DIP: COLLABORATIVE RESEARCH: MIXED-REALITY LABS: INTEGRATING SENSORS AND SIMULATIONS TO IMPROVE LEARNING

Summary. Physical labs provide rich context and multi-sensory experiences, but often fail in showing the underlying concepts clearly. Virtual labs help focus student attention on the concepts through visual, interactive simulations, but often lack the sense of reality. By combining these two types of learning into single mixed-reality experiences, the advantages of both can be synthesized to maximize learning. The Concord Consortium and the University of Virginia propose the concept of mixed-reality labs that integrate sensors and simulations to enhance laboratory experiences in high school chemistry and physics courses. The project will develop and investigate mixed-reality cyberlearning environments that permit students to explore physical and virtual labs at the same time. The project will create four different mixed-reality laboratory activities and study student learning with them. Two of the activities use an integration strategy in which data acquired in real time from a physical experiment are used to control a virtual experiment. The advantage of this coupling is that abstract concepts or invisible processes can be visualized on the computer screen while the physical experiment is underway. Whenever the learner's hands-on interaction with the physical experiments changes the sensor measurement, the visualization in the virtual experiment will respond accordingly, creating an intimate link between the two worlds. The other integration strategy uses physical and virtual experiments in parallel, challenging the student to match the results measured by the sensors and the results computed by the simulations. The learning potential in this configuration stems from the ability to go back and forth between both worlds, adjusting the virtual experiment to match the physical experiment and then adjusting the physical experiment to test the fidelity of the virtual experiment. All the activities will be developed in collaboration with classroom teachers who teach high school physics and chemistry. Implementations of the four activities in eight classrooms will be compared to classes covering similar content.

Intellectual merit. The quality of typical laboratory experiences in U.S. science education, as concluded in *America's Lab Report* published by the National Research Council, is poor for most students. The report calls for research, development, and implementation of laboratory learning to build knowledge about how various types of lab activities may contribute to specific learning outcomes. By developing technologies and pedagogies that serve to bridge the gap between virtual and physical labs, this project will demonstrate the capacity of cyberlearning technologies for transforming inquiry in the lab. This project builds on extensive prior and current work by the proposers as well as contemporary research and development in science education. The team is internationally recognized as leaders for developing innovative probeware and simulation tools and for conducting educational research and outreach to schools worldwide.

Broader impacts. This project will add a fundamentally new instructional method to STEM education that has not yet been studied. The proposed strategies for combining physical and virtual labs are broadly useful and the insights and examples developed by this project could be applied throughout STEM education. The project's exploratory research could lead to both more extensive research of mixed-reality methods and the development of many more activities using mixed-reality experiments. Although the project uses sophisticated hardware and software, the resulting materials will be easily implemented, even in the most cash-strapped schools. Because the software will be open source and the materials made available freely from our website, the only expense to schools will be the sensors. We will ensure that the software is compatible with sensors from multiple vendors so that many schools will already have the required hardware.

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> *"Policy makers, scientists, and educators agree that high school graduates today, more than ever, need a basic understanding of science and technology in order to function effectively in an increasingly complex, technological society. Increasing this understanding will require major reforms in science education, including reforms in the laboratories that constitute a significant portion of the high school science curriculum."* — America's Lab Report: Investigations in High School Science, NRC, 2005, p.1

BACKGROUND

Laboratory experiences are indisputably a fundamental part of science education. It is primarily through the hands-on interactions with the material world that students learn about methods and processes of science and come to appreciate how scientific knowledge is acquired, proven, and applied. Unfortunately, the quality of typical laboratory experiences in current teaching practices, as concluded in *America's Lab Report* [1], is poor for most students. The report called for "research, development, and implementation of effective laboratory experiences" to understand how various types of lab activities may contribute to specific learning outcomes. In 2007, the House held a hearing to discuss problems of lab exercises in U.S. science education and highlighted how a strong hands-on experience can create scientifically literate students who become interested in pursuing science [2]. Laboratories provide indispensable opportunities to integrate science content and science practices to achieve literacy [3] and proficiency [4] in science as well as technological literacy and engineering skills [5, 6]. Improved laboratory experiences will be an important part of the new National Science Education Standards [7, 8].

ISSUES WITH PHYSICAL LABS

Data acquisition, a central piece of labs, is often conducted using probeware. Probeware uses sensors, electronic interfaces, and associated software, which can collect, process, and display data from experiments [9-11]. This provides an investigation tool for students to make their own scientific inquiries. However, inquiry-based learning is not as simple as just giving students probeware. A lab activity using probeware can still revert to "cookbook" instructions if students are not prompted to think about the meaning of their measurements.

Most existing probeware systems used for teaching science display results as numbers or charts [12, 13]. In order to understand the concepts acting in the lab, students must place these raw data into a conceptual framework. In many cases, however, there exists a wide gap between the representations of these data and the concepts intended to be learned. For example, to understand heat transfer measured by a temperature sensor, a mental image of the unseen particulate picture of thermal energy is essential; to understand the intensities measured by a magnetic field sensor, an image of the unseen electromagnetic fields is most helpful. The atoms and fields are the conceptual frameworks in these two cases, respectively. These powerful frameworks unify factual knowledge acquired from labs and allow for effective information storage, retrieval, generalization, and application [14].

