J Sci Educ Technol (2009) 18:501–517
DOI 10.1007/s10956-009-9166-2

Teaching and Learning in the Mixed-Reality Science Classroom

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Abstract As emerging technologies become increasingly inexpensive and robust, there is an exciting opportunity to move beyond general purpose computing platforms to realize a new generation of K-12 technology-based learning environments. Mixed-reality technologies integrate real world components with interactive digital media to offer new potential to combine best practices in traditional science learning with the powerful affordances of audio/visual simulations. This paper introduces the realization of a learning environment called SMALLab, the Situated Multimedia Arts Learning Laboratory. We present a recent teaching experiment for high school chemistry students. A mix of qualitative and quantitative research documents the efficacy of this approach for students and teachers. We conclude that mixed-reality learning is viable in mainstream high school classrooms and that students can achieve significant learning gains when this technology is co-designed with educators.

Keywords Inquiry learning · Interactivity · Digital media · Mixed-reality · Chemistry · Titration

Introduction

Interdisciplinary researchers across the domains of Education, Digital Media, and Human Computer Interaction (HCI) are currently developing next generation digital tools and technologies that can potentially strengthen social interactions between students and teachers. A primary focus of this work is at the level of the interface, where new modes of interaction transcend traditional desktop and computing console paradigms. Dourish (2001) recognizes the recent release of Nintendo DS and Wii as visible evidence of this trend and discusses the trend with emphasis on the new social and interaction affordances of so-called embodied computing interfaces. In order for this research to achieve broad impact on K-12 learning, we must purposefully design a new generation of learning environments that incorporate a contemporary understanding of best practices in science education and are evaluated through empirical research in today's science classrooms. To meet this need, our research team has taken a holistic approach to designing and creating new collaborative and interactive digital media. This article presents recent results regarding the impact of a new kind of learning environment, the Situated Multimedia Arts Learning Lab (*SMALLab*).

What is SMALLab?

SMALLab is a mixed-reality environment developed by a collaborative team that includes researchers from education, psychology, interactive media, computer science, and

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Electronic supplementary material The online version of this article (doi:10.1007/s10956-009-9166-2) contains supplementary material, which is available to authorized users.

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the arts. By *mixed-reality*, we mean the integration of physical manipulation objects, 3D physical gestures, and digitally-mediated components where the physical body functions as an expressive interface (Birchfield et al. 2006). Within *SMALLab*, students use a set of "glowballs" and wireless peripherals to interact in real time with each other and with dynamic visual, textual, physical and sonic media through full body 3D movements and gestures. For example, as students work on a spring physics scenario, they are immersed in a complex physics simulation that activates multiple sensory inputs to engage students' attention. They can *hear* the sound of a spring picking up speed, see projected bodies moving across the floor, *feel* a physical ball in their own hands, giving them an opportunity to integrate how a projected ball moves in relation to their own body as they construct a robust conceptual model of the motion system.

SMALLab is a highly collaborative space. It builds upon prior work in the domain of social computing interfaces (Dourish 2001) in that participants can freely enter and exit the space without the need for wearing specialized display or sensing devices such as head-mounted displays or motion capture suits. As shown in Fig. 1, participants seated or standing around *SMALLab* can readily see and hear the dynamic media, and they can communicate directly with their peers in the active space. As such, *SMALLab* establishes a porous relationship between the mediated space and the larger physical learning environment.

Physically, *SMALLab*, is an open cube-shaped space with the following sensing and feedback equipment: a 3D object tracking system, a top-mounted video projector providing real time visual feedback, four audio speakers for surround sound feedback, and an array of tracked physical objects (*glowballs*). A networked computing cluster with custom software drives the interactive system. In past work our team has deployed *SMALLab* in a series of pilot programs regional school and museum programs (Cuthbertson et al. 2007; Birchfield et al. 2008a; Hatton et al. 2008). *SMALLab* is a scalable architecture designed to address the real world financial and logistical constraints of today's classrooms and community centers. All components can be purchased off-the-shelf to ensure that the system is robust and easy to maintain, and the entire system can be purchased and installed for approximately the same cost as a typical desktop computer lab.

Fig. 1 *SMALLab* in the mixed-reality science classroom

SMALLab's affordances can be harnessed to improve science education. To test the environment's effectiveness in the science classroom, we designed a teaching experiment around a learning scenario that synthesizes teacher preferences with best practices in science instruction and collaborative social discourse. The experiment's three major goals were to develop a learning scenario to advance chemistry learning and understanding; to support best practices in science education via guided inquiry; and to demonstrate that a semi-immersive mixed-reality platform is effective for collaborative learning in a conventional K-12 classroom. During the experiment, we sought evidence of gains in student achievement and reasoning; distributed cognition through collaborative social discourse; conceptual blending (Fauconnier and Turner 2002) between molecular concepts and the physical-digital domain; and measurable improvements in teacher practice.

This article begins with a review of inquiry-based instruction, benefits of *SMALLab* that extend beyond other computerized formats, and our methodology, which includes the collaborative design process, scenario description and experiment implementation. The article then presents and discusses findings from coded transcripts and pre-/post-tests performed on both students and teachers.

Theoretical Basis

Based on observations of pilot students in a series of early experiments (Birchfield et al. 2008a, b; Hatton et al. 2008), our team has created a list of best practices for *SMALLab* teaching and learning. In this experiment, we use a subset of these practices as a design imperative framework focused on science and technology learning environments. These imperatives establish that: (1) an inquiry-based approach to teaching and learning stays central to the science classroom; (2) opportunities for distributed cognition and conceptual blending through whole-group socio-collaborative discourse are emphasized and permeate the learning environment; and (3) interactive digital media is purposefully designed to promote conceptual learning in a hybrid manner not easily acquired through traditional means (i.e., not exclusively through physical labs or desktop computer applications). These design imperatives are grounded by contemporary research across education and human–computer interaction.

Inquiry and Modeling Instruction in Science Classrooms

The National Science Education Standards [National Research Council (U.S.) 1996] has embraced "science as inquiry" as a central component of classroom learning. Inquiry enables students to work creatively and reflectively in the scientific process and has been demonstrated to advance students' ability to think critically, problem-solve, communicate, construct and apply scientific models (Llewellyn 2005). Haury observes that "classrooms where students are encouraged to make meaning… are generally involved in 'developing and restructuring [their] knowledge schemes through experiences with phenomena, through exploratory talk and teacher intervention" (Haury 1993). The Modeling Instruction program (Hestenes 1992, 1996) outlines a well-defined, proven approach to inquiry-based teaching and learning, identifying activities and instruction methods for student-centered, collaborative work. Our work integrates this approach with emerging digital media for standards-based content learning.

