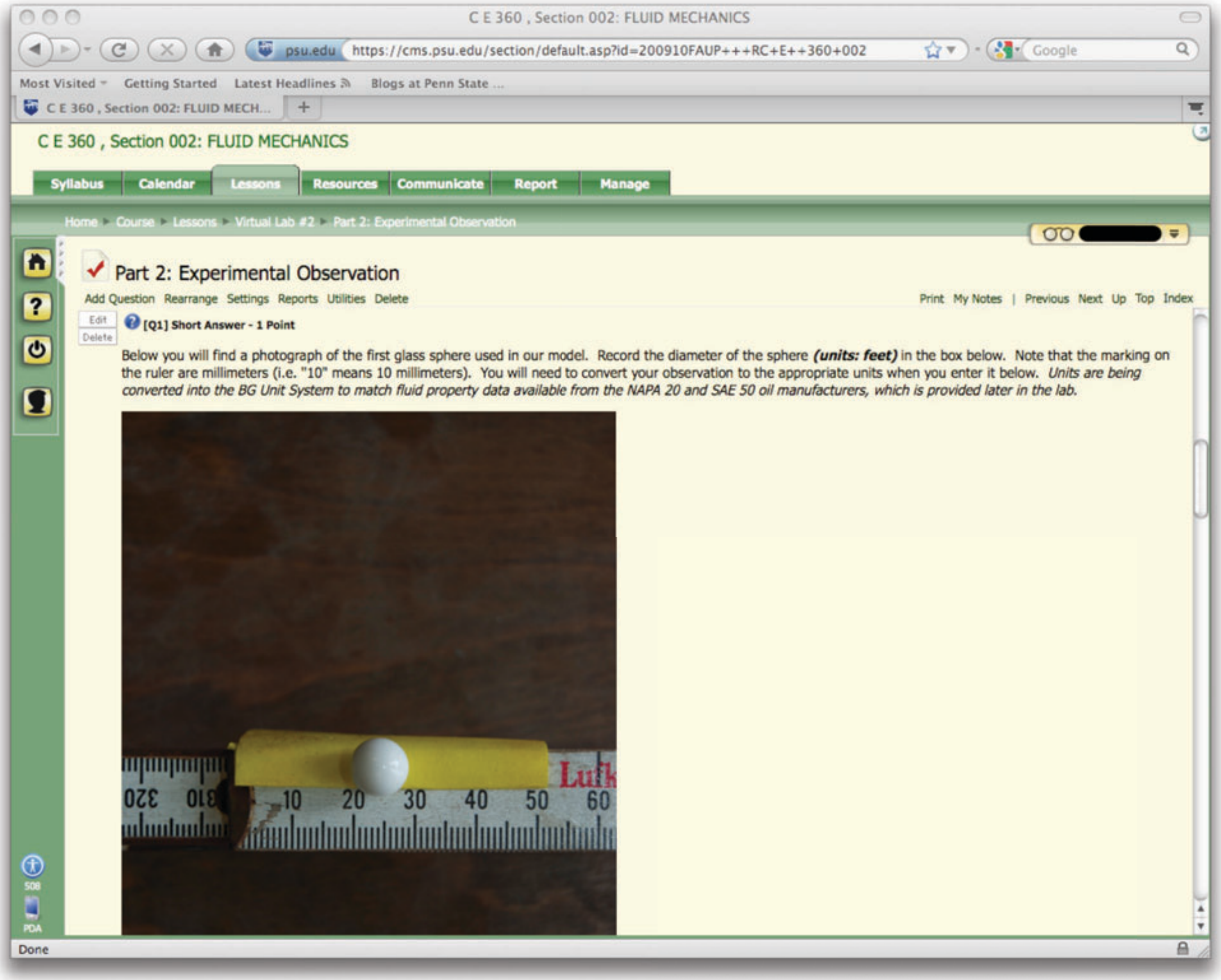
Using the average of the three times recorded and the known properties of the graduated cylinder, calculate the flow rate (Q) observed and report that value below (units: liters per second).

