International Journal of Science Education
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tsed20

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To cite this article: Ji Shen & Marcia C. Linn (2011): A Technology-Enhanced Unit of Modeling Static Electricity: Integrating scientific explanations and everyday observations, International Journal of Science Education, 33:12, 1597-1623

To link to this article: http://dx.doi.org/10.1080/09500693.2010.514012

International Journal of Science Education
Vol. 33, No. 12, 1 August 2011, pp. 1597–1623

RESEARCH REPORT

A Technology-Enhanced Unit of Modeling Static Electricity: Integrating scientific explanations and everyday observations

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What trajectories do students follow as they connect their observations of electrostatic phenomena to atomic-level visualizations? We designed an electrostatics unit, using the knowledge integration framework to help students link observations and scientific ideas. We analyze how learners integrate ideas about charges, charged particles, energy, and observable events. We compare learning enactments in a typical school and a magnet school in the USA. We use pre-tests, post-tests, embedded notes, and delayed post-tests to capture the trajectories of students' knowledge integration. We analyze how visualizations help students grapple with abstract electrostatics concepts such as induction. We find that overall students gain more sophisticated ideas. They can interpret dynamic, interactive visualizations, and connect charge- and particle-based explanations to interpret observable events. Students continue to have difficulty in applying the energy-based explanation.

Keywords: *Modeling-based instruction; Formative assessment; Preservice science teacher education*

Introduction

Static cling, pollination, photocopying, lightning, and sparks can all be explained using knowledge of electrostatics. Explaining everyday phenomena with scientific ideas can make school science more relevant to students and help learners develop coherent understanding (Kali, Linn, & Roseman, 2008). Electrostatics illustrates important

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ISSN 0950-0693 (print)/ISSN 1464-5289 (online)/11/121597–27

DOI: 10.1080/09500693.2010.514012

atomic-level mechanisms. Connecting these atomic-level ideas to observable phenomena can strengthen science understanding (Lee, Eichinger, Anderson, Berheimer, & Blakeslee, 1993; National Research Council, 2000; Stevens, Delgado, & Krajcik, 2010).

We designed and investigated a technology-enhanced inquiry unit on electrostatics consistent with the national standards (National Research Council, 2000). The unit links everyday situations, hands-on experiments, and interactive, dynamic computer visualizations. Students make connections between ideas on charges, atomic particles, and electrical energy. Specifically, the research investigates:

- What trajectories do students follow to develop integrated understanding of electrostatics? How do they integrate observable, charge-based, particle-based, and energy-based perspectives on electrostatics?
- How do interactive computer visualizations of atomic-level interactions contribute to knowledge integration?
- How do typical and experienced students differ in the trajectories they follow?

Knowledge Integration and Students' Ideas on Electrostatics

This research uses the knowledge integration framework to align curriculum design, assessment, and pedagogy (Kali, 2006; Linn & Eylon, 2006). *Knowledge integration* (Linn, 2006a; Linn & Eylon, 2006) is a constructivist framework based on the research in science education (e.g., Kali, Orion, & Eylon, 2003; Lewis & Linn, 2003; Linn, Lee, Tinker, Husic, & Chiu, 2006; Seethaler & Linn, 2004). The knowledge integration framework emphasizes the importance of building on the diverse ideas that students bring to science classrooms (Bransford, Brown, & Cocking, 2000). Students learn by adding new ideas and distinguishing among these views using scientific evidence (Davis, 2004; Linn, 2006a; Linn & Hsi, 2000; Roschelle, 1995).

Students develop diverse and conflicting ideas about electricity and electrostatics (diSessa, 1993; Harrington, 1999; McDermott & Shaffer, 1993; McIntyre, 1974; Osborne, 1983; Otero, 2004; Shen, Gibbons, Wiegers, & McMahon, 2007; Shepardson & Moje, 1994; Shipstone, 1988; Wandersee, Mintzes, & Novak, 1994). These ideas come from textbooks, colloquial uses of language, and everyday experience. For example, students often use the term 'negative' to refer to neutral materials, consistent with usage of negative for results from medical tests (Harrington, 1999). Some students report that charged objects have only one type of charge rather than consisting of an imbalance of opposite charges (Otero, 2004). Students may think that only conductors can carry charges while insulators cannot (Harrington, 1999). Park, Kim, Kim, and Lee (2001) found that over 75% of middle school and college students reported that when brought close to a charged material, only conductors show induction while insulators do not. Many students hold the balancing idea, asserting that charges balance across materials. Thus, students may think that both positive and negative charges transfer between solid materials (Otero, 2004). Students may also believe that charges do not transfer between similarly charged conductors with different potentials, or think that the process stops when one of the conductors becomes neutral (Guruswamy, Somers, & Hussey, 1997). In addition, research shows that students rarely link atomic models and observable phenomena such as electric circuits, lightning, or static electricity (Benseghir & Closset, 1996; Eylon & Ganiel, 1990; Thacker, Ganiel, & Boys, 1999).