Socio-Collaborative Learning: Distributed Cognition and Conceptual Blending

Extensive research has shown the efficacy of collaborative and cooperative learning (Mesch et al. 1988; Brown and Palinscar 1989; Brown et al. 1989; Lave and Wenger 1990; Slavin 1995, 1996; Hestenes 1996; Baker and Piburn 1997; Hollan et al. 2000; Watson and Chick 2001; Megowan 2007), resulting in an increasing trend toward social and collaborative learning experiences in science education. A comparison of individualistic and competitive approaches show compelling evidence that collaborative learning is superior in many respects. Collaborative learning generates significantly higher achievement outcomes, higher-level reasoning, better retention, improved motivation, and better social skills than traditional didactics (Johnson and Johnson 1984, 1989, 1991). It is understood that improved learning, however, does not simply emerge from placing students in groups or imposing tools that accommodate multiple users. To achieve this higher-level thinking and learning, collaborative learning must be structured around well-designed tools, activities and mentoring.

Students who are solving a problem call upon a variety of resources, both mental and physical. They may graph or draw a diagram, make calculations, draw on prior knowledge or experience of a similar problem, or turn to peers for help. This collection of resources transcends the bounds of the individual. To study cognition in this context, we must employ a theoretical model and unit of analysis that allows for the inclusion of tools, artifacts, representations and other people in addition to a single individual's mental models. The Theory of Distributed Cognition (Hollan et al. 2000) provides an apt description of this group dynamic. Fauconnier and Turner's concept of Conceptual Blending (Fauconnier and Turner 2002) also grants a useful framework for understanding the reasoning processes that take place within such units of analysis (Megowan and Zandieh 2005). This theory divides this type of cognition into three phases: (1) mapping thoughts from input spaces (e.g., a chemistry concept or a representation of a geometric shape such as a sphere) into a blended space (e.g., an image of molecules in a beaker of water) which may include anchoring the concepts using words, pictures, diagrams or other tools, (2) filling in details and coordinating elements from the two input spaces (e.g., applying the rules that govern chemical reactions and molecular motion) in order to complete the new knowledge structure in a blended space, and finally (3) elaborating or manipulating the newly assembled concept (e.g., adding reactants and observing what products result) to see what new insights it reveals. This last step is often called "running the blend".

Interactive Digital Media for Science Learning

A number of initiatives (Chemical Education Research Group 2008; Perkins et al. 2006) have demonstrated that digital media can benefit science learning across multiple content areas. In studying these examples and others, we have identified three key features of well-designed interactive digital media.

First, digital media can be used to *generate multimodal representations of complex concepts* (e.g., visual, textual, sonic). Garcia-Ruiz and Gutierrez-Pulido (2005) have published a substantial review of computer software and virtual environments that support learning and comprehension of molecular information and combine auditory display (Hermann and Hunt 2005) with visual representation. Their work highlights auditory displays used for applications such as recognizing pattern repetitions in DNA analysis (Ohno and Ohno 1986), the use of haptic and visual modalities for understanding and performing protein docking in an immersive virtual environment (Brooks et al. 1990), and learning activities where students created musical compositions by mapping notes onto DNA base sequences (Miner and Della Villa 1997). In these applications, chemical reactions, molecular bonds and patterns are represented, highlighted, or clarified through multimodal representations. There is also compelling evidence that interactive graphing calculators and motion detectors can successfully aid students in moving between real world phenomena and these types of abstract representations (Lapp and Cyrus 2000; Radford et al. 2003). Our own work builds upon this prior work.

Second, digital media can *represent dynamic processes at multiple temporal and spatial resolutions*. This is a powerful feature for the study of complex systems in particular because interactive tools empower students to rapidly move between multiple levels of detail and abstraction (e.g., microscopic rendering vs. high-level process rendering) that would not otherwise be possible. This is critical to learning as it enables students to zoom in to see details and zoom out to view the "bigger picture" (Megowan 2007). Christopher Dede's *ScienceSpace*'*s Immersive Virtual Worlds* (Dede et al. 1997, 1999) offer working examples of learning environments that leverage virtual reality and multisensory cues to allow users to explore scientific concepts (e.g., electromagnetic fields, gravity, and chemical bonding) by interacting with spatial representations from various frames of reference.

Third, digital media can *provide students and teachers with high-level control* over processes or simulations they are studying (e.g., the ability to start, pause, play, and reset). Kara and Yesilyurt present several examples of learning environments that can be used to improve the teaching of scientific processes in biology. They highlight that the "computer enables repeated trials of an experiment with considerable ease in a limited time, provides immediate feedback, allows simultaneous observation of graphical representations, and offers a flexible environment that enables students to proceed with their own plans" (Kara and Yesilyurt 2008). This type of control means that students and teachers can pause and resume a process, opening up space for discussions and inquiry at the exactly the moment that it arises. The Concord Consortium's *Molecular Workbench* (Pallant and Tinker 2004; Tinker and Xie 2008) is one example of a desktop computer application that enables a student to change parameters, pause, and play back chemical atomic movement through interactive simulations.

A Potential Gap Between Real World and Digital Environments

Though there are potential benefits to using interactive digital media, technology's promise of significantly increasing learning is not always fulfilled. In recent years, desktop computers have become permanent fixtures in today's science classroom (Gee 2007). The movement to provide this type of broad technology access has had, in many ways, a positive and transformative effect on the practice of science teaching and learning. Opportunities to think beyond the computer desktop, however, must grow in order for technology to take advantage of powerful social features that already exist in the traditional science classroom. For example, science labs can be highly collaborative activities designed to advance learning by harnessing students' innate social and collaborative capabilities (Roth et al. 1996). This contrasts with the traditional desktop computing paradigm, where the standard mouse/keyboard and screen interface is inherently designed around single user interaction (Dourish 2001). A science lab with an array of desktop computers can sometimes lead to cases where there is disconnect between students' highly socio-collaborative experiences with physical tools and their use of digital tools that potentially isolate them from their peers. As an example, we refer back to the work at Iowa State University (Chemical Education Research Group 2008). The site contains numerous well-designed digital media areas that address many of the same learning goals in chemistry that are the focus of our study. However, the site's interface and interactive features are constrained to the browser-based learning environment.

Presently, there is emerging research targeted at transforming the computing interface itself. This invites an exciting opportunity to help close the gap between students' experiences in the real world and in the technology environment, to move beyond conventional computing platforms and toward mixed-reality platforms such as *SMALLab*, and to reach a new stage in the evolution of technology-based teaching and learning. Our own research is rooted in this context, seeking to advance the quality of human-to-human interaction within technology-based learning environments. As illustrated in Fig. 1, we are working toward a vision of the next wave of technology integration where the powerful affordances of mixed-reality technologies are wed with successful approaches for hands-on, collaborative learning in the classroom. We term this integration as the mixed-reality science classroom. By way of example, we now present a recent *SMALLab* teaching experiment.

