Advances in Engineering Education

SUMMER 2012

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

DEBRA M. GILBUENA
Oregon State University
Corvallis, OR

F. ADAM KIRSCH
Crescent Valley High School
Corvallis, OR

and

MILO D. KORETSKY
Oregon State University
Corvallis, OR

ABSTRACT

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

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

INTRODUCTION

Over the last seven years we have developed, implemented and been assessing the Virtual Chemical Vapor Deposition (CVD) Laboratory Project [1–3]. Since 2008, more than 600 high school students have completed this project in 26 cumulative classes at 5 high schools. We employ technology to simulate a complex industrial process that would not be accessible to students in a conventional laboratory environment and allows future engineers to practice the skills they will need in industry, in much the same way a flight simulator is used for training pilots. The Virtual CVD Laboratory Project was developed as a capstone experience for university engineering students. However, we recognized that, with appropriate curriculum modification, this project could fill a critical need at the high school level. This paper discusses the adaptation of the Virtual CVD Laboratory project at the high school level.

Informed by research on student learning, the American Association for the Advancement of Science (AAAS), in its Benchmarks for Science Literacy - Project 2061, describes the need for fundamental shifts away from rote learning and content knowledge, and the necessity for transitioning to pedagogical approaches that emphasize process, critical thinking, and problem solving within multiple contexts [4]. This group also stresses the need for all students to obtain scientific literacy. Such emphasis is reinforced by the National Science Education Standards (NSES) with the call for a "step beyond 'science as a process'" [5]. Engineering can provide a particularly powerful context to meet these goals through the integration of math, science and technology coupled with the development of problem solving and design skills.

The ideals communicated in Benchmarks and the NSES continue to drive curricular reform. Fifteen states now have explicitly labeled engineering components within standards [6], and some states such as Massachusetts [7] and Texas [8], have issued a separate State Engineering or Technology Standard. At the high school level, 14 states have explicitly included an engineering design component and an additional 10 have explicitly included technology design in state standards [9]. There have been recent discussions regarding creating National Standards for K-12 in Engineering [10]; however, the Committee on Standards for K-12 Engineering Education recommends integrating engineering core ideas into existing National Standards for science, mathematics, and technology [11].

While the incorporation of engineering into K-12 state standards is diverse and varies in scope, there is general alignment with the broad framework presented in the recent National Research Council report, *A Framework for K-12 Science Education* [12]. The framework is constructed across three dimensions: practices, cross-cutting concepts, and core disciplinary ideas. The report emphasizes the use of this framework to accomplish the goal of having "students, over multiple years of school, actively engage in science and engineering practices and apply crosscutting concepts to deepen their understanding of each fields' disciplinary core ideas," [pp ES-2] and that "introduction to engineering practice, the application of science, and the interrelationship of science and technology is integral to the learning of science for all students" [pp 1-4]. Moreover, the authors assert, "that helping students learn the core ideas through engaging in scientific and engineering practices will enable them to become less like novices and more like experts" [pp 2-2]. This framework is reported to be instrumental in the Next Generation Science Standards currently being developed [13].

Laboratories offer students one way to actively engage in science and engineering practice. They also develop students' beliefs about the nature of science, i.e., "the epistemology of science, science as a way of knowing, or the values and beliefs inherent to scientific knowledge and its development" [14, pp833]. The passing of and continued support for the America COMPETES Act [14] recognizes the consensus in the scientific community regarding these integral roles of the laboratory experience and explicitly mandates improved laboratory learning and "development of instructional programs designed to integrate the laboratory experience with classroom instruction" [15, pp 694]. Although a substantial case can be made as to the value of a curricular approach with this emphasis, pedagogical decisions must account for the realities of limited resources, especially time and budgets. The latest reauthorization of the America COMPETES Act [16] acknowledges these limits and promotes the use of technology to "enhance or supplement laboratory based learning" [pp 32]. Virtual laboratories offer an attractive curricular option from a budgetary standpoint; once software has been developed, the transfer cost is relatively small, consisting mostly of developing teaching materials and teacher expertise.

Virtual laboratories have been used as a teaching tool since the early 1980's [17-19]. They are often used to replace physical laboratory equipment that is too expensive to purchase and maintain or too complex, dangerous or time consuming for students to use [20]. There are reports of successful integration of various virtual laboratories directed specifically at content-specific domain knowledge at the high school level in biology [21], chemistry [22], and physics [23,24].

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

CLAIMS

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

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

PHILOSOPHY AND CONTEXT

The Virtual CVD Laboratory Project is intended to provide an authentic engineering environment in which students learn through applying knowledge and skills to a practical and challenging engineering task. As implemented at the high school level, this project embodies the integration of practices, crosscutting concepts, and core ideas, three dimensions which have been identified as "needed to engage in scientific inquiry and engineering design" [12, pp ES-1]. These dimensions are present in this project to varying degrees depending on the instructional design. A cumulative summary of dimension components that have been incorporated into this project at the high school level is given in Table 1.

Project-based learning (PBL) provides a pedagogical approach consistent with this framework. PBL has engaged students in engineering design at all levels in K-12 education [25] and has involved students in learning and doing scientific practices [26]. The project discussed in this paper embodies a project-based pedagogy that incorporates engineering experiences into classroom practice, similar to projects described by Krajcik et al [26]. One review of research on PBL put forth five criteria that projects must meet to be considered PBL experiences [27]. The first criteria is that projects must be (1) central to the curriculum. The next two address student ***motivation*** and the last two criteria address ***cognition***.