Figure 1: Screen-shot of ANGEL user interface. Note that equations can be displayed for users. Student responses can be collected in multiple formats, including free-response or multiple choice.

hemispherical deflector (Figure 5B). A single trial with the hemispherical deflector is presented as a video, and students calculate impact force for this trial and several additional trials.

Module 2: Theoretical Calculations. After having observed behavior in the laboratory setting, students analyze the laboratory apparatus using the principles of conservation of linear momentum, and conservation of energy (in the form of the Bernoulli Equation). Students compute theoretical impact force for all trials completed in Module 1.

Module 3: Comparison of Results. In this module, students compare their observations (Module 1) and theoretical calculations (Module 2). Students graph observed versus theoretical impact forces to assess the ability of their theoretical analysis to predict behavior of the apparatus. Students hypothesize sources of error in the experiment. Finally, students assess the need to apply the Bernoulli Equation, as opposed to making a simplifying assumption.



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Part 2: Experimental Observation

[Q1] Short Answer - 1 Point

Below you will find a photograph of the first glass sphere used in our model. Record the diameter of the sphere ***(units: feet)*** in the box below. Note that the marking on the ruler are millimeters (i.e. "10" means 10 millimeters). You will need to convert your observation to the appropriate units when you enter it below. *Units are being converted into the BG Unit System to match fluid property data available from the NAPA 20 and SAE 50 oil manufacturers, which is provided later in the lab.*

Figure 2: Example of student interface for collecting lab data. In this example, a glass sphere used in Lab 2 is photographed adjacent to a scale and students are asked to record the diameter in the appropriate units.

Module 4: Design Exercise. In the design exercise, students are given the task of designing a sluice gate given physical constrains. After a preliminary design problem (similar to an in-class example), additional and conflicting constrains are applied which cannot be readily met (simulating a more realistic design problem). Students are asked how the constrains might be modified to achieve a functional design, including a logical explanation of their proposal.

Virtual Lab #2: Dimensional Analysis, Similitude, and Modeling

The second virtual lab explores dimensional analysis, similitude, and modeling applied to both a laboratory problem and a simulated design. The goal of the exercise is to demonstration the application of scale modeling and dimensionless parameters (relatively abstract concepts, per instructor surveys). The lab is delivered as the following four modules:

Module 1: Dimensional Analysis. The goal of determining drag forces on a sphere falling through a fluid is introduced. The laboratory apparatus (Figure 6) is introduced to students, and Buckingham's Pi Theorem is applied to the problem.

Module 2: Experimental Observation. Students make experimental observations of a sphere falling through a column of oil. Through photographs and video clips, students observe the necessary physical properties of the problem (i.e., oil temperature, sphere