Methodology

In Summer 2007, we began a partnership with a large urban high school in the greater Phoenix, Arizona, metropolitan area. *SMALLab* has been permanently installed in a classroom at this location, and teachers and researchers have collaborated closely in a K-12/university Professional Learning Community [PLC] (Hord 1997; Wenger 1998; DuFour et al. 2006) to focus on the development of learning scenarios for science. The PLC consists of four science teachers—a.k.a. our *partner teachers*, and three university researchers which include the authors, who meet once each week for 2 h. PLC members devise new approaches to mixed-reality learning, new pedagogical approaches and suitable assessment methodologies that work in areas specific science subjects and learning.

During the spring of 2008, the PLC developed an innovative learning experience for chemistry students. The teaching experiment was designed to achieve three main goals: to advance students' content learning and reasoning through a new collaborative mixed-reality learning scenario incorporating science standards; to foster best education practices with a focus on guided inquiry methods; and to demonstrate that a semi-immersive mixed-reality environment is viable for learning in a conventional classroom. We describe the collaborative design process, the scenario itself, and its associated 3-day curriculum.

Collaborative Design Process

The first stage of the design process was to identify areas of chemistry where students tend to struggle. The team determined that students often have difficulty conceptualizing titration and neutralization at the molecular level. *Titration* is a common laboratory method used to determine the molarity of a solution of unknown concentration by combining it with a reactant of known molarity. Our partner teachers observed that many of their students could solve molarity conversions and equations but could not explain the observable chemical properties or mechanisms that lead to a chemical color-change during the lab. Students' limited ability to describe the relationship between formulaic equations and observable chemical reactions suggested a more fundamental need to help them link these concepts. Unifying scientific concepts with processes and understanding chemical reactions and molecular structures of physical science are listed as national science standards [National Research Council (U.S.) 1996].

A number of studies have shown that high school chemistry students experience considerable difficulty describing and relating acid–base chemistry concepts to actual solutions (Sheppard 2006); whereas, there is little specific prior work documenting students' specific understanding of titration at the molecular level. As a result, the PLC chose the unification of formulaic understanding with molecular and physical understanding as the primary learning goal for students. A more specific set of titration-related topics was also developed to motivate the content of the *SMALLab Titration* scenario and curriculum. For 6 weeks, members of the PLC implemented and tested multiple iterations of the scenario, improving the scenario's look, feel and sound.

In conjunction, the group developed an overarching lesson plan and teaching strategy to fit the original design objectives. This led to a learning experience design that promoted whole-group socio-collaborative discourse and leveraged interactive digital media for conceptual learning through guided inquiry. The next section details chemistry processes that students learn, features of the scenario, and the participation framework used during students' 3 days in SMALLab.

SMALLab Titration: an Interactive, Mixed-Reality Learning Scenario

The SMALLab titration scenario is modeled after a traditional titration lab, where students gradually add a known solution of known molarity (acid or base) to a known reactant of unknown molarity until the endpoint of reaction occurs, which turns a solution with indicator from colorless to pink. During class, students sit around the *SMALLab* perimeter, where they can both see and hear activity in the space (see Fig. 1). The visual interface (see Fig. 2) features a large square in the center with a background image of water droplets. This area represents the system's "virtual flask", where the titration process unfolds. Students can add acid, base, and indicator molecules to this flask to observe how they would interact in water. The flask is surrounded by four panels, three of which contain selectable molecules; acids are in the red panel, bases in the blue panel, and indicator in the gray panel. The fourth panel (in green) dynamically displays a numeric pH level, which adjusts as the presence of acid and base particles in the flask changes. The panels and

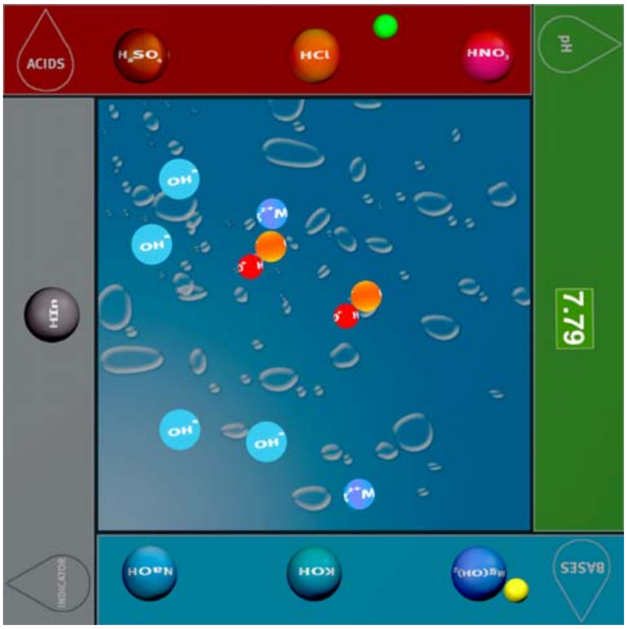

Fig. 2 Screen capture of the visual interface (floor projection) with particles floating in the virtual "flask"

text are visually rotated around the space to accommodate students sitting around and interacting within the space.

Figure 2 shows blue-colored and red-colored particles in the flask. These particles are ions that have resulted from *dissociation* or *ionization* after acid or base molecules were added to the flask (for example, KOH becomes K^+ and OH^-). By design, each particle in solution retains colors similar to the original molecule and panel, adding clarity to the types of particles present in the solution. The colors—red for acid and blue for base—follow a common scientific representation schema for depicting acids and bases. To distinguish particles, each molecule and ion is also labeled with its chemical formula.

The visuals are complemented by a sonic display designed to heighten students' awareness of interactions and reactions that take place. For example, a student hears a low bass tone when he/she selects and drops a molecule; there is a 'pinging' tone if a hydroxide ion collides with a hydrogen ion to form a water molecule; and non-reacting particles bounce off one another with the sound of a 'plink'. Each action and system event is coupled with a distinct sonic event, where each sound draws from a musical vocabulary influenced by electronic dance music. These sounds contribute to a richer soundscape that captures students' attention for specific events while still communicating an overall sense of activity within the system, meanwhile encouraging a sense of play in the learning experience.

Unlike traditional desktop computing activities, the *SMALLab Titration* scenario allows interaction to be simultaneously distributed across multiple participants. The primary interaction of selecting and adding molecules is divided among two individuals or teams of students. This is accomplished by using two tracked glowballs (see Fig. 3), each of which are tied to a subset of selectable molecules. A handheld wireless device provides participants with further high-level control of the system—pause, play, and reset. These controls enable a teacher or lead student to support moments of class reflection that could include system analysis, question-and-answer, or a hypothesis retest.