The Technology-Enhanced Electrostatics Unit

A partnership of teachers, technology experts, and educational researchers designed the electrostatics unit following the knowledge integration framework (Kali, 2006). The unit elicits students' ideas using prompts so that students are poised to distinguish their ideas from those in the unit. The unit uses dynamic, interactive computer visualizations to add atomic-level views of electrostatics to those held by the learner using open source Molecular Workbench software developed by the Concord Consortium (Xie & Tinker, 2006; http://mw.concord.org/modeler). The unit helps students distinguish ideas using critique and collaborative discussion (Clark & Sampson, 2007, 2008). The unit encourages students to sort out their ideas and make meaningful connections among scientific concepts and corresponding observations using reflections (Cuthbert & Slotta, 2004; Davis, 2003; Gobert & Pallant, 2004). Overall, the unit helps students integrate their own views on everyday experiences, hands-on experiments, and interactive visualizations to achieve coherent understanding (Kali et al., 2008).

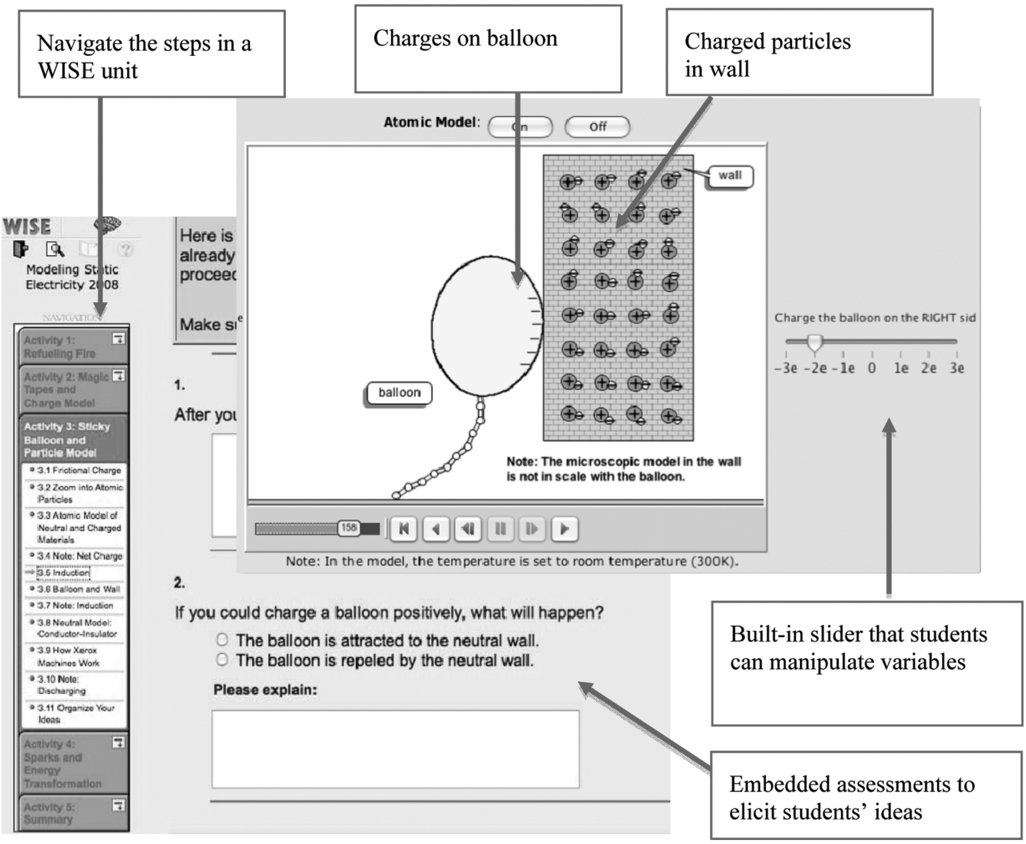
The electrostatics unit delivered using the Web-based Inquiry Science Environment (WISE; Linn, Clark, & Slotta, 2003; Linn, Davis, & Bell, 2004) lasts for about one week (Figure 1). WISE supports guided inquiry activities, embedded assessments, group discussion, peer collaboration, as well as teacher customization. The current version of the unit was a refinement of an earlier version that took a historical perspective (Casperson & Linn, 2006).[1] Results of the embedded and pre-/post-assessments revealed students' confusions and guided the revision. Both versions benefited from a rigorous design review process (Slotta & Linn, 2009).