If a lab activity does not result in an increased understanding of conceptual frameworks, its educational value is limited. It is, however, unrealistic to expect novice learners to be able to derive a complex concept directly from the raw data alone. Scientists can do this because they already possess the conceptual frameworks needed to process what they see in a graph or table, but learners seldom have that ability. The traditional instructional design for supporting concept development is to have students learn facts and theories through lectures and texts and then have them see how these ideas may be verified or applied in real-world situations. But this traditional instructional design is not guaranteed to close the gap. Too often the two learning activities—acquiring facts and theories from texts and lectures and experimenting in the lab—run in parallel, failing to help students develop coherent mental pictures of concepts. Even if students have studied a concept and performed well on a written exam, they can fall back on their possibly erroneous preconceptions in a lab activity, as if they had not been taught about it [14, 15].

ISSUES WITH VIRTUAL LABS

Contemporary science increasingly relies on virtual experiments[1]—computer simulation of physical experiments—to understand how the world works, especially when the physical experiments are too hard, too dangerous, or too expensive to carry out [16-18]. Virtual experiments based on accurate computational models offer an additional learning pathway to the one provided by physical experiments. Visual, interactive simulations make it possible to experiment with the embodied science in much the way we would like students to experiment in the lab [19]. Having the potential to strengthen students' conceptual frameworks, virtual labs are recognized as an important part of cyberlearning by the NSF Task Force on Cyberlearning [20].

While many educators agree that virtual labs have many affordances that foster learning [21-25], more thorough research and development need to be carried out to substantiate their effectiveness and potential [26, 27]. One problem we have identified in applying simulations to learning is that students have difficulty making connections between computer models and the world around them, even when the learning activities are carefully designed to make the connections explicit [28]. For instance, when students were asked to explain how a molecular visualization relates to the real world, they gave answers such as, "It's just a chemical reaction, really, there's no cute moral to relate it to real life" or "We are not scientists and haven't seen it really happen." These students' comments reflect typical shortcomings of virtual labs due to the lack of reality. In response to the virtualization trend in science education, the National Science Teachers Association and the American Chemical Society issued their position statements in 1999 [29] and 2008 [30], respectively, which—while acknowledging the usefulness of computers to science education—suggested that computer simulations should not completely substitute for hands-on labs. Given these concerns, the research on how students best learn from virtual labs is important for situating cyberlearning in the context of 21st century laboratory experiences [1].

GOAL AND OBJECTIVES

We see an exciting opportunity to combine the strengths of physical and virtual labs to create *mixed-reality* [31, 32] learning environments. In this project, the Concord Consortium (CC) and

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[1] Throughout this proposal, a "virtual lab" means a computer system that simulates a physical lab. A "virtual experiment" means a specific interactive activity supported by a virtual lab to learn certain science concepts. We also use "simulation" interchangeably with "virtual experiment" throughout. A virtual lab can be implemented at different levels. Virtual labs that try to mimic the look-and-feel of physical labs are commonly seen. In this proposal, we focus on virtual labs that simulate the unseen world, which powerful apparatuses in physical labs reveal. For instance, a virtual experiment at the molecular level can show how gas molecules move when pressure or temperature changes. The virtual lab in this case simulates an atomic microscope. A virtual experiment for studying heat transfer simulates an infrared thermal imager, if it shows the temperature field and its time evolution.

the University of Virginia (UVA) will join forces with the goal of developing the mixed-reality technology and investigating how it can enhance students' conceptual understanding. Teams from CC and UVA will collaborate closely on the following five project objectives:

1) **Develop sample mixed-reality technologies**. We will develop a total of four illustrative mixed-reality technologies based on two examples of each of two strategies for integrating physical and virtual labs. The first strategy is to develop software that couples the physical and virtual labs so that student activities in the physical world will influence the virtual world. This can create meaningful associations of knowledge, such as a micro-macro connection or a structure-function relationship, between the two worlds. The second strategy is to develop an integrated software system that allows students to compare data acquired by sensors and data calculated by virtual labs at the same time. This combination allows the sensor data to be contextualized and rationalized in a virtual experiment and can provide richer information and experiences.

2) **Develop integrated instructional units**. We will develop a set of instructional units that guide students to explore the four mixed-reality activities. The units will be developed for high school physics and chemistry and integrated into the science curriculum and classroom instructions. Each unit will require approximately three class periods to complete. The units will be used in field tests, revised, and used in research.

3) **Study the educational impact of mixed-reality laboratory experiences**. We will conduct a three-phase study of the affordances of mixed-reality labs and their educational effectiveness. The first phase will be a design-based observational study [33] in four pilot classes, looking for evidence that the two strategies do enhance student conceptual understanding. The second phase will be a quasi-experimental study to examine whether the mixed-reality materials are more effective at concept development than materials based on purely physical labs or purely virtual labs. The third phase will be a full implementation based on revised technologies and materials. Comparing the results of the third phase with those from earlier phases will allow us to evaluate the improved affordances and recommend design principles for effective mixed-reality labs.

4) **Prototype other mixed-reality systems.** To better understand the generality of using mixed-reality systems in education, we will explore and document as many additional systems as feasible while the project unfolds. Prototypes will be built to demonstrate the affordances. The documentations will describe the novelty of the possible educational applications and the enabling technologies.

5) **Disseminate the materials and findings**. We will disseminate our materials and findings widely. We will give talks at conferences and publish in peer-reviewed journals and teacher-oriented publications including our newsletter *@Concord*. A project website will be set up to make the project-generated technologies and materials freely available to the public. This project will use widely available sensors from leading education vendors to ensure that our materials can be used widely, and we will explore the possibility of productizing our technologies and materials with vendors (see "Industry Collaboration and a Sustainability Plan" in a later section).