Fig. 3 Students use motion-tracked *SMALLab* glowballs to select and add molecules into the virtual solution

To select and add either an acid or base to the flask, a student uses a *glowball*, a silicone ball containing colored LEDs (see Fig. 3). The student selects a molecule by waving the ball over it; he/she then adds it to the solution by lowering the ball over the flask with some movement. Increased movement will provide increased velocity of the particles inside the flask. This interaction can be likened to a combination of the physical lab actions of adding single drops of some solution to the flask, and then stirring the flask to increase the rate of reaction. After a molecule is added, students will see one or more particles appear. These particles represent the aqueous components each molecule in solution.

As particles in the flask collide with each another, they undergo one of four reactions based on the general properties of acid and base in aqueous solution. Particles that collide and "bounce off" each other do not react, indicating they remain aqueous in solution. A *neutralization* reaction occurs when an H_3O^+ particle encounters an OH^- particle, in which case they disappear with sound to reinforce they have reacted to form water. Finally, two separate reactions can occur around two different states involving the indicator molecule. Initially, an indicator (HIn) particle loses its hydrogen atom when it encounters an OH^- particle, forming water and reducing the indicator into its In^- component; this results in its color turning from gray to pink. In reverse, if the In^- particle encounters an H_3O^+ ion, it regains its hydrogen atom and its HIn state; its color turns back to gray.

Implementation

Once the development of the *SMALLab Titration* scenario was complete, our two partner teachers integrated the scenario into their existing lesson plans. The teachers held their chemistry classes in *SMALLab* for three consecutive days (a total of three 50-min sessions). At a general level, the central learning goal was to help students better understand chemical reactions at both molecular and physically observable levels. In the context of this specific activity, the teachers hoped students would also improve their abilities to explain the processes of titration and neutralization, visualize matter on an atomic scale, and understand that chemical reactions are a complex and dynamic process. These goals aligned with the students' ongoing curriculum and served as a review for material that students had studied earlier in the school year.

In their first day in—and first exposure to—*SMALLab*, students started with an introductory demonstration and exploration of the interactive space. Both second and third days began with a review of concepts learned on the previous day, followed by a whole-group discussion of questions or observations that students had made. The teacher facilitated discussion and activities in a general inquiry lab format procedure, asking students to make observations and using these observations to guide the conversation. If a student had a question, the teacher first turned the question over to the class for an explanation from peers. At this time, the teacher asked students to return to their notes, discuss among themselves, and demonstrate a potential answer or solution using *SMALLab*. If students could not come up with an answer, the teacher would intervene. Once the classroom reached consensus on a solution or conclusion, the teacher helped them expand their understanding by probing with deeper questions and or directing the conversation into other related concepts.

Students were divided up into teams to work on shared goals by making predictions and team decisions, and forming unified positions or perspectives on the state of the system based on their team identity. During the course of each session, student teams rotated through a number of different roles. For example, the "acid team" and "base team" were each lead by a student who would directly interact in *SMALLab*, each adding particles using a *glowball*. Students were tasked to engage one another throughout the sessions by prompting their peers to take an action or by asking direct questions. A "questioning team" was formed to lead such discussions. As a final strategy for reinforcing students' knowledge, teachers asked students to design a simple game using the titration scenario and apply concepts they had learned. The students played these in *SMALLab* during the third and final day. For example, one team of students designed a game where a fixed number of acid and base particles were preloaded in the virtual flask. Teams of competitors were tasked to neutralize the solution in as few "moves" as possible where a "move" is the action of adding one additional acid or base particle to the flask. This game served as a catalyst for further hypothesis development and testing as teams of students competed to win through efficiency.

Student Participants

In total, there were 136 students in five participating classes. These classes were aggregated for analyses into honors ($n = 2$) and regular ($n = 3$). We collected pre- and post-treatment test data, and both scores are available for a total of 97 student participants. These students were enrolled in 10th and 11th grade and they reflect the demographic of the entire school where students are 50% white, 38% Hispanic, 6% Native American, 4% African American, and 2% other. Approximately 50% of students in the school are on free or reduced lunch programs.

Measures

Coded Video Data. For each of the teaching sessions using *SMALLab*, we collected qualitative data about the classroom experience by observing the classroom, taking notes, and videotaping with audio from two cameras. Video excerpts were then analyzed and correlated with researchers' field notes.

Concept Knowledge. This was an experimenter-designed invariant pre- and posttest. The test consisted of seven questions developed by the two science teachers and a science education assessment researcher in accordance with student learning objectives and traditional science standards. Each question contained a multiple-choice component and an open-ended explanation component. It should be noted that the "pretest" actually measured knowledge level after several traditional teaching sessions on the topic of titration. Thus, any gains seen by "posttest", (i.e., after the *SMALLab* sessions) represent gains above and beyond what can be expected after a typical learning situation.

Spatial Rotation Reasoning Task. This timed measure factor Kit from ETS (Ekstrom et al. 1979) has 160 items. A perfect score is 160. Students need to determine whether a figure had been rotated or flipped in comparison with an index figure. We hypothesized that after students spent 3 days in *SMALLab* visualizing and confirming abstract images, students might perform significantly better on a test like this.

Reformed Teaching Observation Protocol (*RTOP*). To understand the teacher's instructional methods, we applied the Reform Teaching Observation Protocol [RTOP] (Sawanda et al. 2002). The RTOP is an observational instrument designed to measure "reformed" teaching—teaching that arises from the central tenets of a student-centered, constructivist approach to learning (Vygotsky 1978; Driver et al. 1994; von Glasersfeld 1996). The protocol evaluates multiple facets of the learning environment including lesson design and implementation; the content of the lessons including propositional and procedural knowledge; and the classroom culture including communicative interactions and students/teacher relationships. RTOP scores range from 0 to 100. A score of 70 or above is typically regarded as high, indicating that the teacher is making effective use of reformed teaching practices.

Results

This section starts with an analysis of several coded transcripts. These transcripts illustrate student–student and student–teacher interactions in *SMALLab* and show evidence of collaborative thinking and reasoning. Data from student performance on pre- and post-session concept tests and spatial rotation tasks follow. The results conclude with a comparison of teacher performance before and during SMALLab class sessions using the Reformed Teaching Observation Protocol.