Electrostatics Activities

The unit has five activities and each activity consists of several steps. To connect electrostatics to observable phenomena, in the first activity students watch a video clip about a refueling fire accident at a gas station.[2] The unit then elicits students' initial ideas about static electricity by illustrating the operation of copying machines and other phenomena.

In the second activity, students conduct hands-on experiments to explore static electricity using charged adhesive tapes and other physical materials (e.g., Mazur, 2004). Students observe interactions between the positively charged, negatively charged, and neutral objects to explore electrostatic phenomena. They represent their charge-based views and reflect on the connections between their observations and their initial ideas.

In the third activity, students explore several virtual experiments and atomic-level visualizations including one of the balloon and wall (Figure 1) to connect


Navigate the steps in a WISE unit

Charges on balloon

Charged particles in wall

Built-in slider that students can manipulate variables

Embedded assessments to elicit students' ideas

Note: The microscopic model in the wall is not in scale with the balloon.

Note: In the model, the temperature is set to room temperature (300K).

2.

If you could charge a balloon positively, what will happen?

○ The balloon is attracted to the neutral wall.
○ The balloon is repeled by the neutral wall.

Please explain:

Figure 1. Screenshot from the WISE electrostatics curriculum illustrating interactions between a charged balloon and a wall (www.wise.berkeley.edu) using Molecular Workbench (http://mw.concord.org/modeler)

observable phenomena with atomic-level processes. They can change the charge of the balloon to study induction and conduction at the atomic level. They relate this virtual experiment to an example of distinguishing insulators and conductor in an electric circuit.

In the fourth activity, students build a simple electrophorus to generate sparks (electrostatic discharges) in the classroom. They connect their observations to the idea of an electric field and the concept of energy transformation and represent the electric field, potential energy, and kinetic energy with the aid of computer visualizations. The activity uses the electric field to provide a mechanism for action-at-a-distance previously encountered in the charge-based and particle-based explanations. The concept of potential energy is thus linked to the concept of field.

In the last activity, students review what they have learned in the unit and write an explanation for the refueling fire video using the evidence from their experiments and interactions with the visualization. They exchange explanations with their classmates and provide constructive critiques of the views of peers.

The unit introduces three views of electrostatic phenomena:

- The charge-based view uses the two types of charges, positive and negative, to account for electrostatic attraction and repulsion. Students explore positive and negative charges in hands-on (e.g., adhesive tape) and virtual experiments (e.g., Figure 1). Specifically, they learn that: (a) two types of charges (positive and negative) explain electrostatic interactions; (b) charges can be transferred between objects; and (c) excessive charges can be produced for one material by rubbing against other materials.
- The particle-based view uses the movement of particles and interactions among particles to account for electrostatic interactions. They explore the movement of particles in several visualizations. Specifically, they learn that: (a) objects consist of numerous small particles; (b) charge is a property of particles; and (c) charged materials have excessive electrons or positive ions.
- The energy-based view emphasizes the visualization of the electric field, the conservation of total energy, and transformation of energy to account for phenomena such as shocks, sparks, and fire caused by static electricity. They explore the energy-based view using the electrophorus and visualizations. Specifically, they learn that: (a) kinetic and potential energy can be transformed into each other; (b) potential difference drives the movement of charged particles, and can explain the charging and discharging processes; and (c) an electrical field is associated with charged particles or objects.

The activities in the unit were designed to help students integrate all three views and connect them to everyday experience (pollinating, static cling, lightening, electric shocks, photocopying). The emphasis on connections to everyday experience prepares students to revisit their ideas about electrostatics in the future and continue to integrate their ideas.

The unit presents complex phenomena involving different aspects of electrostatics so that students may use different accounts to explain the same observations. For instance, the refueling fire accident involves charging and discharging processes that may elicit different views. Embedded questions ask students to consolidate these different views. For instance, after students have learned the charge-based view, they are asked to answer: ‘what exactly are charges? … where do the charges come from?’