The NSF Task Force on Cyberlearning has recommended "funding centers to identify effective ways to provide laboratory experiences given the power of cyberlearning technologies" (Opportunities for Action #2, p. 37) and beginning "investment in leveraging the use of virtual world and mixed-reality environments for STEM learning" (Opportunities for Action #3, p. 39) [20]. With the above goal and objectives, this project is set to answer these calls for action.

RATIONALE AND VISION

Sensors are important to science because they push the envelope of the observable world. Science, however, is not limited to physical observables. It includes unobservable objects of the mind and constructs of mathematics like fields, atoms, and quarks, which were derived from experiments. Computational science provides numerical solutions to digitally construct the unobservables according to the corresponding scientific principles and make the concepts perceivable in cyberspace. The integration of sensors and simulations through the proposed mixed-reality labs thus fills a gap in the continuum of science. It simultaneously supports inquiry in the physical world through the use of sensors and inquiry in the virtual world through the interaction with simulations. Integrating the learning in both worlds, such an approach maximally exploits the power of technology to transcend the limitations of physical labs and yet retains their tangibility to make learning physically relevant to students [34].

This new vision will contribute to the conceptualization of 21st laboratory experiences that will leverage the transformative power of cyberlearning to fundamentally improve scientific inquiry in the lab. The products of this project will also provide prototypes for the "missing pieces" in current educational technology identified in the recent *Prepare and Inspire* report by the President's Council of Advisors on Science and Technology [35] (e.g., coherent integration and interoperatability of various learning technologies).

PRIOR WORK

Development of Microcomputer-Based Laboratory Instructional Materials (1983-1987. $1,692,322. MDR-8319155. Tinker, PI). This project at TERC received funding for probeware development from the NSF Applications of Advanced Technology program. The grant originated the acronym MBL and the educational ideas it encompassed [36]. It also undertook the first research in the field and stimulated other research. This project developed and disseminated the ultrasonic motion detector and simulated some of the earliest probeware-based products. Work begun with this project continues to suffuse many projects at CC and gave birth to commercial probeware.

Molecular Workbench: Reasoning with Atomic-Scale Models (12/99–8/04. $1,364,944. REC-9980620. Berenfeld, PI). **Molecular Logic**: Bringing the Power of Molecular Models to High School Biology (2/03–6/06. $1,416,623. ESI-0242701. Berenfeld, PI). **Science of Atoms and Molecules** (10/06–5/09. $1,139,836. DRL-0628181. Berenfeld, PI, Tinker, Co-PI). **Electron Technologies**: Modeling Pico Worlds for New Careers (6/08-5/11. $898,516. DUE-0802532. Xie, PI). These projects supported the PI of the proposed project at CC to develop the *Molecular Workbench* (MW) software (mw.concord.org), a versatile modeling platform for learning many basic science concepts through virtual experiments made possible by computational physics [37-39]. In addition, MW has many characteristic features of a cyberlearning system described by the NSF Task Force on Cyberlearning [20]. It includes a Web delivery system for interactive simulations and digital curricula, an authoring system to create and customize them, embedded assessment tools to track student progresses and report to teachers, and plug-in support to incorporate new types of simulations. The PI of the proposed project at UVA, in collaboration with CC, has conducted extensive research studies to delineate the conditions under which MW simulations embedded in inquiry instruction can enhance learning outcomes through several other NSF-funded projects awarded to the University of California at Berkeley [40, 41].

Enhancing Engineering Education with Computational Thinking (10/09-9/12. $2,191,552. DRL-0918449. Xie, PI). This ongoing project (energy.concord.org) focuses on studying how computational thinking, primarily through modeling tools, can enhance engineering education in high schools. Computational fluid dynamics and sensors are used extensively to engage students in designing scale model houses that achieve energy efficiency through step-by-step improvements guided by a sequence of instructional units.

Although sensors and simulations were both used in several of our prior projects, they were used separately. The concept of mixed-reality labs that combine them represents a significant advance from our prior work. It will be the first systematic effort to fuse these different technologies to provide integral educational solutions.

MIXED-REALITY LABS: EXAMPLES

Considering the flexibility of computers, many types of mixed-reality technologies can be envisioned. In the following subsections, examples of the two different classes of mixed-reality lab environments and their affordances are sketched. These examples will be developed into full-fledged cyberlearning modules used in our research.

Strategy #1: Virtual Experiments Driven by Sensor Data

In the first class of mixed-reality labs, data obtained in real time from a physical experiment are used to control, assist, or augment a virtual experiment. For example, a change of a property that a sensor registers can instantaneously change the corresponding variable in the virtual experiment. This coupling of sensors and simulations can create rich mixed-reality laboratory experience. The advantage of this is that abstract concepts or invisible processes can be visualized on the computer screen while the physical experiment is underway. Whenever the learner's hands-on interaction with the physical experiments changes the sensor measurement, the visualization in the virtual experiment will respond accordingly, creating an intimate link between the two worlds.

Example #1: A Gas Lab

Gas laws are often demonstrated in the lab using a gas pressure sensor and/or a temperature sensor with a gas sample under a piston [42, 43]. Typically, the probeware system collects these data and shows the changes of the properties as time-varying curves. Merely observing these curves, however, does not necessarily cultivate a conceptual understanding of the kinetic molecular picture behind gas laws, which is often the learning goal.