Coded Transcripts

Evidence of inquiry sequences and effective inquiry techniques emerged throughout the course of the teaching experiment. This first excerpt contains a series of conversation iterations whereby students followed through an inquiry sequence from an initial hypothesis to a refined conceptual model about dissociation, ionization, and neutralization. The table outlines the speaker (left column), the video transcript (center column), and category descriptors (right column) that highlight important features of the inquiry process. Students began with an *acclimation phase*, where students were introduced to the space. They made *preliminary observations*, describing what they saw and heard prior to forming or articulating a mental model about the system. Students built upon these observations to create a *hypothesis*, at which point, they would justify why they believed a specific observed event (e.g., some sound or visual cue) had occurred. Then they would *test their hypothesis*, attempting to reproduce the event as they recreated the circumstances under which the event occurred. After testing, the full classroom would come to a consensus and final *conclusion* about why the event occurred.

Throughout the process, students kept refining their hypotheses (*re-hypothesizing*) and modified their overall understanding (*refining the conceptual model*) based on information that was newly observed or introduced. They practiced and engaged in inquiry, and their improvements were observed through an increase in the number and sophistication of their questions. These improvements are coded at moments where teachers were able to *elicit better questioning from students*.

[Transcript for general chemistry class, Day 1. Students have just learned about the visual layout and are about to add particles to the space for the first time.]

Speaker	Responses [with notes]	Descriptors
Teacher:	[Student 1], would you do me a favor? Would you pick up the green ball and would you touch any one of the three acids? [*Student picks up ball and selects acid.*] Okay, now, just go ahead and touch the water area. Go ahead and take that back out so you can see it. [*Student touches area particles appear in the water area. Particles are created and move around in the flask.*]	Acclimation phase
S(tudent)1:	Dude, that is so cool!	
Teacher:	Okay. What happened? [*Lots of students simultaneously make lots of observations, including…*] (**various students**): It split up./It made cool noises./The pH was changed.	Preliminary observation
Teacher:	So the acid, when it went into the water, what did it do?	
S2:	It broke into H_3O^+ and HCl.	
Teacher:	What do we call that process?	
(students in unison):	Ionization.	Hypothesis
Teacher:	Ionization. That’s right. And as [Student 2] said, it broke up into its conjugate acid and its conjugate base. Taylor, what were you saying? What is H_3O^+?	
S3:	It’s a conjugate acid.	
Teacher:	How many hydroniums did it produce? It just produced one. Aaron, would you pick up the green ball and touch the H_2SO_4, the sulfuric acid. [*He has trouble selecting. Finally selects it.*] There you go. Okay what happened there?	Testing hypothesis
S3:	It broke them up.	
Teacher:	So it basically the same thing. Didn’t it? [*A student says something.*] Wait say that again?	

continued

Speaker	Responses [with notes]	Descriptors
S4:	It produced 2 H_3Os.	
Teacher:	So it doesn't matter what you do, they're all going to do the same thing.	Conclusion
S5:	The pH changed.	Preliminary
	observations	
Teacher:	Say that again? Did everybody hear that? The pH changed. Did it go up or down? [*Many students say*, "*Down*."] It went down, so that makes it more acidic. Okay, but what's something different between the H_2SO_4 and the HCL?	
S5:	Two Hs.	
S6:	Different colors. Wait, nevermind.	
Teacher:	Hold on a second, let's see. [*Pauses the scenario*.] Yeah, look at the SO_4 and the CL. Are they the same color?	
S5:	No.	
S6:	That one's a dark color, and that one's a light orange color.	
Teacher:	And that's because they came from a different acid.	
S5:	SO_4 has a -2.	
Teacher:	And what about the CL?	
S5:	Just -1.	
Teacher:	[*Resets it.*] [Student 7], would you pick up the red ball and put in a sodium hydroxide? [*She selects it. Sound is made, everyone laughs*.]	
Teacher:	Alright, what did that one do?	
(any students):	Broke it up.	
Teacher:	Just broke it up. And what do we call this process?	
S7:	Ionization?	Hypothesis
Teacher:	Not ionization. Bases don't ionize.	
S6:	They dissociate.	New hypothesis
Teacher:	(Teacher confirms) They dissociate.	
S5:	The pH went up.	
Teacher:	Thank you, and the pH went up… What's the difference between ionization and dissociation, just looking at what we've seen here?	
S7:	When you dissociate, you just, like, break it up into their main elements, like, the Na and the OH.	Conclusion
Teacher:	Right. All that happens is it just takes it and splits the ions apart. How is that different form ionization? [*student mumbles*] Okay. So the hydrogen actually does what with the water?	Hypothesis
S8:	It mixes it.	
Teacher:	Mixes isn't the exact word I'm looking for. Remember how we write it. What's it actually doing with the water?	
S9:	Changing it?	
Teacher:	What do we call it when it changes in chemistry? It actually reacts with it	
S9:	What is it?	
Teacher:	The acid actually reacts with the water. Antonio, would you grab the green [ball] and put in one of the acids? [*Student adds a molecule*.] Okay, notice the difference. The NaOH, it just broke up into two parts.	Testing hypothesis
S7:	It goes "clink" (referring to the sound). Did you hear that?	
S5:	The pH went down from 7.09 to 7.0.	Preliminary
	observations	
Teacher:	Why do you think it went down again?	
S5:	Because we added an acid.	Hypothesis
Teacher:	And why do you think that would cause it? What kind of pH is this?	

continued

Speaker	Responses [with notes]	Descriptors
S5	Neutral.	Hypothesis
Teacher:	Okay it's neutral. Why would it now be neutral?	
S5:	Because we have an acid and base.	Refines conceptual model
S3:	Because they cancel each other out.	Refines conceptual model
Teacher:	Yes, excellent, thank you. They cancel each other out, because they are now in what kind of proportions?	
S3:	1:1.	Refines conceptual model
Teacher:	Right, they're in 1:1; they're in equal proportions. [*Students continue writing these observations down.*]	

As students became more acclimated to *SMALLab*, they focused less on the novelty of the technology and began developing a refined understanding of the system through the lens of their current understanding of chemistry. The teacher helped them apply specific chemistry vocabulary to the preliminary audio-visual observations they make. In supplementary materials that accompany this article online we have provided additional transcripts from a later episodes that show student's deepening conceptual understanding.

Evidence of Collaboration, Distributed Cognition, and Conceptual Blending

Distributed cognition and conceptual blending emerges throughout the SMALLab sessions. The next transcript shows honors students determining how many water molecules were created after a large number of acids and bases had been added and fully reacted in the flask. In this moment, the teacher had paused the scenario so students could see the molecules in fixed positions on the floor. Students negotiated their answers by using the projected display to *map* and anchor their conception of molecules and ions onto visual images projected on the floor, *completing the blend* by filling in the details of chemical reactions they understood to have happened based on the state of the visual elements. They elaborated or *ran the blend* to deduce the number of water molecules made, referring back to reactions they observed as the scene unfolded. Beyond demonstrating individual understanding of the learning content, students constructively questioned each other and shared reasons for their conclusions.