Electrostatics Visualizations

Interactive computer visualizations can help students learn science concepts (Chabay & Sherwood, 1999; Chang & Shen, 2008; Clark & Jorde, 2004; Gilbert, 2005; Pallant & Tinker, 2004; Wu, Krajcik, & Soloway, 2001). In electrostatics, research has shown that computer visualizations can represent phenomena too small to see and provide a promising way to help students grasp key concepts (e.g., Casperson & Linn, 2006; White, Frederiksen, & Spoehr, 1993). For example, Frederiksen, White, and Gutwill (1999) designed an interactive computer visualization of electric current based on particle diffusion. Three levels of explanation were employed: particle level, aggregate level, and symbolic level. Their results showed that high school students who saw a transient process of particle distribution outperformed those who only saw initial and final states of particle distribution. Miller, Lehman, and Koedinger (1999) tested a computer microworld, electric field hockey (Sherwood & Chabay, 1991), and showed that it was essential to carefully select learning tasks employing computer visualization to improve understanding.

Specific curricular decisions were made for the unit using knowledge integration design principles (Kali, 2006; Linn, Davis, & Eylon, 2004). For example, the design principle, *making science accessible*, is instantiated in two ways. First, by *connecting to personally relevant examples* in the hands-on experiments using charged tapes and using these connections to explain everyday experience such as photocopying, static cling, lightning, and electrostatic shocks. Second, by *connecting multiple levels of representations*, the unit integrates the particle-based view and the charge-based view to explain concrete observations of macroscopic phenomena (Clement, 1993; Frederiksen et al., 1999). In this case, the balloon and wall simulation is linked to an atomic-level view (see Figure 1). When students charge the balloon using the slider, they see charge signs appear on the balloon. Observable objects are deliberately incorporated in the design (the *balloon* either moves towards or away from the *wall*). By connecting observable and atomic representations, the unit helps students interpret the particle view.

In another example, the design principle, *making thinking visible*, is used to engage students in representing their knowledge explicitly and in employing visualizations to illustrate scientific ideas (Gobert & Pallant, 2004; Linn, 2006a). Throughout the unit, students are asked to take notes or to draw their interpretations of the computer visualizations to make their ideas visible. At the end of each activity, students organize their knowledge into explanations that draw on relevant observational evidence. These embedded assessments help teachers interpret student progress. They also allow students to communicate their ideas to their classmates.

Methods

We compare the responses of high school students from a typical (typical students) with a magnet school (experienced students) to capture the impact of the unit on students with varied prior knowledge (see Table 1). Computer learning environments such as WISE have the potential to support a wide range of student expertise by allowing learners to work at their own rate.

Participants

The experienced group ($N = 38$) attended a magnet school that focuses on science and technology. Neither group had studied electrostatics or electricity in high school, but the experienced group had more exposure to the particulate nature of matter and atomic-level explanations. The magnet school offers advanced courses targeting the top science students in the area. The typical group ($N = 41$) attended a typical, public school that enrolls more than 1,500 students. The typical school has a

Table 1. Characteristics of experienced and typical students

	Experienced group	Typical group
Sample size	38	41
Teachers' experience of teaching	28 years	2 years
Teachers' experience of using WISE	2 years	0 year
Teachers' subject area	Physics, math	Physics
Teachers' self-report of class instruction pattern	60% lecture, 10% small group, 30% labs	60% lecture, 20% small group, 20% labs
Electricity and electrostatics coverage	None to some	Some
School mean SAT score		
Verbal	625	451
Math	675	459
State test proficiency level	NA	Science 18% (state 35%), Math 9% (state 40%)
School diversity	Medium	High

large proportion of students who receive free or reduced-price lunches (54%) and who are non-native speakers of English (28%). The experienced group had an experienced teacher with over 20 years of teaching experience and some WISE experience. The typical group had a teacher who was new to technology-enhanced instruction and new to teaching. The students were assigned by their teachers to work in pairs. Occasionally students worked individually due to absences. On average, it took students four to five class hours to complete the unit.

Data Collection and Analysis

The first author observed both classrooms, took field notes, and answered students' questions regarding technical or content issues. The first author also conducted informal interviews and recorded responses while the students were running the unit.

Assessment

The pre-, post-, and delayed post-tests were constructed to measure the knowledge integration (Liu, Lee, Hofstetter, & Linn, 2008). The pre- and post-tests were identical and contained five explanation items and took students about 30 minutes to complete. The tests were administered a day before and immediately after the unit. Overall, 34 of 38 students in the experienced group and 27 of 41 students in the typical group individually completed the pre- and post-tests. The items asked students to interpret observable electrostatic phenomena by using their understanding of electrostatics:

- Item Hair asks about the phenomena of fluffy hair when combed on a dry day. Successful responses explain that the combing action causes the strands of hair to become similarly charged (or to carry excessive positive ions), therefore repelling each other.