The mixed-reality gas lab provides a straightforward solution that connects the pressure sensor or the temperature sensor to a visual molecular dynamics simulation [44] to control the pressure or temperature in the simulation (Figure 1). The simulation visualizes particles representing gas molecules in constant thermal motion. The temperature or pressure data of the gas sample are collected frequently enough to guarantee responsive real-time connections. When a new measurement is taken, the simulator is notified and a new temperature or pressure is set for the simulation. This system thus shows, in real time, the changes of molecular motion and interactions when a real-world condition changes. Students can study, for example, how the velocities of molecules, which are represented by the vectors in the visualization, change when the temperature changes. This sensor-simulation coupling embodies the idea of micro-macro relationship: It allows students to really "see" what is happening at the molecular level when they heat or cool the gas sample or push or pull the piston in the physical world. This mixed-reality activity offers a superb learning experience as if students were directly manipulating molecular motion.

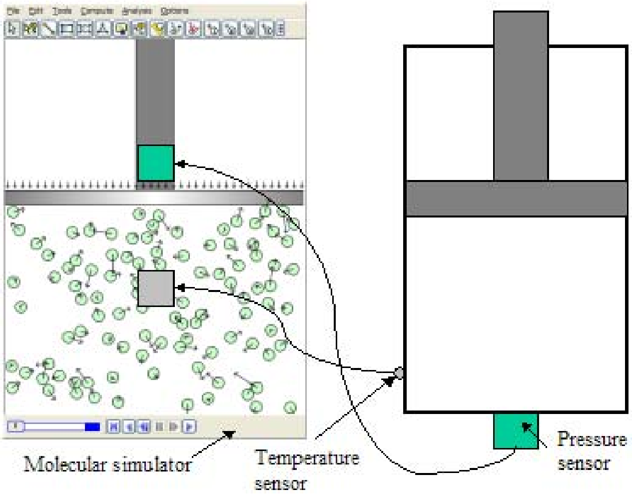

Figure 1. A fast-response temperature sensor and a gas pressure sensor are used to study gas laws with a piston system, such as a syringe. One of them can be connected to a molecular dynamics simulation to create a mixed-reality gas lab for learning the Kinetic Molecular Theory underlying the gas laws.

It is important to note that the response of a simulation to a physical change can be amplified or exaggerated by the instructional designer to illustrate qualitative differences more outstandingly. Another thing to note is that, when multiple sensors are linked to a simulation, they must represent independent variables in order to avoid conflicting controls. For instance, if the volume of the gas sample is fixed, only one sensor, either the temperature sensor or the pressure sensor, is allowed to connect to the gas simulation shown in Figure 1, as the temperature and pressure of the gas are correlated in this case according to Gay-Lussac's Law.

Example #2: Image-Based Motion Tracking and Augmented Reality

A second example involves using pattern recognition software and augmented reality techniques to attach data to moving objects in an experiment. For example, a digital camera could be used to capture the motion of an object driven by a spring or an impact. In real time, motion-tracking software would be used to locate the object. The data is then analyzed on the fly and the results used to annotate the video instantaneously. For example, a vector representing velocity, acceleration, or net force could be added to the image. A student would see the experiment augmented in real time by the addition of these vectors on the screen. Because this system responds in real time, students could perform many experiments and develop their intuitive understanding about the concepts. The example given could be applied to mechanics experiments of all kinds of motion, including few-body systems, collisions, pendulums, and vibrations. If an object has additional physical properties that cannot be readily observed by the naked eye or a camera, a physics simulator can be used to produce visualizations that augment the video. For instance, when videotaping an electroscope in action, the electrostatic field resulting from the charges detected by a charge sensor [45] could be computed by dynamically solving the Poisson equation and overlaid on the image to render a more informative picture of fields and interactions. A similar technique can be used to investigate electromagnetic induction.

Strategy #2: Comparing Physical and Virtual Experiments

A second class of mixed-reality designs involves engaging students in comparing the results measured by sensors and the results computed by simulations. Ideally, the comparison will be done just as the experiment is being performed. When synchronizing a physical experiment and a virtual experiment is not possible or not preferred, students should be provided with the convenience of comparing data from multiple runs in both the physical and virtual worlds. The learning potential in this configuration stems from the ability to go back and forth between both worlds, adjusting the virtual experiment to match the physical experiment and then adjusting the physical experiment to test the fidelity of the virtual experiment. The parameters in a well-designed virtual experiment help students understand the role of invisible properties such as the thermal conductivity or the friction coefficient. A well-designed physical experiment allows students to vary these properties and test whether the virtual experiment reflects these changes.

Example #3: A Simple Pendulum

In this experiment, students capture the motion of a pendulum using a rotary motion sensor [46] as both the pendulum support bearing and angle detector. The data from the sensor is displayed in a graph against time. The simulation displays a virtual pendulum that models the real one and generates a second curve on the same graph. Students can explore the effects of mass, length, and starting angle on period by matching data from the sensor and from the simulation.

Students will quickly notice the effect of friction as the pendulum swings lower each time. Their task is to set up a simulation that fits that behavior. There are two sources of damping forces: the air friction and the sliding friction of the bearing, both of which are modeled in a mechanics simulation. By adjusting these two parameters, students can discover that the two kinds of friction result in different behaviors of decay. The envelope of the graph with air friction is a decaying exponential, whereas when the sliding friction dominates, the envelope is a straight line. Trying to "fit" the data with the simulation will lead students to discover which type of friction dominates. To investigate this further, they could lubricate the bearing or hinder its rotation.