Speaker	Response (with notes)	Category
Teacher:	Alright, how much water did we make here? We still haven't made that one, but once it happens…	
S1:	[*counting to himself*] 1 2 3 4 5 … 5?	
S2:	[*student's answer is inaudible in tape*]	
Teacher:	How'd you get that?	
S2:	Well, I counted all of the particles, except the [remaining] H_3O^+ and the OH^-.	
Teacher:	But aren't some of those positive and some of them negative?	Mapping
	[*Long pause in the classroom. Another Student 3 is pointing at the particles and counting to himself. Student 2 starts pointing and counting again.*]	
Teacher:	[Student 3], how many did we make?	
S3:	[*starts pointing and counting*] 12.	
Teacher:	How did you get 12?	
S3:	Is it right?	
Teacher:	I'm not saying if it's right or wrong, I just want you to explain how you got 12.	

continued

Speaker	Response (with notes)	Category
S3:	I just counted the SO_4^{2-}s, because it takes two Hydrogens to mix with SO_4^{2-}.	Completing
Teacher:	Okay.	
S3:	Oh, okay, nevermind. Maybe it's 6.	
Teacher:	Why is it 6?	
S3:	Because its two Hydrogens to make one water and there's 12 Hydrogens.	
S4:	[*raises hand and says*] I counted 26.	
	Teacher: 26? How'd we get 26?	
S4:	Because there's two for every [*points to a Magnesium particle*] Magnesium. Two Oxygens for Hydroxides. [*Teacher acknowledges she is in agreement with, "Mhmm."*] And I was counting all the acids, too. [*Brief silence in classroom.*]	
Teacher:	Let's go back to the beginning, how's the water made? Donald.	
S5:	The water's made when a Hydronium reacts with a hydroxide. So, we've made 12 waters but we can make one more with the Hydronium and the hydroxide.	
Teacher:	How do we count 12?	
S5:	We're counting 12 because for every sulfate, there's 2 Hydrogens which have reacted.	
Teacher:	So how many sulfates are there?	
S5:	[*points and motions to specific particles in the space*] There's 5 Sulfates, which is 10. And then there's three Nitrates [*Teacher acknowledges explanation with, "Okay."*] which is 13. But, one of them—one of the Hydrogens from the Nitrate, which is in the Hydronium, hasn't reacted. So we've made 12 waters, and we can make one more? [*poses this question*]	Running the blend
S1:	[*student interjects with another answer*] There's 7.	
Teacher:	Why are there 7?	
S1:	There are 14 negative ions and 7 positives.	
S5:	[*acknowledges Student 1's explanation*] Oh, I didn't see the chloride. So that would make it 13…	
S1:	But it's 2, 4, 6, 7, 8 … [*her comment trails off as she keeps counting*]	

Here, several students mapped their conceptual models of ionized acids, bases and water molecules onto the displayed images, filling in the details of their model with known information about ionic reactions, and reasoning together.

Multimodal, Game-Like Learning

Students' also clearly leveraged audio-visual cues to articulate and communicate their conceptual understanding. The following transcripts come from Day 3 in SMALLab, where students used the titration scenario to design games for their peers to play. Each dialogue stems from the fact that a large quantity of bases has been added to the system. The number of particles and their rapid speed in the system made it difficult for students to keep a visual count. Students, working in opposing teams, followed instructions to either titrate the solution or prevent titration before the system reached its maximum number of particles (roughly 30).

[Students are in opposing teams; one tries to titrate the system, and the other tries to prevent titration. Each team has students take turns adding particles, and players rotate once the system reaches particle capacity.]

Speaker	Response (with notes)
S1:	It's right over there! [*Student motions to moving OH^- molecule.*]
S2:	Wait, there's still one in there—[*Sound indicating an indicator molecule changed color from pink to gray plays*]—how come the music stopped? [*Sound indicating that the pink indicator reacted with OH^- plays, turning it back to gray.*] Thank you. [*Classmates laugh.*]
S3:	[*Student points to two OH^- molecules left in the space.*] Two more of that
S4:	Is that bad for us?
S5:	Add another HCl
S2:	So that bad boy's got to go to that one?

Table 1 Means, standard deviation, number and effect sizes by test and class type

Class type	Concept pretest	*n*	Concept posttest	*n*	ES	Spatial pretest	*n*	Spatial posttest	*n*	ES
Honors	4.59 (3.16)	37	8.05 (3.04)	37	1.12	102.81 (24.67)	36	123.15 (27.85)	34	.77
Reg.	4.95 (3.17)	99	5.33 (2.52)	60	.13	104.49 (32.31)	87	124.25 (26.08)	59	.68
Total	4.85 (3.16)	136	6.37 (3.02)	97	.49	104.00 (30.18)	123	123.85 (26.60)	93	.70

Above, students were relying on sound to know if the system is still titrated. They also map character traits onto particles, which suggests they are taking on the particle's point of view and motivated by the activity.

[This team of students tries to titrate as quickly as possible. The system contains many particles moving at a rapid pace. Many students are speaking and exclaiming out loud, watching particles and directing their team member to place an acid strategically so it reacts quickly.]

Speaker	Response (with notes)
S1:	It's not going to work
S2:	It's right there!
S3:	Touch it, touch it
S1:	I can't catch them, they're going really fast. [*students laugh*]
S2:	No, dude, you've added too many
S1:	Now there's pinks! I've always got to get the pinks!
S4:	[*to Student 1*], you've already got it, don't worry; it's going to get it sooner or later

This last transcript shows students working together to help their teammate titrate the system. Because they have a strategy, we infer that they had formulated an understanding about how titration works. In addition, they encouraged each other and also appeared to be motivated and enjoying the game activity.

Results from Quantitative Measures

Pre-Post Test Samples. Students were given an invariant conceptual reasoning test before and after the treatment. The test consisted of seven questions, where each question was comprised of a multiple-choice question and an open-ended written explanation section. Our team created the test to address concepts explored in the *SMALLab Titration* scenario. The questions are based on typical questions that the teachers had used previously in their classrooms. An example question:

Question: When you've reached the endpoint of a neutralization reaction you will have____

a. More water molecules
b. Fewer water molecules
c. The same number of water molecules
d. None of the above

Explain why you chose this answer.

Concept Knowledge Gains. The experimenter designed concept test had two sections (multiple choice and explanation-based). Because these two were correlated, we report the test as a whole. There were 136 participants at the time of pretest. Due to absences and test schedule constraints, a different number of students took the pre and posttests, and the resulting n's have been noted. Table 1 lists the descriptive statistics by classroom type. Effect Sizes (ES) are the subtracted group means divided by the pooled standard deviations.