- Item Balloon asks students to explain why a charged object attracts neutral objects (i.e., induction). Successful responses explain that although the pieces of paper are neutral, the electrons in the paper can be induced to realign themselves so the two materials attract each other.
- Item Silk asks students to explain what happens between charged objects. Successful responses explain that the net force between oppositely charged objects is attraction.
- Item Electroscope asks students to predict and explain the behavior of an electroscope, an apparatus used to detect if an object is charged or not. Successful responses link induction, conduction, and interactions between charged objects to explain its behavior.
- Item Shock asks students to describe two ways of avoiding electric shocks at home and explain why their strategies work. Successful responses describe ways to discharge show that students electrostatics ideas to observable phenomena.

There were 30 embedded assessment prompts in the unit and most students worked in pairs to respond to these prompts (20 entries from the experienced group and 21 entries from the typical group). Student responses to embedded prompts provided evidence to study their knowledge integration progress and mechanism. We selected two pairs of students to trace their progress when responding to the embedded notes related to induction to illustrate knowledge integration mechanism.

In addition, 30 of the 41 students in the typical school took a delayed test two months later. The delayed test was used to measure the impact of WISE experience on student learning on various science topics in a larger study by the Technology-Enhanced Learning in Science center. The delayed test only included two electrostatics items (item Balloon and item Silk). The experienced group did not take the delayed test due to a scheduling conflict.

Knowledge Integration Construct and Scoring Rubric

The pre-, post-, delayed tests, and the selected embedded notes were coded using the knowledge integration rubric (Table 2). The rubric specifies a general sequence of levels of knowledge integration (Liu et al., 2008). Each knowledge integration item has a specific scoring rubric based on the item content. Column 2 in Table 2 shows the general framework that runs across all items; Column 3 describes the specific scoring rubric for the particular item Hair; Column 4 provides typical student responses. The first author coded all the items. To ensure that the coding process is reliable, two graduate students separately coded a random sample of pre- and post-tests (n = 20). The pre- and post-tests were mixed so raters did not know which one they were grading. The inter-rater reliability for all items is greater than 0.8.

Analysis of these and other knowledge integration items revealed that items scored following the general framework form a coherent Item Response Theory scale, have good reliability, and good validity (Liu et al., 2008).[3]

Table 2. Knowledge integration scoring rubric and example using item Hair. The item asks students to explain 'why Chris's hair stands up after being combed on a dry day.' Level describes the level of knowledge integration for the score

Score	Level	Description	Students' responses
0	*No answer* *Off-task*	[blank] Students write some text, but it does not answer the question being asked.	[blank] I don't know. Guessed.
1	*Irrelevant/incorrect* Have incorrect/ irrelevant ideas. Make links between relevant and irrelevant ideas.	Responses do not add new information, irrelevant to the context, or scientifically incorrect.	Because of friction. Static electricity in the air [note: incorrect connection between static electricity and air]. It stands up as an attempt to regain electrons by the surrounding area.
2	*Partial* Have relevant and correct ideas but do not fully elaborate links between them in a given context.	One or several without connections of the statements about charging process, charging status, and force using either the particle model or the charge model.	Because the electrons in the comb move to Chris's hair strands. The charge of the comb changed his hair making it repel itself. [The response did not specify the same type of charge on hair.]
3	*Full* Elaborate a scientifically valid link between two ideas relevant to a given context.	Meaningfully connect two of the statements about charging process, charging status, and force (see above) using either the particle model or the charge model.	Strands of hair repel each other because his hair is charged and like charges repel. The electrons transferred from the comb to the hair are repelling each other.
4	*Complex* Elaborate two or more scientifically valid links among ideas relevant to a given context.	Meaningfully connect three of the statements about charging process, charging status, and force (see above) using either the particle model or the charge model.	By combing his hair, Chris is giving each strand a charge which, on a dry day, does not dissipate quickly, since each strand has the same charge, they repel each other and extend out in all directions.

Representing Knowledge Integration Trajectories

Knowledge integration is a complex cognitive process. To capture student progress in knowledge integration, we coded explanations on ideas and links between the three views of electrostatics presented in the unit (charge based, particle based, and energy based), between different aspects of electrostatics (charging status, charging process, and interaction mechanism), and between scientific ideas and everyday phenomena. We see all these links are essential for an integrated understanding. The integration of the three views enables students to use different ways to explain electrostatics phenomena. The links between the three aspects of electrostatics help students develop in-depth understanding of the phenomena. The connections to everyday experience help students see the value and relevance of science knowledge. The electrostatics unit was designed to help students make all three types of connections (see the arrows in Figure 2). All of the pre- and post-test items except the item Electroscope (a new observation) include an everyday experience scenario.