The two criteria described to promote student ***motivation*** are that projects must be (2) student-driven, and (3) authentic, real-life challenges [27]. According to the National Research Council (NRC) report *How People Learn*, students value situated, authentic projects more highly than

Science & Engineering Practices	Crosscutting Concepts	Core Ideas*
1. Asking questions (for science) and defining problems (for engineering) 2. Developing and using models 3. Planning and carrying out investigations 4. Analyzing and interpreting data 5. Using mathematics, information and computer technology, and computational thinking 6. Constructing explanations (for science) and designing solutions (for engineering) 7. Engaging in argument from evidence 8. Obtaining, evaluating, and communicating information	• Patterns • Cause and effect: Mechanism and explanation • Scale, proportion and quantity • Systems and system models • Energy and matter: Flows, cycles, and conservation • Structure and function • Stability and change	Engineering, Technology, and the Application of Science (2 of 2) ETS 1 – Engineering design ETS 2 – Links among engineering, technology, science, and society Physical Sciences (2 of 4) PS 1 – Matter and its interactions PS 3 – Energy Earth and Space Sciences (1 of 3) ESS 3 – Earth and human activity Life Sciences (1 of 4) LS 1 – From molecules to organism: Structures and processes

*numbers in parentheses after each disciplinary area refer to the number core ideas addressed by this project out of the total number of core ideas identified by the Committee on Conceptual Framework for the New K-12 Science Education Standards. Crosscutting Concepts and Science & Engineering Practices are complete.

Table 1: Components of practices, crosscutting concepts, and core ideas [12] that have been incorporated into the Virtual CVD Laboratory Project.

traditional coursework and, consequently, are more motivated and more willing to invest time and effort into learning [28]. This assertion has been demonstrated in several project-based learning environments which reported high student motivation and involvement [29-31]. However, while student motivation is necessary, Blumenfeld et al. [31] emphasize the need for a strong link between motivation and cognition.

Cognition is the basis for the last two criteria for project-based learning environments, which require that a project (4) consist of driving questions that lead students to confront concepts and (5) contain central activities that promote transformation, construction and integration of knowledge [27]. In this paper, we explicitly address how the Virtual CVD Laboratory Project promotes the integration of knowledge and metacognition. Linn et al. [32] describe knowledge integration as “when teachers use students’ ideas as a starting point and guide the learners as they articulate their repertoire of ideas, add new ideas including visualizations, sort out these ideas in a variety of contexts, make connections among ideas at multiple levels of analysis, develop ever more nuanced criteria for evaluating ideas, and regularly reformulate increasingly interconnected views about the phenomena” “ [pp 1049]. Promoting knowledge integration, especially within authentic, situated learning environments, has been shown to be an effective and durable teaching approach [28]. Finally, reflection and evaluation play a critical role in metacognition, the act of assessing and regulating one's own learning. This type of regulation has been shown to enhance one's learning and ability to transfer what is learned to new contexts [28].

Epistemology is an important aspect of project-based learning pedagogies that is often not addressed. We define students' epistemological beliefs about engineering as their ideas about what it means to learn, understand, and practice engineering. The sophistication of high school students' epistemological beliefs has been positively linked to the likelihood of integrating knowledge [33], undergoing conceptual change, critical thinking, motivation, communication, and the ability to learn from team members [34]. Studies in engineering have posited that complex, ill-structured projects can enhance epistemological beliefs [35]. It has also been suggested that virtual laboratories are a rich environment that affords the opportunity for growth of epistemological beliefs [36]. A desired curricular outcome of the Virtual CVD Laboratory Project is to give students experience with an authentic, iterative, ill-structured problem such that they will develop more sophisticated epistemological beliefs that move towards those of practicing engineers and scientists.

THE VIRTUAL CVD LABORATORY PROJECT

The Virtual CVD Laboratory Project was created as an undergraduate chemical engineering laboratory project. The purpose was to fill a gap in the curriculum and provide students with a different type of laboratory experience than found in traditional laboratories. In a traditional laboratory, students often perform confirmation experiments in which they follow a prescribed investigation path and focus on getting the equipment to function properly in order to collect data. While these laboratories provide students with needed hands-on experience using physical equipment and can show students theory in practice, they have limitations. Time and materials constraints restrict the degree to which students can direct their own investigation. Students may even begin to have the epistemological belief that part of the nature of science and engineering is simply to run experiments to confirm an expected result as opposed to gathering information to guide the direction of investigation. Using a project-based learning pedagogy, the Virtual CVD Laboratory Project was created and used in college courses [1, 2]. It was then appropriately modified and extended to the high school level.