Overall, students who took both the concept pretest and posttest demonstrated a significant gain of 2.26 points (2.84), paired $t_{(96)} = 7.87, p < .001$. The effect size for this sample (ES = .80) was gathered by using the pretest scores from only those participants who *also* had posttest scores, thus it ended up being higher than the total ES presented in Table 1. We were interested in whether there were differential gains depending on class type. That is, did the honors students make greater gains compared to the regular students? At pretest, the two groups were matched, although the honors groups scored somewhat lower at pretest (the difference was random and not significant), $t_{(134)} < 1.0$; however, by concept posttest the two groups differed significantly, M diff = 2.72. A repeated measures ANOVA revealed a significant posttest gain, $F_{(1,95)} = 78.76$, $p < .001$. The ANOVA included the interaction term of pretest by class type and this was also significant, $F_{(1,95)} = 11.72$, $p < .001$, revealing that the average gain shown by the honors' classes significantly exceeded the average gain demonstrated by the regular classes. Stated another way, of the 60 participants in the regular classes who took both the pretest ($M_{\text{reg}} = 3.80$) and the posttest, a significant gain was witnessed, paired $t_{(59)} = 4.79, p < 0.001$, nonetheless, the honor's classes gain was even greater.

Spatial Rotation Reasoning Task. On the spatial reasoning pretest, the two class types were matched at pretest, $t < 1.0$. A repeated measures ANOVA with class type as a between subjects factor and the interaction variable of test by class type, revealed that at posttest, all students showed significant gains, $F_{(1,84)} = 81.25$, $p < .001$, whole group ES = .70. The interaction revealed a trend for the honors classes to gain somewhat more by posttest, $F_{(1,84)} = 3.23$, $p = .07$.

Table 2 RTOP gains by partner teachers before and during the SMALLab experiment

RTOP measure	Honors teacher before *SMALLab*	Honors teacher in *SMALLab*	General teacher before *SMALLab*	General teacher in *SMALLab*
Lesson design and implementation	7	14	10	16
Propositional knowledge	13	14	13	15
Procedural knowledge	5	14	9	14
Communicative interactions	9	13	12	13
Student teacher relationships	11	13	13	17
Total	45	68	57	75

Retest Gains. Because all teachers of chemistry at the school wanted to partake of the *SMALLab* experience and they all covered the same material in the same timeframe, we were unable to secure an untreated control group in a chemistry situation. However, past literature on the spatial tasks gives one an idea of the sorts of test-retest gains that can be expected on some of the spatial reasoning subtests. Johnson-Glenberg (2000) used a younger sample, 3–5th graders, in a reading comprehension study and administered the paper-folding subtest of the ETS Factor Referenced Kit to assess spatial skills. The lag between pretest and posttest was 10 weeks. The students in the non-visualizing experimental condition showed a gain of .46 and an ES of .15 by posttest. This ES of .70 witnessed in the current *SMALLab* experiment far exceeds the retest effect seen in that earlier spatial reasoning task administered by Johnson-Glenberg. From these results, we draw the conclusion that students did in fact gain in spatial reasoning and in their understanding of titration at the molecular level—particularly in their ability to explain their answer choices.

Teacher Performance on the RTOP. To assess teacher's abilities to teach in *SMALLab*, we used the RTOP to measure teacher performance twice, first in the regular classroom prior to entering *SMALLab* and again during their final *SMALLab* session. A test of Directional Probability was run comparing all pretest data to all posttest data for each teacher. Using each of the five dimensions, the probability that each variable would improve in a positive direction (.5 to the 5th) is .031. Table 2 shows that indeed both teachers improved in each dimension by posttest.

Discussion and Limitations

Based on our direct classroom observations and follow up discussions with our partner teachers, there is strong evidence that participating students and teachers engaged in an effective inquiry learning process within *SMALLab*. We observed that with each passing day during the study, students improved in their ability to directly question and respond to their peers. Importantly, these interactions were carried out in the context of whole-group discussions that were rooted in the hands-on activities.

Day 1 was the most teacher-centered due to the necessity of introducing students to the new learning environment and expectation. During day 2, students increasingly assumed greater control over the pace of the learning process. By the final activities of day 3, the students themselves defined and led the game-like problem solving activities. This qualitative data is borne out by the results of the RTOP instrument. We found that both partner teachers were more successful in framing a student-centered, inquiry-based learning environment in *SMALLab* than in their regular classrooms. We attribute this outcome to several factors in both the environment and the experimental design.

First, our partner teachers were active collaborators at every stage of the *SMALLab Titration* design process. During this process, they had the opportunity to role play effective teaching strategies, often soliciting feedback and critique from their teacher-peers in the group. As such, our team was able to develop a new scenario that is grounded in the teachers' perspectives of student learning and that accommodates the teaching styles of these particular individuals. There can also be no doubt that teacher performance was advantaged by the sheer time and attention they spent in preparing for the implementation of this curriculum.

Secondly, the physical architecture and interactive interfaces that comprise *SMALLab* reframe student and teacher relationships in new ways. As shown in Fig. 1, students are situated around the interactive space where all students can see and communicate with one another. As the team interaction leaders manipulate the *glowballs*, these students are in full control over the decision-making process, relegating the teacher to a role on the sidelines. We posit that by its very nature, this participation framework promotes direct peer-to-peer interaction and empowers students to take ownership over the process. Moreover, we observe that the architecture and scenario design for *SMALLab* enables the teacher to take on a role that is different from what one might expect in a desktop computer dominated classroom. For example, as illustrated by the transcripts, the teacher often facilitates whole-class discussion and reflection. This is an area we expect to examine more closely in future research.

Thirdly, we attribute the efficacy of the learning experience to the multimodal interaction and feedback in the mixed-reality environment. We observed that many student discussions arose from their attention to the visual, auditory, and kinesthetic elements in the scenario. For example, one student expressed his visual understanding of an important part of the back-titration process by stating that one particle was "getting the pinks." Though this language is not scientifically precise, it is an important observation that led students to reason through a consensus understanding of this complex process. In other cases, in order to increase the speed of the titration process, students coached one another to physically "touch" new acids or bases to existing molecules in the virtual flask. Finally, students relied on a combination of their senses to understand the state of the system as a whole. Specifically, they often relied upon the audio feedback to support their observations when visual feedback was unclear or difficult to interpret. These multimodal representations provided multiple pathways for students to understand and engage the underlying concepts. As a consequence, students were able to enter into and contribute to the whole-group thinking and reasoning process in a variety of ways. Moreover, each display modality provided yet another representation of the underlying process, thus increasing the opportunities for learning to occur.