For the links among scientific ideas, we coded the three views: charged based, particle based, or energy based (see the columns in the left side box in Figure 2). We expected the particle-based view to build on the charge-based view. Since the energy-based view is more abstract and comprehensive, we expected it to be built on the particle-based view by adding the electric field and energy ideas. We categorized students' explanation types and examined the trends from the pre- to post-test to capture student trajectories.

We scored student explanations for three key aspects of electrostatics: charging status, charging process, and interaction mechanism (see Figure 2). Charging status refers to whether an object is positively charged, negatively charged, or neutral. Charging status can also be described at the particle level (e.g., negatively charged means excessive electrons) or electric potential (e.g., accumulated charges build up a high electric potential). Charging and discharging processes refer to how particles or charges transfer from one object to another, or how particles realign during induction. The energy-based explanation adds that particles tend to move to minimize the potential energy. The interaction mechanism refers to relationships among charged objects or particles such as opposite charges attract while like charges repel, or

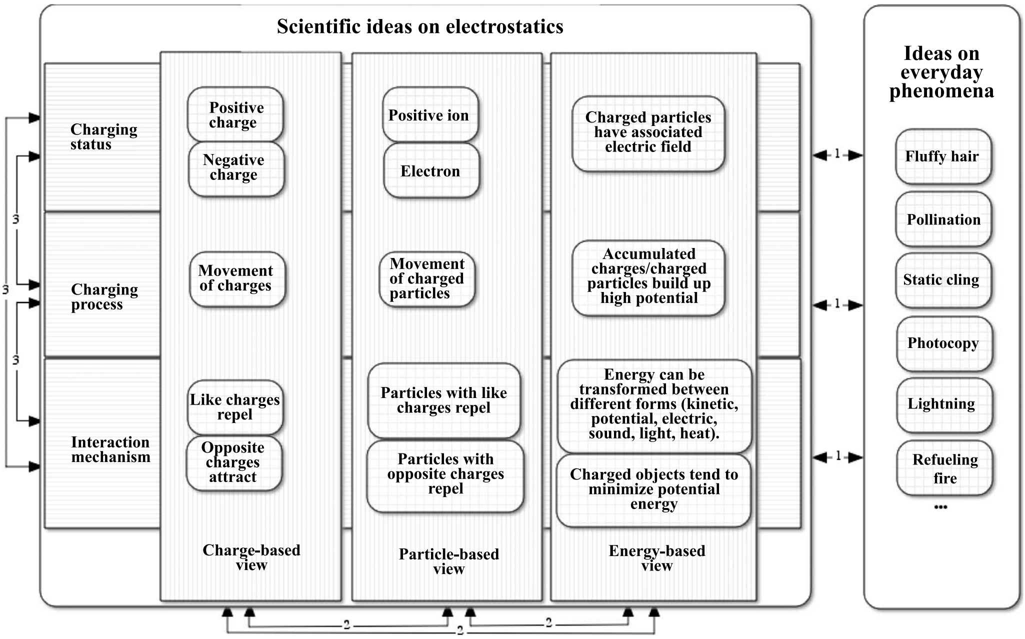


Figure 2. Possible connections among students' ideas about static electricity. Students can link: scientific ideas to everyday phenomena (arrows 1); the three views of electrostatics (arrows 2); ideas about aspects of electrostatics (arrows 3)

Table 3. Statements associated with the three views of electrostatics illustrated for item Hair

Key statements	Charging status	Charge process	Interaction mechanism
Charge-based view	Strands of Chris's hair carry the same charge.	Charges transfer from one material to the other (does not matter which to which). Chris's hair is charged after being combed.	Like charges repel (opposite charges attract). Strands of Chris's hair repel each other.
Particle-based view	Chris's hair contains excessive electrons (or lacks electrons).	Electrons transfer from one material to the other (does not matter which to which).	Electrons repel each other. Strands of Chris's hair repel each other.
Energy-based view	Electric potential energy of hair is high after combing.	Combing his hair produces an electric field.	The electric field of his hair causes his hair to stand up.

electrons and positive ions attract each other. The interaction can also be described using electric fields instead of action-at-a-distance. These key aspects of electrostatics can be described using any of the views of electrostatics.

These aspects of electrostatics are illustrated in student explanations shown in Table 3. For example, in item Hair, a student used a charge-based view and stated that strands of hair repel each other because 'his hair is charged and like charges repel.' This connects the final charging status (similarly charged) and interaction mechanism (repulsion between charged objects). Another student, using a particle-based view, stated that 'the electrons transferred from the comb to the hair are repelling each other.' This statement involves the transfer process of electrons (charging process) and repulsion between them (interaction mechanism). Both students received a knowledge integration score of 3.