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

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

Software Design

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

Student Interface

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

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

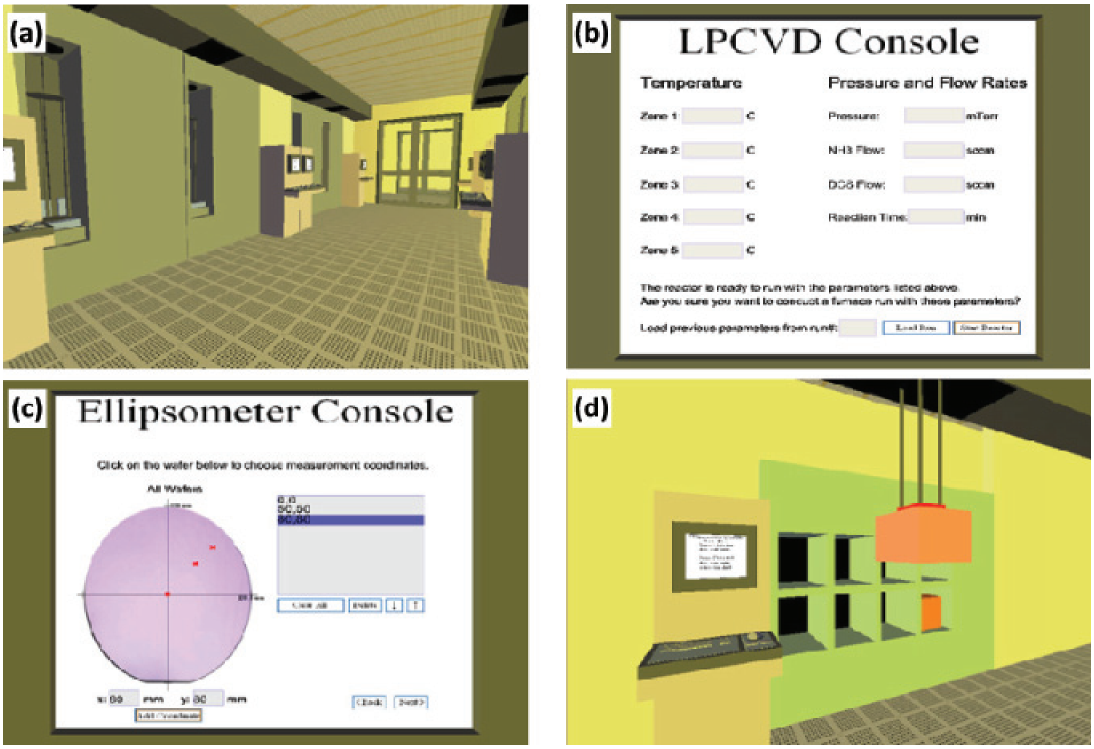

Figure 1. Images of the student interface (a) navigating in the reactor bay, (b) inputting reactor variables to run the reactor, (c) choosing measurement positions in the ellipsometer console, and (d) watching wafers as they load into the ellipsometer.

Instructor Interface

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

METHODS

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

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

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

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

INSTRUCTIONAL DESIGN – PILOT AT THE HIGH SCHOOL LEVEL

The Virtual CVD Laboratory Project was used in eight classes (one section of *Introduction to Engineering* and seven sections of *Chemistry*) during the 2007-2008 academic year. In total, 123 teams completed over 1,500 runs and made over 60,000 measurements. The curriculum leveraged materials developed for undergraduate students, but modified and further scaffolded instruction to be level appropriate. A key element in the success of the pilot was involvement of a graduate student (one of the authors) in the high school curricular development and initial classroom delivery. While four teachers were involved in the pilot implementation, perceptions and data regarding these classes is from only one of those teachers and the graduate student collaborator. The pilot implementation is discussed in greater detail elsewhere [37].

Introduction to Engineering

Introduction to Engineering, comprised of 53 students most of whom were 9th-graders, was team taught by one science and one applied technology teacher. The Virtual CVD Laboratory Project was used to address the student learning objectives of the development of critical thinking and problem solving skills. It was expected to reinforce concepts of engineering design as embodied by the IDEAL model (**I**dentify, **D**evelop, **E**valuate, **A**ct, **L**ook back) [38], a model emphasized in class. The project was also expected to provide a context for an introduction to the discipline of chemical engineering. The primary activities and the corresponding class days allocated are shown in Figure 2. The assignment icons are hyperlinked and can be clicked to access the assignment documents given in class.

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

The Initial Problem Statement (IPS) handout, presented in Step 1, was read by students outside of class. In Step 2, the instructor delivered an introduction PowerPoint (PPT) presentation, PPT presentation I, to provide an overview of transistors and ICs and an introduction to the CVD process used to manufacture transistors. Introduction to the Virtual CVD Laboratory 3-D student interface