This simple interplay between physical and virtual experiments demonstrates how it is possible for students to use a simulation to detect otherwise invisible effects and verify their findings through additional experimentation. This integration enriches the lab experiences and gives students access to abstractions that are not immediately evident.

Example #4: Understanding Heating and Cooling of a House

An example of another way to link physical and virtual experiments uses a computational fluid dynamics simulator called *Energy2D* [47], which is under development by the PI at CC. This example engages students in learning heat transfer. Students measure the air temperature inside a scale model house that is heated by a lamp cycled on and off. These data are plotted in a graph of temperature against time. Students can experiment with different duty cycles, outdoor temperature, and insulation. They can also measure the temperature at different locations in the house (Figure 2). While this is a common activity [48, 49], the physical origin of the resulting temperature data are not obvious to students.

In a mixed-reality environment, *Energy2D* visualizes the temperature distribution and heat flow throughout the house based on the shape of the structure, air circulation, heating by the lamp, and losses to the outside. The user can set the locations where the calculated temperature will be sampled. The sampled temperatures are then superimposed on the same graph in which the actual data from the temperature sensors are also displayed.

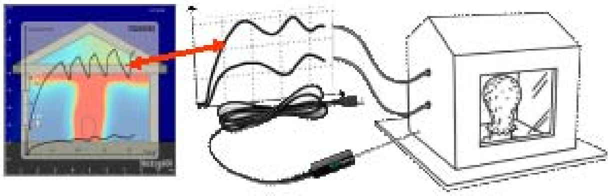

Figure 2. This illustration shows an example of data from a simulation being compared to lab data. The scale model house on the right generates temperature-time graphs near the ceiling and floor shown in the center. The temperatures at similar places generated by the computational fluid dynamics simulation on the left are sampled to generate comparable graphs, shown over the visualization. The simulation makes it obvious why the ceiling temperatures are so much higher and suggests other locations within the scale model house to measure. Students could determine whether there is a narrow rising column of hot air, whether it spreads out across the top, and where to place better insulation or fans.

By adjusting physically meaningful parameters such as the insulation values and the heat capacities of the walls, roof, and foundation, students can tune the calculated results until they agree with the sensor data qualitatively. Because the simulation is only two-dimensional, it is impossible to exactly fit the curves. But when their shapes can be matched using data from several locations, it is a good approximation to reality.

The thermal visualization provides a conceptual framework that helps students make sense of the sensor data. It is far more informative and comprehensible than the temperature curves alone. It illustrates the underlying science concepts that—besides explaining the curves—are actually what the lab is intend to teach. For instance, the reason why the lower sensor measures lower temperature than the upper sensor in the scale model house becomes obvious in the visual simulation—natural thermal convection causes the temperature to be higher near the roof than near the floor (see the image on the left of Figure 2).

Mixed Reality Across Science Disciplines

Many other sensor-simulation couplings are possible. For example, a relative humidity sensor [50] and a temperature sensor or a salinity sensor [51] can be combined with a molecular dynamics simulation to study the effect of temperature or salinity on the evaporation rate. An anemometer [52] can be linked to a computational fluid dynamics simulation to investigate fluid flow. An electrical conductivity probe [53] can be linked to a biomolecular simulation to study the diffusion of ions through membranes. An electrical current probe [54] and a differential voltage probe [55] can be integrated with a circuit simulator to explore series and parallel circuits and much more. A motion detector [56] and a force sensor [57] can be used with a mechanics simulator to study kinematics, statics, or dynamics. An electromagnetic field sensor [58] can be used with an electrodynamics simulator to study many invisible field effects of electromagnetism. This project will explore these intriguing integrations and build a wide variety of prototypes that will constitute a solid technological and scientific foundation to support our research on mixed-reality labs.

Theoretical and Pedagogical Considerations

Mixed-reality experiments such as the ones sketched above share a number of characteristics. In all the examples, sensors and simulations are integrated to enrich laboratory experiences. The simulations help students perceive the underlying causes that are responsible for what the sensors measure. All the mechanisms are invisible—the forces among atoms, velocity/acceleration vectors, electromagnetic fields, the friction in a pendulum, and the flow of air and heat. The simulations visualize them and lead students to construct derivational linkages [59] between concepts embodied in them and the physical measurements. During the construction process, misconceptions will surface as they may result in contradictions. Reconciliation of conflicting interpretations provides opportunities to fix the misconceptions.

From a cognitive perspective, having both sensor data and computed data available at the same time should reduce extraneous cognitive load and increase germane cognitive load. Students do not have to rely on their memory of one when using the other. Instead, students can focus on learning how the two relate to each other and the targeted concepts they both connect to. Conventional lab tasks can result in students paying too much attention to logistics or small details, perceiving data as a collection of disconnected points. Early probe research suggests that even a delay of 20-30 seconds between an experiment and its graphical representation degrades learning [60]. This suggests near-simultaneity will allow students to devote more cognitive resources to synthesizing, distinguishing, and reflecting upon information. It is also possible that because simulations can be controlled by only a few parameters, once students are familiar with a simulation the relatively few parameters add little cognitive load to the mixed-reality context.

RESEARCH QUESTIONS, DESIGNS, PLANS, AND OUTCOMES

Questions. Project research will investigate whether the integration of virtual and physical experiments through mixed-reality strategies can promote deeper conceptual understanding. There have been few comparable studies. There is some research on the effectiveness of probeware [10, 11, 61, 62] and ample studies on the use of simulations of all kinds [63-68]. A number of studies have looked at the relative effectiveness of virtual and physical labs [21-25] and even the benefit of combining distinct virtual and physical labs [69]. But there have been no studies on how virtual and physical experiments can work together to transform student learning.