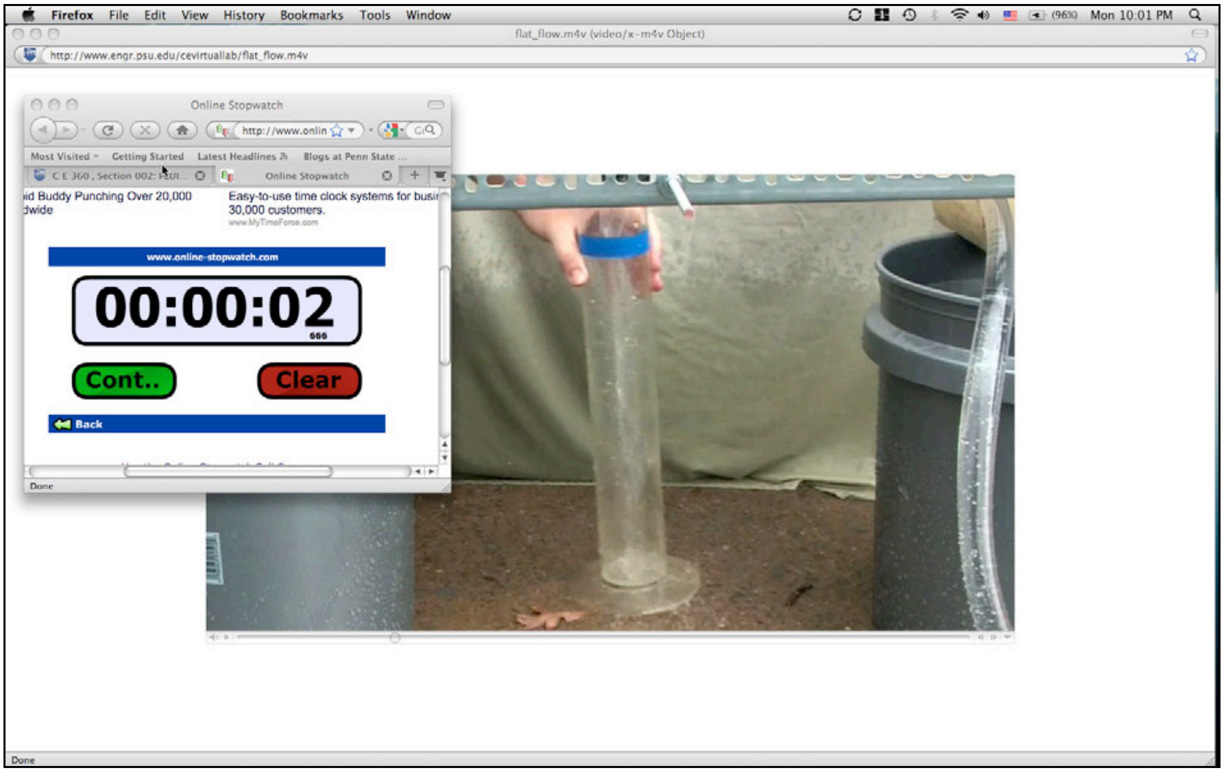

Figure 3: Sample of integration of video into Lab 1. Video clips open in separate browser windows and students are asked to make observations. In this example, an online stopwatch application is used to estimate the flow rate of water based on the time it takes to fill a 1 L graduated cylinder.

weight, sphere diameter) and make observations of the velocity of the sphere. A free-body diagram is used to calculate a force-balance and quantify the affect of drag force on the sphere.

<u>Module 3: Modeling and Similitude.</u> The observational results and theoretical relationships developed in Modules 1 and 2 are used to predict the terminal velocity of the sphere in a different column of fluid. Students calculate the theoretical terminal velocity using multiple methods (e.g., Pi Group Equivalence, empirical relationships) and make laboratory observations. Finally, students assess the predictive power of their derived relationships and identify potential sources of error.

<u>Module 4: Design Exercise.</u> The final module is a design exercise in which students use Reynolds number to analyze the design of a storm water pipe. In the example, changes to a parcel of lab increase flow-rate, and students must analyze the existing design and propose improvements to meet a design requirement (specified minimum Reynolds number). Finally, students must explain in common language why simply doubling the size of the designed pipe would not meet regulations, prompted by a client concerned about flooding.

Results

Student Evaluation of Labs

Student evaluations of Lab 1 suggest that the lab was generally not well received by students (Table 2). Only 8% of the students found the lab instructions to be clear and easy to understand. We hypothesize that the difficulty with understanding the instructions may have influenced students' responses to the other survey questions. Student reviews indicated that the primary weaknesses of the lab included confusing lab apparatus, a lack of an instructor's presence to provide guidance or affirmation they were "on the right track", and the lack of actual hands-on experience. Despite these weaknesses, students responded positively to some aspects of Lab 1, including (1) educational value in laboratory demonstration and real-world application of abstract concepts, and (2) flexibility to work at their own pace and from home.

Student evaluations were used as guidance to develop Lab 2; successful strategies and modifications are summarized in the subsequent section of this manuscript. Specific improvements to Lab 2 are highlighted in the Discussion section below. In summary, we improved the experience by providing additional guidance to students and explanation of the laboratory apparatus involved. Improvement in the structure and content of Lab 2 is evidenced by the improvement in student perceptions (Table 2). Substantial improvements in the clarity of lab instructions and format, in addition to increased immediate feedback through use of multiple-choice questions led to a more successful student experience. This improved experience translated into student perception of increased understanding and relevance of the material, in comparison to Lab 1.