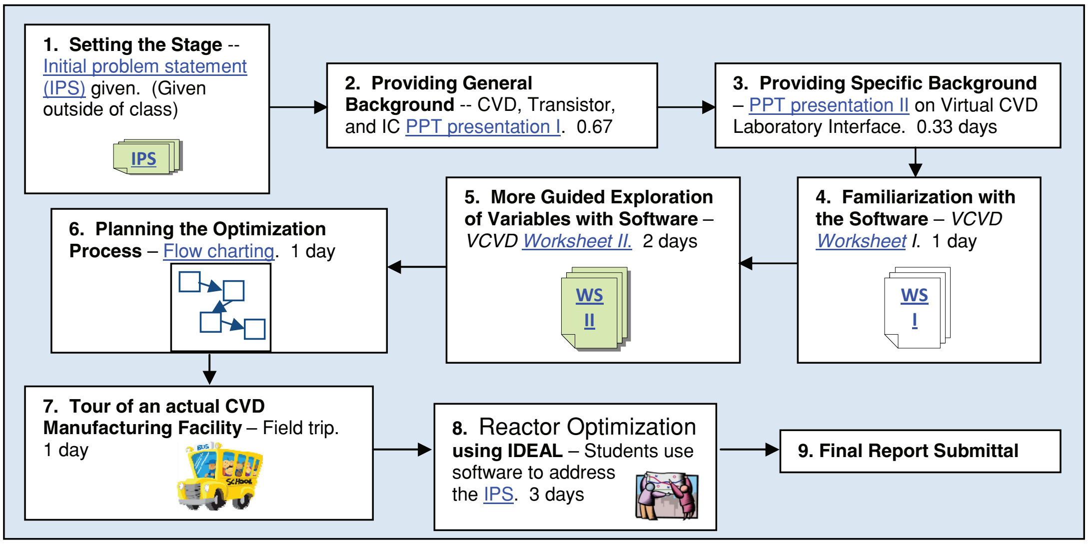

Figure 2. Activities for the Virtual CVD Laboratory Project in Introduction to Engineering class. Click on links or icons to view assignments.

occurred during Step 3 through PPT presentation II. Step 4 provided hands-on experience in which students were guided through their first run with the step-by-step instructions of Worksheet I (WS I). In Step 5 students were given a second worksheet, (WS II), to complete which provided additional scaffolding. On this second worksheet, students were instructed to sequentially alter specific variables (e.g. change all reactor zone temperatures simultaneously by the same amount, increase the temperature of a single reactor zone, change chemical flow rates, and modify reaction time). Each change was made one at a time, to gain initial insights regarding variable impact on film deposition.

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

Chemistry

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

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

ADAPTATION AND IMPLEMENTATION – A DEMONSTRATION OF VERSATILITY

In this section, we present evidence that the instructional design of the Virtual CVD Laboratory Project is ***versatile*** and adaptable to needs of students, teachers, class, and context. This evidence includes an account of the different types of classes in which this project has been used, the variety of goals and objectives teachers have addressed with this project, the flexible timelines that have been utilized, and the rich selection of activities that have been chosen to meet the goals and objectives. Table 2 summarizes the types of classes in which the Virtual CVD Laboratory Project has been used, the corresponding need in teaching it fulfilled, and the content and concepts it addressed.

These elements were identified by the teachers in surveys and interviews, as described in the Methods section of this paper. We associate the second element with the teachers' goals and the third element with the teachers' learning objectives. The project has been implemented in a diverse set of classes including: *Introduction to Engineering*, *General and Advanced Placement (AP) Chemistry*, *General and AP Physics*, and *AP Biology*. These classes range in size from as small as 6 students to more than 50 students. Class demographics range from 100% male students to more than 70% female students, with a variety of ethnic compositions.

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

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

Figure 3 shows a timeline of the project delivery for each of the classes. Across each row, a daily account of the activities that a given instructor chose to deploy is shown in chronological order. Many of the activity icons are hyperlinked and can be clicked to access the actual assignments. The overall in-class time ranged from four to nine days, demonstrating flexibility in the timeline. The longest implementations were in the classes where students spent significant project time

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

Table 2: Summary of the needs in teaching and specific concept and content objectives for each class in which the Virtual CVD Laboratory Project was implemented.

optimizing the reactor (*Introduction to Engineering* and *Physics*). Although the length of a class day varied, this unit of measurement offers a reasonable basis for comparison.

Another demonstration of the ***versatility*** of the Virtual CVD Laboratory Project is the variety of activities that were employed in instruction. This project affords teachers the ability to structure activities in ways that reinforce the goals and objectives of a specific class; thus each implementation followed its own path. Some classes started the project with a homework assignment, often included in the Initial Problem Statement, similar to preparatory homework included in IPS-Chem. Two classes included in-class preparatory instruction prior to the project on skills and knowledge the students