Statistical Analysis

Non-parametric statistics were calculated for individual items to compare students' results on pre- and post-tests for both groups (Wilcoxon signed-rank test in repeated measures, see Siegel & Castellan, 1988). A repeated measures analysis of variance (ANOVA) was run to compare the means of the pre-, post-, and delayed tests for the typical group. Chi squares were calculated to compare the frequencies of response patterns. Effect sizes were reported by using Cohen's (1988) *d* statistic.

Limitations

This study was conducted in complex learning contexts. It assesses the overall impact of the instruction including the technology-enhanced unit, the teacher contributions, and the peer interactions. Using embedded prompts, we can document progress before and after specific events (e.g., using a visualization). This study uses identical pre- and post-tests, which may inflate outcomes. However, the constructive nature of knowledge integration items (students need to explain what happens) suggests that memorization is not sufficient for success. The sample size of the study is small and student absences reduced the sample size.

Results and Discussion

The onsite observations and interviews revealed that the unit was implemented as intended. Students could navigate the steps easily and found the science challenging. Many remarked that they learned new things, enjoyed doing the hands-on activities, and liked the computer visualizations. Both teachers agreed that the unit run was successful. They provided feedback on how to improve the unit and planned to run the unit again in the future.

Progress of Typical and Experienced Students

The typical and experienced students made significant overall gains from pre- to post-tests on the knowledge integration items (Table 4). For the typical group, the pre-test average was 0.96 compared to 1.70 for the experienced group; the post-test average for the typical group was 1.47 compared to 2.70 for the experienced group. Based on the Wilcoxon signed-rank test, the students also made significant gains on all individual items except the item Hair for the typical group. As can be seen, the post-test average for the typical group was lower than the pre-test average for the experienced group. The average effect size gain was greater for the experienced students than for the typical students (typical group, effect size = 0.81; experienced group, effect size = 2.21; see Table 4).

The typical students started with very few correct ideas. The majority of the students only had incorrect or irrelevant ideas. On the post-test, many students added one valid idea but few could generate valid links. In the experienced group, most students started with one correct but isolated idea (a knowledge integration score of 2) on all items except the item Escope. Their average scores increased about one knowledge integration level. Students in the experienced group earned post scores close to the score of 3 (indicating one valid connection). Thus, experienced students started with some correct but isolated ideas, added ideas, and integrated existing and new ideas. For the item about the electroscope, experienced students lacked ideas on the pre-test and the average scores increased about one knowledge integration level. On the post-test, most had one correct idea.

These results show that the unit is effective in multiple contexts and across a broad spectrum of student knowledge levels. This is important because teachers often need to instruct students with a wide range of prior knowledge, and learning environments can be designed to meet the needs of students with varied prior experiences.

The experienced group had the advantage of an experienced teacher, which may explain the more substantial effect size gain for these students (Linn, 2006b;

Table 4. Results for the pre-, post-, and delayed tests for typical and experienced groups

		Mean				
School	Items	Pre (*SD*)	Post (*SD*)	df	*Z*	*d*
Magnet	Hair	2.00 (0.99)	3.21 (1.04)	33	4.02***	1.20
	Balloon	1.65 (0.60)	3.00 (0.35)	33	5.11***	2.76
	Silk	1.85 (0.93)	2.56 (0.89)	33	3.20***	0.78
	Escope	0.94 (0.95)	1.76 (0.92)	33	3.48***	0.88
	Shock	2.06 (1.04)	2.97 (0.83)	33	3.30***	0.96
	Average	1.70 (0.49)	2.70 (0.41)	33	5.03***	2.21
Typical	Hair	1.56 (0.85)	1.78 (0.89)	26	1.15	—
	Balloon	1.19 (0.79)	1.70 (0.78)	26	2.43*	0.65
	Silk	0.96 (0.85)	1.37 (0.97)	26	1.98*	0.45
	Escope	0.44 (0.75)	1.04 (1.06)	26	3.00**	0.66
	Shock	0.63 (0.93)	1.48 (1.34)	26	3.02**	0.74
	Average	0.96 (0.54)	1.47 (0.71)	26	3.50***	0.81
	Balloon[a]	1.63 (0.67)		24	–0.85	—
	Silk[a]	1.30 (0.84)		24	–1.43	—

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

[a] Delayed test (typical group only) was administered two months after the post-test. The Wilcoxon signed rank tests were conducted for the typical school students who took both the post- and delayed tests ($n = 25$).