Virtual Lab Effectiveness

End-of-semester surveys were used to assess our goal of improving student understanding of course material through virtual labs. Similar to the collection of baseline data by students in the previous semester and by the instructors, students in the class using the virtual labs were asked to rate the difficulty of class topics. Student feedback for the topics highlighted by each lab suggests that virtual labs can affect student understanding of course material (Table 1). Specifically, a well-designed lab (i.e., Lab 2) can improve student understanding, while a poorly designed lab (i.e., virtual Lab 1) may increase confusion with the material.

Discussion

Lessons Learned

Formative assessment from the pilot labs provided invaluable information, which allowed for substantial improvement between Labs 1 and 2. The need for collection of student feedback and an adaptive development strategy is highlighted by the improvements made during our pilot project. Our experience and conclusions are summarized below as lessons learned:

<u>Lesson 1: Complex equipment requires detailed instruction.</u> Laboratory equipment for Lab 1 was complex, and student feedback indicated that a more substantial introduction to how the equipment functions was missing from their experience. In response, we improved the introduction of lab facilities during Lab 2. We recommend that virtual labs including complex laboratory equipment include a short introductory video, which could be delivered either online or in class.

<u>Lesson 2: Introduction of online software.</u> We believe that the lower ratings for Lab 1 were, in part, due to the demand for students to complete a task that was unfamiliar. To the best of our knowledge, this is the first virtual lab experience for students, and they may have been unfamiliar with the online software or unsure of how to complete the work. An in-class introduction would likely benefit students in their approach to the virtual lab.

<u>Lesson 3: Lab documentation.</u> As with a traditional lab, we emphasized the need to record observations and refer back to them several times. For Lab 2, we developed a worksheet for students to save on their computer or print. The worksheet provided guidance for students to clarify what values they should record, and to help with the correct use of units throughout the lab.

<u>Lesson 4: Immediate feedback and milestone questions.</u> Students reported feeling lost in Lab 1, and wished there were a lab instructor present to help them. To address this feedback, we implemented a sequence of hints to help students interpret their results. For example, a hint might suggest “you’ll need to compare this to previous observations” or “be sure to complete the calculations, not simply report the value observed”.

Figure 4: Laboratory apparatus for Virtual Lab #1 (manufactured by TecQuipment, Ltd.). The nozzle discharges a jet of water that impacts the deflector plate. A weight is used to balance the force of the impact jet, and moments are summed about the hinge to calculate the force due to the jet of water

Figure 5: (top) Flat-plate deflector and (bottom) hemispherical deflector used for laboratory observations. The shape of the hemispherical deflector provides a theoretical 2-fold increase in the vertical component of force due to the water jet over the flat-plate deflector.

Table 1: Summary of virtual lab effectiveness, as evidenced by post-course surveys administered to populations taught pre- and post-implementation of the virtual labs. Student feedback was reported on a scale ranging from very easy to very difficult (scores 0 – 4), and was normalized to the mean. Data presented demonstrate deviation from the average difficulty, and rank within the fourteen course topics.

	Topic Difficulty		**Difficulty Rank**	
Topic	**Pre**	**Post**	**Pre**	**Post**
Lab 1: Conservation of Momentum	1.12	1.41	6	3
Lab 2: Topic) Dimensional Analysis, Similitude, Modeling	1.02	0.50	7	13

Additionally, the inclusion of milestone (multiple-choice) questions throughout the lab allowed automated feedback for students. An incorrect multiple-choice answer would prompt students to back up and review their work, beginning at the previous milestone.

Lesson 5: Provide a rubric or example of expected performance. The intent of the lab was to replicate the benefits of a traditional lab, including the opportunity for students to communicate and interpret their hypotheses, observations, and results. Student responses to open-ended questions ranged from single-word answers to complete, multiple-paragraph discussions. We suggest providing students with examples of well-formed responses. Alternatively, a rubric for grading essay responses for the entire lab would be helpful, including expected length, depth, grammatical requirements, and components (i.e., hypothesis, recommendation, etc.) of a quality response. Providing this rubric to students in advance would help to communicate expectations for performance on the lab.