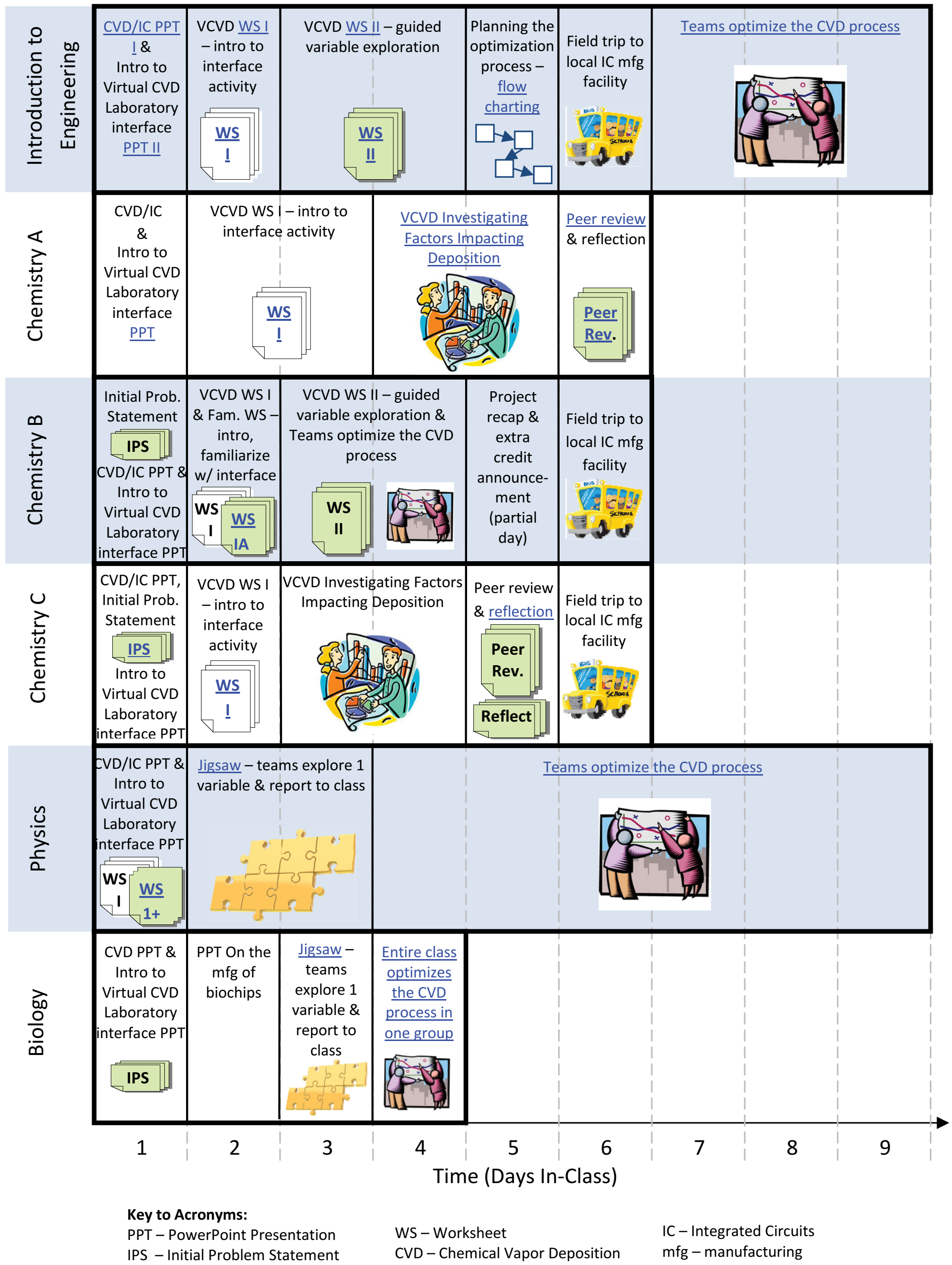

Figure 3. Timeline and in-class curricular activities of implementations. Out-of-class activities (e.g., IPS for ITE and IPS-Chem) not shown. Click on links or icons to view assignments.

would need (computer basics in *Physics* and reaction kinetics in *Biology*). While all classes had introductory PowerPoint presentations for the project, their content varied to align with the context of the class and background of the students. For example, in *Biology*, the introductory presentation uniquely included "*the manufacture of 'biochips' and layer deposition on DNA microarrays.*"

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

Four of the six classes incorporated an explicit optimization portion of the project, one of which put the entire class on a single optimization team. Another class had an implicit optimization, as evidenced by student work. As shown in Figure 3, the *Introduction to Engineering* class included a flow charting activity to scaffold engineering design in the optimization process. Three classes incorporated a field trip to a local IC manufacturing facility to reinforce the authentic nature of the project and provide students with an opportunity to connect with and ask questions of engineers in industry.

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

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

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

PROJECT EFFECTIVENESS – OUTCOMES

Motivation

We claim that the authentic nature of the project provides ***motivation*** for students. Every teacher identified the authentic nature of the project, both as a goal and an outcome. Authentic projects have been shown to increase student motivation [23]. Although none of the questions to them specifically addressed motivation, four teachers directly commented on perceived student motivation and engagement:

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

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

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

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

Cognition

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

Knowledge Integration

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

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

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

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

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

Engineering Design Strategy

Engineering design strategy was explicitly identified as an objective by three teachers. Not only is engineering design a core idea (ETS 1, shown in Table 1) in *A Framework for K-12 Science Education*, but the intentional focus on engineering design strategy also reinforces the practices of science and engineering described in the framework [12]. Engineering design strategy is demonstrated as

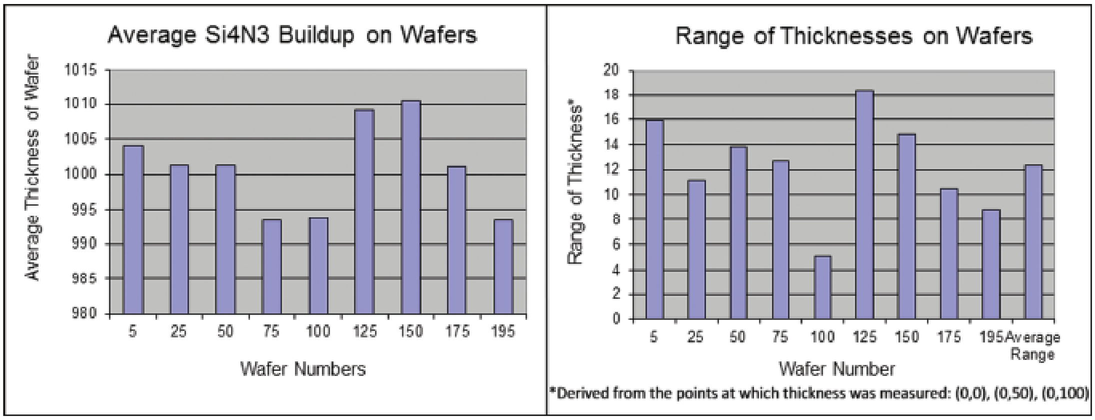

Figure 4. Graphical results reported from one team in Introduction to Engineering. They report measurements of central tendency and measurements of dispersion. Note: y-axis units are missing.

an outcome in every class; for example, consider again the student team from the statistics discussion above (Figure 4). This team explored process and measurement variation. In the Virtual CVD Laboratory, four different ellipsometers can be used to measure film thickness. While in this class, all of the ellipsometers had the same measurement error, some students perceived differences between readings when using different ellipsometers and this particular team made sure to perform all measurements using the same ellipsometer to reduce measurement variation.