In the face of this lack of prior research, we plan formative research designed to identify important issues for later, detailed studies. We will focus on the following research questions:

1) How do students use mixed-reality activities? What kinds of new opportunities and practices do the mixed-reality labs afford students and teachers? How do these affordances correlate with learning and epistemologies of science?
2) How can mixed-reality labs promote deep and coherent learning of science content and processes? Are mixed-reality activities more effective than similar activities that do not combine sensors and simulations?
3) What kinds of teacher and curricular support can best enhance teaching and learning based on mixed-reality labs?

Research sites. The project will work with teacher/developers near CC and UVA. Letters of commitment from districts and teachers are included in the Supplementary Documents. The four examples described above will be developed into complete cyberlearning activities suitable for high school physical sciences. They will be linked to typical standards for these courses [70] so that teachers will be comfortable substituting our activities for their current activities (see “Other Project Plans” for more details). Each activity will require three class periods.

Observational methods. To understand how students use mixed-reality materials, we will observe classes and use technology to monitor student actions. We will develop observational protocols and scoring rubrics to capture the following features:

1) Engagement. Observers will note the time students spend using the mixed-reality activities, and their apparent level of interest.
2) Use of mixed-reality affordances. Observers will note the frequency a group shifts attention between the virtual and physical experiments and record any evidence that observations from one environment are transferred or applied to the other.
3) Inquiry skills. Observers will note cases in which students developed a hunch about some aspect of the physical or virtual experiment, whether the hunch stemmed from the physical or virtual experiment, how the students conduct subsequent experiments, and the conclusions drawn.

Because our ability to observe classes will be limited, we will supplement observations with automatic analysis of student logs that are generated as students use the activities. The following are strategies for inferring the importance of the features above by analyzing student interactions with the mixed-reality labs:

1) Engagement. We will record the total time each student or student group spends on the physical and virtual experiments in an activity.
2) Use of mixed-reality affordances. The software can determine whether students used both physical and virtual labs and how frequently they shift from one to the other.
3) Inquiry skills. For virtual labs, the system can determine whether, during a virtual experiment, one parameter was changed at time and whether the full range of parameters was explored. Through monitoring the use of the probeware, the system can note when students run multiple physical experiments. From this information, one can infer how well students conducted the mixed-reality experiments and whether their explorations were more extensive.

These automatic measures are no substitute for an experienced observer, but they can be used with every student or student group in every class. To estimate the reliability of these measures, we will compare observer scores with scores generated automatically.

Outcome measures. The Knowledge Integration perspective [41, 71] provides an appropriate learning framework for evaluating students' concept acquisition. Knowledge integration is the process of synthesizing multiple ideas into a common model for understanding a given question or topic. Assessments based on the knowledge integration framework probe the presence of just the kind of coherent learning that we expect mixed-reality environments to foster.

Assessments based on knowledge integration typically consist of two-part questions. The first part is multiple choices and asks for a prediction using distractors carefully chosen from common student ideas. In the second part students provide an open-response justification for their choice. All justifications are scored the same way on a zero-to-four-point scale. The highest score is reserved for responses that correctly link two or more relevant ideas or concepts to justify their responses. Lower scores are given for well-defined departures from this ideal. Knowledge integration scoring is more sensitive than multiple-choice items and is effective for a wider range of student knowledge [41].

We will develop embedded assessments and post-tests for each of the four activities using knowledge integration items. The multiple-choice parts of the items will be automatically scored and made available immediately to teachers for grading. The open-ended items will be scored by staff and used to determine the kinds of concepts and connections that students make with the mixed-reality labs.

Other measures. One of the inputs to the planned analysis will be student prior knowledge. We will develop pre-test for each activity consisting of a short, general assessment of background knowledge using items from the many concept inventories available in physical sciences [72, 73]. We will also include items on the pre-test and post-test to measure students' epistemologies of science and use of conceptual models [74].

Research design. Project research will have three phases, one for each year of the project. In the first year, as the software and curriculum for the four planned activities are being developed, parts will be tested informally in classrooms of participating teachers and with individual student groups in our facilities. At the same time, we will develop, test, and refine our observational protocols, scoring rubrics, and outcome measures. Each of the four activities will have an associated teacher who will participate with staff in the development and informal testing of the activities in this first year.

Also in the first year four additional teachers will be recruited for research in the following two years selected, so that there are four teachers near CC and four more near UVA. In selecting these teachers, we will ensure that the teachers reach diverse communities. In the summer, these eight teachers will receive four days of professional development to equip them with the pedagogical content knowledge needed to use the activities effectively.

During the second year, the four completed activities, associated assessments, and electronic logging algorithms will be tested by four of the teacher-leaders. Because most of these teachers will have multiple classes, this test will encompass at least 300 students. Teachers will be required to test at least three of the activities and their pre- and post-assessments, so each one will be used by at least 180 students. Each classroom will be observed at least twice when each of the activities is being used. Teachers will keep logs of their classroom observations and will be interviewed shortly after each activity is completed. The logs and interviews will help inform the revision of the materials prior to testing in the third year.

The additional four teachers' classes will serve as a comparison group during the second year. The participating teachers will administer the same pre-tests and post-tests, but use either only virtual or only physical activities. From these groups we will compare the affordances and the learning outcomes of the mixed-reality labs.