Lesson 6: Highlight real-world relevance. Student feedback indicated that the design exercises were beneficial in highlighting the relevance of the material in applied scenarios. For Lab 2, over 20% of student believed the virtual lab experience would be valuable in their future careers.

Higher-order Learning

Among our stated goals for the project was to enhance student achievement of higher-order cognitive skills through the virtual lab experiences. Virtual labs require students to complete the same cognitive processes as traditional, hands-on labs. Students interpret experimental design and conditions (analysis), make hypotheses (synthesis), and interpret results (evaluation). Real-world applications allow students to apply the lab concepts to realistic problems (application), and asked students to defend their design to hypothetical clients or teams (evaluation).

Our review of student feedback and grading of student responses suggest, qualitatively, that this goal was achieved. Successful completion of the lab by students included meaningful, well-justified hypotheses and interpretation of lab results. Students justified the potential sources of experimental error, and used sound logic to support their results in the design component of the labs. No comparison of student responses or scores on

Figure 6: Apparatus used to determine the drag force on a sphere falling through columns of different fluid (by Armfield, Ltd.). SAE 50 (left) and NAPA 20 (right) oils were used for the experiment.

the virtual labs with traditional assessment data (i.e., scores on exams, course grades) has been made at this time.

Future Work

A second delivery of the virtual labs is planned for the Fall 2010 semester. Student and instructor feedback from the pilot project will be used to revise the content and delivery of both experiments. Additional student feedback from the same measures will be collected, both after each lab and at the end of the course. Student feedback, data on learning outcomes and student performance (i.e., correlation between virtual labs and student grades), and overall reflections on the course will be used to gage both lab effectiveness and improvement of the pilot project.

Table 2: Summary of student perceptions of virtual labs. 78 students were enrolled in the course, n student responded to the survey.

VIRTUAL LAB #1	**n**	**Strongly Agree**	**Agree**	**Neutral**	**Disagree**	**Strongly Disagree**
Instructions and use of the virtual laboratory were clear and easy to understand.	49	0.0%	8.2%	4.1%	49.0%	38.8%
The learning objectives of the virtual lab were clear.	49	2.0%	28.6%	16.3%	32.7%	20.4%
The time and effort spent on the virtual laboratory was comparable to that which I typically spend on a homework assignment.	48	0.0%	37.5%	10.4%	20.8%	31.3%
The virtual laboratory component improved my understanding of fluid mechanics concepts.	49	0.0%	10.2%	26.5%	38.8%	24.5%
This method(s) of presenting information enhances my learning.	49	0.0%	16.3%	10.2%	44.9%	28.6%
Virtual laboratory components should be included in other courses to supplement classroom experiences.	49	0.0%	10.2%	22.4%	32.7%	34.7%
The virtual laboratory provided experience which will be valuable in my future career.	49	0.0%	4.1%	30.6%	34.7%	30.6%

VIRTUAL LAB #2	**n**	**Strongly Agree**	**Agree**	**Neutral**	**Disagree**	**Strongly Disagree**
Instructions and use of the virtual laboratory were clear and easy to understand.	34	2.9%	52.9%	41.2%	0.0%	2.9%
The learning objectives of the virtual lab were clear.	35	5.7%	45.7%	40.0%	5.7%	2.9%
The time and effort spent on the virtual laboratory was comparable to that which I typically spend on a homework assignment.	35	2.9%	40.0%	31.4%	20.0%	5.7%
The virtual laboratory component improved my understanding of fluid mechanics concepts.	35	5.7%	28.6%	45.7%	14.3%	5.7%
This method(s) of presenting information enhances my learning.	35	5.7%	40.0%	40.0%	8.6%	5.7%
Virtual laboratory components should be included in other courses to supplement classroom experiences.	35	0.0%	20.0%	45.7%	28.6%	5.7%
The virtual laboratory provided experience which will be valuable in my future career.	34	2.9%	20.6%	44.1%	20.6%	11.8%

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