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

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

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

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

Evaluation and Reflection

Elements of evaluation and reflection were demonstrated in all the classes in many different ways. For example, a student team from the *Chemistry A* class graphed reaction time versus film thickness, as shown in Figure 5. Teams were instructed to use linear regression to quantify the correlation between variables, essentially, asked to develop simple models of the cause and effect relationship between variables and performance metrics. Towards this end, this team evaluated the suitability of using five data points to sufficiently quantify the relationship between film thickness and reaction time.

> *"We believe that we have collected sufficient data because of the consistency and the number of points we had. If we were only to test 2 or 3 points, we still wouldn't be able to say much about the deposition thickness, because we don't have enough data points.*

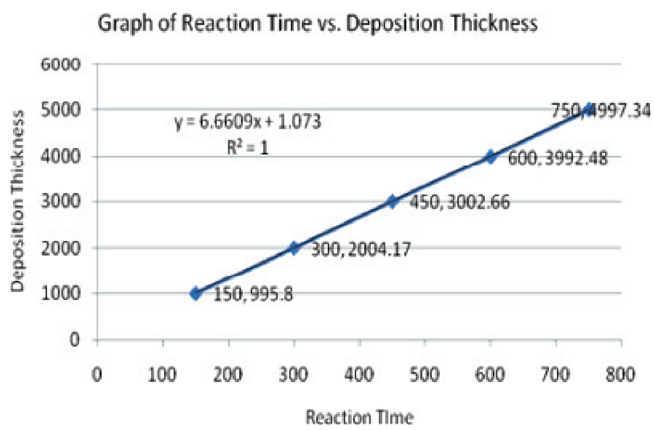

Figure 5. Graphical results reported by one team in* Chemistry*, showing their method for determining the effect of reaction time on film thickness. Note: axis units are missing.

However, we have five total data points (excluding the point (0,0)), which we believe is enough to come up with a rough sketch of the graph. In addition, the data points have an amazing correlation. They are almost perfectly linear. On the graph, it can be seen that the thin, black line matches almost perfectly with the thick, blue line (the one that corresponds to the data points)." (student team Chemistry A)

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

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

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

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

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

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

Teachable Moments – Assessment and Identification of Missing Knowledge

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

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

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

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

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

Epistemological beliefs

As discussed above, one goal of all of the teachers was to provide an authentic, real world project through placing students in the role of engineers or scientists in this industrial context. We believe that providing learning in such a context leads to development of students' epistemological beliefs, i.e., their views about what it means to learn, understand, and practice engineering. Survey responses of university students reported elsewhere [3] indicate that perceptions of the nature of the tasks and the cognitive demands embedded in the Virtual CVD Laboratory Project coincide with more sophisticated epistemological beliefs, even more so than the open-ended physical laboratories in their senior year. However, at the high school level, neither students nor teachers were asked directly about their epistemological beliefs, and this claim warrants more investigation.

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

> *"There's definitely a push in education to go more inquiry. When I was in high school and probably when you were in high school, it was more like there was [sic] these set paths, labs that you do and you have to have these results [referring to confirmation experiments]. And there is more and more wanting them to be like real scientists to do, discover their own stuff. So I'm feeling like this [the Virtual CVD Laboratory Project] is kind of meeting that need too. We need to do, a lot of our chemistry labs are still very prescribed, and so I'm trying to work away from that and this is one way that we are definitely doing it and allowing them to act like real scientists and real engineers." (Teacher B)*

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

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

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

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

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

> *"Using Microsoft excel, we also calculated that the average wafer deposition is about 999.2 angstroms with a standard deviation of about 6.74. What this means is that 68% of all wafers are between 992.5 and 1005.9 angstroms in deposition, and 98% of all wafers*

are between 985.7 and 1012.7 angstroms in deposition. Assuming that all wafers produced must be within 15 of 1000 angstroms, only about 1% of all wafers produced would have to be discarded due to defects."(student team Introduction to Engineering)

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

A general and holistic examination of this work leads to the claim that the students' epistemological beliefs become more sophisticated as they complete this project. To investigate this claim further, a reliable and valid instrument like the Epistemological Beliefs Assessment about Physical Science (EBAPS) [39], which was specifically developed for high school students, could be administered before and after the project.

BARRIERS TO ADOPTION

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

IT Infrastructure

Beyond having access to a computer, the two primary IT requirements for this project are internet access and appropriate performance specifications. The 3-D interface requires installation and appropriate video drivers in order to operate smoothly. In contrast, The HTML interface requires no installation and minimal performance specifications. During implementation, two teachers exclusively used the 3-D interface, two exclusively used the HTML interface and one used both. Three teachers commented on issues with IT infrastructure, one of whom used only the HTML interface because the 3-D interface could not be installed on school computers, despite simple and successful installation at home. Both teachers that were interviewed expressed the need to check school computers each year to verify that settings and software updates weren't conflicting with the operation of the 3-D interface; both had experienced issues resulting from computer changes. IT infrastructure is a potential barrier for any educational technology and other technology-based educational tools have faced similar challenges [40]. Currently, the HTML interface affords the use of the Virtual CVD

Laboratory Project for schools that cannot support the 3-D interface. A web-page embedded, 3-D option is in development to help mitigate IT infrastructure issues.