In the third year, revised activities and assessments will be used in a final study with all eight teachers that participated in year two using the mixed-reality materials. The second year a teacher uses novel materials is often far more effective because the teacher understands the content and pedagogy better. Therefore, any impact of the mixed-reality materials should be more pronounced in this year for the original four teachers.

Analysis. Because this is early-stage research, we will use a variety of exploratory data analysis techniques to look for patterns in the data. The primary statistical technique will be to use linear regression on the outcome scores using student baseline pre-test scores, and the three scores obtained from observation and student logs (i. e., engagement, use of mixed-reality affordances, and inquiry skills). The analysis will be applied to each of the four activities separately and to combined scores for all activities. We will compare students of first-year teachers with students of second-year teachers and conduct design experiments based on the results of the efficacy studies in year two. It is not feasible to test a hierarchical model, so the effect of teachers and schools will not be considered in this analysis, but it will be able to suggest trends for further research.

OTHER PROJECT PLANS

Developing the Mixed-Reality Technologies

The development of the mixed-reality technologies involves designing the laboratory systems, building the application programming interfaces between sensors and simulators, adding the software capacities needed to integrate them, and creating deployment and assessment solutions. In some cases, a prototype apparatus, a new type of sensor, a new driver for an existing sensor, and a new simulator will need to be created. For the sensor part, we will work closely with our industry partners to ensure that our technologies will be based on affordable products and eventually become stable and scalable.

Developing the Integrated Instructional Units

Any technology, however sophisticated, must be integrated into the curriculum in order for its potential to be fully realized. Lab activities using mixed-reality technologies are no exceptions. Drawing on principles of learning derived from cognitive science, *America's Lab Report* [1] proposed the concept of "integrated instructional units," which is a strategy for connecting laboratory experiences with other types of instruction. The report recommended four design principles: 1) Design with clear learning outcomes in mind; 2) Thoughtfully sequence lab activities into the flow of classroom science instruction; 3) Integrate learning of science content with learning of science practices; 4) Incorporate ongoing student reflection and discussion. These design principles will guide our curriculum development and implementation. The science topics to which the technology apply will be selected from the Massachusetts Science and Technology/Engineering Curriculum Framework [70]. Our instructional units will draw upon widely used curricula, such as the Vernier Curricula [12], Active Physics [48], Great Explorations in Math and Science (GEMS) [75], and Full Option Science Systems (FOSS) [76]. Together with the supporting mixed-reality technologies, they will be iteratively developed, tested, and revised through design experiments [33].

Industry Collaboration and a Sustainability Plan

The proposed project is a close collaboration between CC/UVA and major vendors of sensors and lab supplies including PASCO and Vernier. Both companies are interested in the concept of mixed-reality labs and see this innovation as a potentially important contribution to the future of their product lines (see letters from PASCO and Vernier's representatives). The software and curriculum to be developed in this project might eventually be integrated into the collaborating companies' future commercial products and thus become sustainable.

Project Evaluation

Formative evaluation will assess the degree to which the project activities and implementations align with the project plan, and will justify and describe any substantive changes. Formative evaluations will also measure how closely project activities follow the outlined timeline, with the specified personnel, and within the proposed budget. In each project year, we will work with the

Advisory Board members to evaluate how project activities lead to achieving the project goals and objectives.

PROJECT SCHEDULE AND MANAGEMENT

In the Program Solicitation, NSF recommends 4-5 year duration for a Design and Implementation Project. However, we have contacted NSF and obtained a permission to shorten it to three years.

The project will consist of cycles for literature review, technology development, curriculum development, teacher training, field tests, a design-based study, a quasi-experimental controlled study, dissemination, and evaluation, scheduled as follows.

> **October 1, 2011 - September 30, 2012:** We will focus on developing the mixed-reality technologies and the integrated instructional units they support. Following the framework of design-based research and in collaboration with the teacher-designers, we will create, test, and iterate our hardware, software, instructional units, and design principles.
>
> **October 1, 2012 - September 30, 2013:** Our development and design experiments will continue throughout this year. We will design the pre/post tests and the classroom observation protocols. A quasi-experimental study will be conducted in this year, as described above.
>
> **October 1, 2013 - September 30, 2014:** As described earlier, we will focus on more field tests, revisions, data collection, and data analysis. Our mixed-reality technologies will mature and a non-commercial version will be made freely available online.

Throughout the three project years, CC staff will manage the project and coordinate with UVA staff to ensure that the project follows the above timeline. Each year the Advisory Board will spend two days meeting with the staff and partners to discuss the progress, make suggestions, and evaluate the project.

PROJECT PERSONNEL

The Advisory Board

An Advisory Board consisting of prominent educators, researchers, and scientists across the nation will oversee this project. The advisors will hold a two-day meeting with the staff annually to review the technology progress, the instructional units, the research plans, and the results. This exceptional Advisory Board will also serve as the external evaluator. They will ensure that the research study is properly conducted according to the proposed timeline, the instructional units are scientifically accurate and pedagogically sound, and the research data are appropriately collected and analyzed. They will compile a report after each meeting that will include recommendations addressed to the staff and forwarded to the cognizant program officer. The advisors are:

> **Matthew Anthes-Washburn** is Physics Educational Technology Specialist at Vernier. Matthew has extensive experience in high school science and successful educational technology. He will advise us on the integration with his company's products.
>
> **Dr. John Belcher** is Professor of Physics and Director of the Center for Educational Computing Initiatives at MIT. An originator of the TEAL Project, he is heavily involved in the effort to reform introductory physics at MIT. He will advise us on strategies for effectively integrating cyberlearning into lab education.