As a result of this treatment, students were able to achieve significant learning gains in standards-based chemistry content knowledge. This suggests that student performance in the context of *SMALLab* can transfer to success in more traditional measures of student achievement. However, extensive study is required to fully validate this finding and generalize beyond the studied population. Furthermore, the study would need to be extended to include a greater number of teachers and classrooms, as only two were involved in the present study. In addition to recording content learning gains, we documented an increase in participating students' spatial reasoning abilities as measured by their performance on a spatial rotation task. We attribute this finding to the nature of visual processing and physical immersion in the environment. *SMALLab* projects critical visual information on the floor of the environment, and as students interact, they are in a state of constant motion, continually shifting their perspective to orient themselves to the display. Thus, their processing of detailed visual information requires that they execute spatial rotation tasks in real time. This is an encouraging finding in the present study, but further research is required to better understand the implications of these gains.

One other limitation of the current study is that we were unable to gather retest data on an untreated control group for the knowledge assessment measure. While it is true that the post-test measures what was learned beyond the "typical" learning situation, this activity does represent additional time on task. We are currently designing a new set of studies to address this limitation. Nonetheless, the student performance gains documented in this study are greater than one would expect from a simple retest-only effect. For example, Roediger and Karpicke (2006) demonstrated an approximate 5% gain as a result of retest in a similar study with college students.

Conclusion

We have presented a summary of recent research and prior work that motivates the need for a new wave of K-12 technology integration. Newly emerging technology-based learning environments can benefit from an emphasis on drawing together rich socio-collaborative discourse with well-designed interactive digital media. Our work in this area suggests that the realization of a new mixed-reality learning environment, *SMALLab*, is viable in a traditional K-12 high school context, as demonstrated in a teaching experiment and study that emerged from our collaborative partnership with a local urban high school.

Qualitative results from transcripts across all of the sessions showed evidence of improved thinking and reasoning skills, collaborative learning, and effective use of the mixed-reality environment to develop shared conceptual knowledge of chemical equilibrium and titration reactions. Teachers demonstrated the use of best teaching practices grounded in scientific inquiry for science learning. Quantitative data illustrated that participating students achieved significant content learning gains and spatial reasoning ability. RTOP observations showed that the performance of our partner teachers positively increased in *SMALLab*. Beyond these gains, we found strong evidence that participating students are high motivated to learn in this new way. Exiting the classroom on the final day, one student remarked, "Wow, that's the first time I *got* chemistry this entire year!" In sum, we conclude that the mixed-reality science classroom can be a powerful learning environment that is viable in a mainstream high school context.

Acknowledgments We gratefully acknowledge that these materials document work supported by the National Science Foundation CISE Infrastructure grant under Grant No. 0403428 and IGERT Grant No. 0504647 and work supported by the MacArthur Foundation under a grant titled "Gaming SMALLab: a game-like approach to embodied learning." We extend our gratitude to the students, teachers, and staff of Coronado High School for their overwhelming commitment to collaboration and exploration in support of learning. We also thank Arthur Glenberg for his invaluable insights and advice in the analysis of the evaluation data.

Appendix

The next example builds on the classroom's inquiry practice as the teacher attempts to help students deepen their conceptual understanding. The transcript comes from the second day of classes and starts after the teacher has divided students into four teams: acid, base, pH, and questions teams. During this dialog, the teacher first prompts students with simple questions and then encourages students to ask questions of one another.

[The teacher asks the base team to make a decision. After a short team discussion one girl team member uses the orange ball to select a base molecule. With hesitancy, the girl is reluctant to drop the base into the flask, and her teammates encourage her to "just drop it in there." She asks if she can put two molecules in. The teacher says, Yes, and the student adds another molecule to the water.]

Speaker	Response (with notes)	Category
Teacher:	Okay, now lets stop for a minute, okay. pH team, what do you notice? [*Lots of responses from different students can be heard.*]	
S1:	That there's more light blues than dark blues.	
Teacher:	Okay, all these things that you guys are noticing, you should write down. We have more light blues than dark blues.	
S2:	What base was it that she added?	
Teacher:	[Student 3], what bases did you add?	
S3:	NaOH and umm… I don't remember.	
(multiple students):	$Mg(OH)_2$.	
Teacher:	$Mg(OH)_2$. So sodium hydroxide, magnesium hydroxide. [*Students are writing this down.*] Okay, we added two bases, so how many hydroxides are there? And I shouldn't be asking these questions. Question team? [*Some students laugh.*] Come up with questions.	Eliciting better questions
S4:	How come the pH went up? Is that a good question?	
	Teacher: That is a very good question. [*Lots of students are responding with explanations simultaneously. Teacher points to a student.*] Okay. We've got—what, say that again, [Student 5].	
S5:	'Cause there's more hydroxide.	
Teacher:	Excellent.	
Teacher:	[Student 6], what'd you say?	
S6:	It's less acidic.	Refines conceptual model
Teacher:	Okay, it's less acidic. It's less acidic because of what Ashley said—there's more hydroxides floating around. 'Kay, question team, more questions.	
S7:	Why are there more light blues than dark blues?	
Teacher:	Okay, why are there more light blues than dark blues?	
(two students together):	What does light blue and dark blue stand for?	
S7:	Light blue is OH^-.	
Teacher:	Let's stop it just for a minute. [*Teacher pauses the scenario.*] It makes it a little easier to read. The big blues are what?	
(many students) together:	OH^-s.	
Teacher:	The dark little blue is…	
(many students):	Mg.	
Teacher:	And the lighter little blue is…	
(multiple students):	Na.	

continued

Speaker	Response (with notes)	Category
S8:	Oh—Mg has 2 OH^-s.	
Teacher:	Mg has 2 OH^-s, so that answers your question.	
S9:	Wait, what is that one? Dark blue?	
Teacher:	This one right here?	
S9:	Yes.	
Teacher:	That is an Mg. … Mg positive 2. [Student 10], why does it have a positive 2?	
S10:	'Cause that's its charge.	Refines conceptual model
Teacher:	Ah ha, and why does it have that charge? Do you remember? Do you remember what group it's in?	
S11:	[*exclaims*] Group 2! [*Group 2 refers to groupings on the periodic table.*]	
Teacher:	Right, it's in Group 2. This is actually good because it's review for the final, too.	Refines conceptual model

By the end of this dialogue, the teacher was able to engage the students in meaningful questioning. An added benefit, he also helped them improve their conceptual model to incorporate elements not explicitly built into the scenario itself, e.g., they related the concept of atomic charge back to the periodic table.

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