Preparation Time

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

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

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

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

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

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

Project Assessment

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

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

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

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

CONCLUSIONS

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

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

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

ACKNOWLEDGMENTS

The authors are grateful for support from the Intel Faculty Fellowship Program and the National Science Foundation's Course, Curriculum and Laboratory Improvement Program, under Proof-of-Concept grant DUE-0442832 and Phase 2 grant DUE-0717905. The authors would also like to acknowledge the high school teachers that integrated the Virtual CVD Laboratory Project into their classrooms and providing valuable feedback and insight. In addition, the authors would like to acknowledge the high school students who completed this project and contributed to this work. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

REFERENCES

[1] Koretsky, M. D., D. Amatore, C. Barnes, and S. Kimura. "Enhancement of student learning in experimental design using a virtual laboratory." *Education, IEEE Transactions on* 51, no. 1 (2008): 76–85.

[2] Koretsky, M. D., C. Barnes, D. Amatore, and S. Kimura. "Experiential learning of design of experiments using a virtual CVD reactor." In *Proceedings of the 2006 American Society for Engineering Education Annual Conference & Exposition*, 2006.

[3] Koretsky, M., C. Kelly, and E. Gummer. "Student perceptions of learning in the laboratory: Comparison of industrially situated virtual laboratories to capstone physical laboratories." *Journal of Engineering Education* 100, no. 3 (2011)*: 540–573*.

[4] American Association for the Advancement of Science Project 2061. *Benchmarks for science literacy*. Oxford University Press, USA, 1994.

[5] National Committee on Science Education Standards and Assessment, and National Research Council. *National Science Education Standards*. Washington DC: National Academy Press, 1996. http://www.nap.edu/catalog.php?record_id=4962.

[6] Strobel, J., R.L. Carr, N.E. Martinez-Lopez, J.D. Bravo. "National Survey of States' P-12 Engineering Standards." In *Proceedings of the 2011 American Society for Engineering Education Annual Conference & Exposition*, 2011.

[7] Commissioner of Education, and Board of Education. *Massachusetts Science and Technology/ Engineering Curriculum Framework*. Malden, MA: Massachusetts Department of Education, October 2006. http://www.doe.mass.edu/frameworks/scitech/1006.pdf.

[8] *Engineering Standards*. Texas State Board for Educator Certification, January 9, 2004. http://www.sbec.state.tx.us/sbeconline/standtest/standards/8-12engin.pdf linked from http://www.tea.state.tx.us/index2.aspx?id=5938&menu_id=2147483671&menu_id2=794.

[9] Purzer, S., J. Strobel, R. Carr. "Engineering in the National and State Standards." In *Proceedings of the 2011National Association for Research in Science Teaching Annual International Conference*, 2011.

[10] Bybee, R. W. "K-12 engineering education standards: Opportunities and barriers". Washington, DC: National Academy of Engineering Keck Center of the National Academies, 2009.

[11] Committee on Standards for K-12 Engineering Education, National Academy of Engineering. *Standards for K-12 Engineering Education?* The National Academies Press, Washington, DC, 2010.

[12] Committee on Conceptual Framework for the New K-12 Science Education Standards, National Research Council. *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas.* The National Academies Press, Washington, DC, 2011.

[13] Next Generation Science Standards. "Next Generation Science Standards." Accessed October 28, 2011. http://www.nextgenscience.org/

[14] Lederman, N.G. (2007). Nature of science: past, present, and future. In S.K. Abell & N.G. Lederman (Editors), Handbook of research on science education (pp. 831-880). Mahwah, NJ: Lawrence Erlbaum Associates.

[15] Gordon, B. *America Competes Act*, 2007. http://www.gpo.gov/fdsys/pkg/PLAW-110publ69/pdf/PLAW-110publ69.pdf.

[16] Gordon, B. America COMPETES Reauthorization Act of 2010 HR 5116." In *Library of Congress*, 2010. http://www.nsf.gov/statistics/about/BILLS-111hr5116enr.pdf.

[17] Moore, J. L., and F. H. Thomas. "Computer simulation of experiments: A valuable alternative to traditional laboratory work for secondary school science teaching." *School Science Review* 64, no. 229 (1983): 641–55.

[18] Sparkes, R. A. "Microcomputers in science teaching." *School Science Review* 63, no. 224 (1982): 442–52.

[19] Dowd, P. F, T. C. Sparks, and F. L. Mitchell. "A microcomputer simulation program for demonstrating the development of insecticide resistance." *Bulletin of the ESA* 30, no. 3 (1984): 37–41.

[20] Huppert, J., S. M. Lomask, and R. Lazarowitz. "Computer simulations in the high school: Students' cognitive stages, science process skills and academic achievement in microbiology." *International Journal of Science Education* 24, no. 8 (2002): 803–821.

[21] Horwitz, P., E. Neumann, and J. Schwartz. "Teaching science at multiple levels: The GenScope program." *Communications of the ACM* 39, no. 8 (1996): 127–131.

[22] Murray, R. W. "Virtual analytical chemistry laboratories?" *Analytical Chemistry* 79, no. 3 (2007): 790.