Dr. Wayne Grant is Chief Education Officer at PASCO. An expert in human computer interaction, he will advise us on the integration with his company's products.

Dr. Jeffrey Grossman is Professor of Materials Science and Engineering at MIT. As a computational scientist interested in science education, he will advise us on developing cutting-edge computational models to construct better virtual reality in science.

Michael Hacker is Co-Director of the Center for Technological Literacy at Hofstra University. His team develops and researches the academic potential of a hybrid instructional model that infuses computer simulations, modeling, and educational gaming into middle school technology education programs. He will advise us on the educational applications of virtual world technologies and game-like environments.

Dr. Mable Kinzie is Associate Professor of Education at the University of Virginia. Specializing in user-centered instructional design, she will help us apply learning and psychosocial theories to ensure instructional effectiveness.

Dr. Marcia Linn is Professor of Development and Cognition specializing in STEM education at the University of California, Berkeley. She is a member of the National Academy of Education and a Fellow of the American Association for the Advancement of Science, the American Psychological Association, and the Association for Psychological Science. A committee member of the NSF Task Force on Cyberlearning, she will ensure that the overall direction of this project follows NSF's grand visions about cyberlearning.

Dr. Uri Wilensky is Professor of Learning Sciences and Computer Science at Northwestern University. He has authored numerous software packages including the NetLogo modeling software. His recent work on integrating agent-based models, real-world sensing, and collaborative networks will provide precious inputs to this project.

Staff at the Concord Consortium

Dr. Charles Xie will serve as the PI at CC. A physicist by training and an educational technologist by profession, he has created a series of leading-edge educational modeling tools based on contemporary research in computational physics: *Energy2D* is one of the world's first interactive computational fluid dynamics tools for modeling heat and fluid flow in complex structures; *Quantum Workbench* is one of the world's first interactive quantum dynamics simulation tools that explain many quantum concepts in chemistry, physics, and nanoscience; *Molecular Workbench* is perhaps the most popular interactive molecular dynamics simulation tool that teaches many concepts across science disciplines. These tools have reached hundreds of thousands of students worldwide and are becoming a useful part of the cyberlearning infrastructure for science education. Leading several research studies on the effectiveness of educational technology, Charles actively collaborates with educational researchers to engineer research plans that will probe into conceptual understanding in science learning. He will lead the overall research and development of this project, besides committing a substantial part of his time to computer programming and curriculum development. Charles holds a Ph.D. in materials science and engineering from the University of Science and Technology, Beijing.

Edmund Hazzard will serve as the Co-PI at CC. Edmund is an expert on the educational applications of models and sensors and has worked as a senior curriculum developer on six NSF-funded projects at CC. He holds a B.S. in physics from Haverford College, a

Master of Architecture from the University of California, Berkeley, and an M.A. in teaching from Tufts University. He will lead the curriculum development.

Dr. Robert Tinker, President Emeritus and founder of CC, will serve as a senior advisor to this project. Internationally recognized as a pioneer in constructivist uses of educational technology, he invented the probeware and Network Science concepts. More recently, he has spearheaded the development of powerful computational models that students can explore. He holds a Ph.D. in experimental low-temperature physics from MIT.

Dr. Saeid Nourian will be the principal computer scientist. Prior to joining CC, he has conducted research in 3D graphics, haptic interface, and other virtual reality technologies. Saeid holds a Ph.D. in computer science from the University of Ottawa. He will lead the development of human-computer interface for the mixed-reality technologies.

Carolyn Staudt will lead the teacher professional development and coordination with participating schools. She has worked extensively on the educational uses of probes and handheld computers. She holds a Master's of Education from Kent State University and was the 1990 Christa McAuliffe Fellow. She is currently the PI for several NSF-funded projects at CC, which all involve the educational applications of models and sensors.

Staff at the University of Virginia

Dr. Jennifer L. Chiu, Assistant Professor in STEM Education, Curry School of Education, will serve as the PI at the University of Virginia. She will lead the educational research in this project. Jennifer holds a B.S. in engineering from Stanford University and a Ph.D. in science education from the University of California, Berkeley, and was formerly a high school math and science teacher. Jennifer investigates how technology-based inquiry curricula featuring dynamic visualizations can transform the way learners understand scientific phenomena, increase access to science, and help diverse learners develop complex science understanding and learning skills. She has implemented inquiry science curricula with demonstrated learning gains across the country for the past six years.

The Collaboration Plan

In this collaborative project, the CC group will be responsible for developing the cyber-enabled probeware, the assessment technologies, and the curriculum materials, whereas the UVA group will lead the educational research part. As the boundary between the development and research is not (and should not be) clear cut, both groups will be involved in all tasks and in all phases (e.g., the instructional units will have formative embedded assessments that are the result of collaboration between the curriculum developers and the educational researchers). Hence, the roles of all the participants specified above are only approximate descriptions. To coordinate our day-to-day work, a weekly videoconference will be held between the CC and UVA groups. A Basecamp site will be set up to share information and manage the project online. The two groups will gather at the annual Advisory Board meeting to meet with the advisors, report on progress, and work out improvement plans. During the design experiment phase, UVA and CC staff will travel to Massachusetts and Virginia test sites to work with participating teachers. A postdoc from UVA will visit CC for two weeks each year to collaborate closely with the CC staff. CC and UVA investigators will jointly present at conferences and co-author papers for publications. The CC and UVA budgets both include items that support these activities.

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