[23] Dede, C., M. C. Salzman, and B. Loftin. "ScienceSpace: Virtual realities for learning complex and abstract scientific concepts." In *Virtual Reality Annual International Symposium, 1996, Proceedings of the IEEE 1996*, 246–252, 271. IEEE, 1996.

[24] Yang, K. Y., and J. S. Heh. "The impact of internet virtual physics laboratory instruction on the achievement in physics, science process skills and computer attitudes of 10th-grade students." *Journal of Science Education and Technology* 16, no. 5 (2007): 451–461.

[25] Sadler, P. M., H. P. Coyle, and M. Schwartz. "Engineering competitions in the middle school classroom: Key elements in developing effective design challenges." *Journal of the Learning Sciences* 9, no. 3 (2000): 299–327.

[26] Krajcik, J., K. L. McNeill, and B. J. Reiser. "Learning goals driven design model: Developing curriculum materials that align with national standards and incorporate project based pedagogy." *Science Education* 92, no. 1 (2008): 1–32.

[27] Thomas, J. W. "A review of research on project-based learning." *Autodesk Foundation* (2000). http://www.bobpearlman.org/BestPractices/PBL_Research.pdf or http://www.bie.org/research/study/review_of_project_based_learning_2000.

[28] Bransford, J. D., A. L. Brown, and R. R. Cocking. *How people learn*. National Academy Press Washington, DC, 2000.

[29] Hill, A. M., and H. A. Smith. "Practice meets theory in technology education: A case of authentic learning in the high school setting." *Journal of Technology Education* 9, no. 2 (1998). http://scholar.lib.vt.edu/ejournals/JTE/v9n2/pdf/hill.pdf.

[30] Bradford, M. "Motivating students through project-based service learning." *THE Journal (Technological Horizons In Education)* 32 (2005).

[31] Blumenfeld, P. C., E. Soloway, R. W. Marx, J. S. Krajcik, M. Guzdial, and A. Palincsar. "Motivating project-based learning: Sustaining the doing, supporting the learning." *Educational psychologist* 26, no. 3 (1991): 369-398.

[32] Linn, M. C., H. S. Lee, R. Tinker, F. Husic, and J. L. Chiu. "Teaching and assessing knowledge integration in science." *Science* 313, no. 5790 (2006): 1049–1050.

[33] Qian, G., and D. E. Alvermann. "Relationship between epistemological beliefs and conceptual change learning." *Reading & Writing Quarterly* 16, no. 1 (2000): 59–74.

[34] Hofer, B. K., and P. R. Pintrich. "The development of epistemological theories: Beliefs about knowledge and knowing and their relation to learning." *Review of educational research* 67, no. 1 (1997): 88–140.

[35] Marra, R. M., B. Palmer, and T. A. Litzinger. "The Effects of a First-Year Engineering Design Course on Student Intellectual Development as Measured by the Perry Scheme" *Journal of Engineering Education* 89, no. 1 (2000): 39–45.

[36] Antonietti, A., C. Rasi, E. Imperio, and M. Sacco. "The representation of virtual reality in education." *Education and Information Technologies* 5, no. 4 (2000): 317–327.

[37] Koretsky, M., D. Gilbuena, and A. Kirsch. "Engaging High-School Students in Engineering, Science, and Technology Using Virtual Laboratories." In *Proceedings of the 2009 American Society for Engineering Education Annual Conference & Exposition*, 2009.

[38] Bransford, J. D., and B. S. Stein. *The ideal problem solver: a guide for improving thinking, learning, and creativity*. 2nd ed. New York: W.H. Freeman, 1993.

[39] Elby, A., J. Frederiksen, C. Schwarz, and B. White. "EBAPS: Epistemological Beliefs Assessment for the Physical Sciences." Paper presented at *the Annual Conference of the American Educational Research Association*, Chicago, 1997.

[40] Owston, R. "Contextual factors that sustain innovative pedagogical practice using technology: An international study." *Journal of Educational Change* 8, no. 1 (2007): 61–77.

AUTHORS

Debra Gilbuena is a PhD Candidate in the School of Chemical, Biological, and Environmental Engineering at Oregon State University. She currently has research focused on student learning in virtual laboratories. Debra has an MBA, an MS, and 4 years of industrial experience including a position in sensor development, an area in which she holds a patent. Her dissertation is focused on the characterization and analysis of feedback in engineering education. She also has interests in the diffusion of effective educational interventions and practices.

Adam Kirsch teaches physics, chemistry, engineering, electronics, solid modeling, and physical science at Crescent Valley High School. He received his B.S. in Mechanical Engineering from the University of Washington and his M.S. in Science Education from Oregon State University. Mr. Kirsch's eight years as a licensed professional mechanical engineer within the pulp and paper industry prior to entering the teaching profession strongly influences the emphasis within his classrooms. In his eleven years as a high school teacher, Mr. Kirsch has often utilized the context of engineering and its focus upon problem solving to engage students in community-based projects.

Milo Koretsky is a professor in the School of Chemical, Biological, and Environmental Engineering at Oregon State University. He received his B.S. and M.S. degrees from UC San Diego and his Ph.D. from UC Berkeley, all in chemical engineering. He currently has research activity in areas related to thin film materials processing and engineering education and is interested in integrating technology into effective educational practices and in promoting the use of higher-level cognitive skills in engineering problem solving.