Varma, 2006). Observations revealed that the experienced teacher frequently held brief discussions based on students' emerging ideas. For example, when the teacher heard a pair of students mentioning that a charged pen deflected tap water, he asked the whole class to stop for a minute and think about why this was happening. The teacher then conducted a demonstration. In contrast, the novice teacher was less sophisticated when interacting with students. This observation echoes the results of other studies showing the benefit of teacher experience (Lee, Linn, Varma, & Liu, 2010).

Delayed Test for Typical Students

To measure retention of knowledge, a delayed test was administered two months after instruction to the typical group. Using data from 23 students who took all the three tests (pre-, post-, and delayed tests), ANOVA (repeated measure) shows that both post-test and delayed test are significantly better than pre-test (within-subject effect, $F(2,44) = 3.99$, $p = 0.026$) (see Figure 3).[4] These results attest to the value of the knowledge integration framework for promoting integrated ideas. Consistent with other work, when students link ideas they remember them better (e.g., Richland, Bjork, Finley, & Linn, 2005). In addition, integrated ideas are more likely to arise and be revisited in the future (Bjork, 1994).

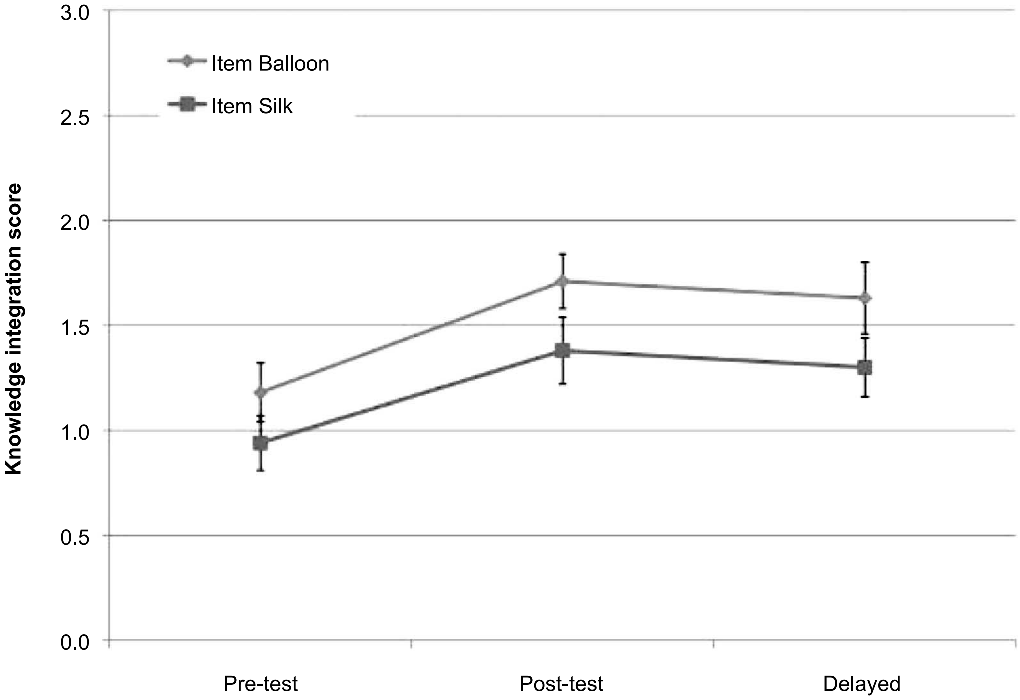


Figure 3. Typical student pre-test, post-test and delayed posttest scores for common items. Each error bar stands for one unit of standard error

Progress on Views of Electrostatics from Pre-Test to Post-Test

To characterize progress on the three views of electrostatics, we categorized students' explanations on four knowledge integration items in the pre- and post-test (we omitted the item Shock in this analysis since most students listed methods of discharging without presenting views on electrostatics). We coded for the three views of electrostatics in the unit (charge, particle, and energy) plus for ideas expressed in colloquial language rather than scientific language (these were not necessarily misconceptions). Responses that did not fall into these four categories were categorized as 'other' (see Figure 4).

The students' response pattern on the post-test is statistically different from that on the pre-test ($\chi^2 = 57.6$, df = 4, $p < 0.001$). Students used fewer colloquial language terms (from 13% to 1%). More responses used charge-based ideas (from 38% to 45%) or particle-based ideas (from 31% to 47%). However, the responses using energy-based views remained low (from 1% to 4%). This suggests the need to strengthen the connections to energy in understanding electrostatics.

We looked at combinations of views to gauge progess in knowledge integration. For example, when responding to item Hair a student may state both the charge-based view and the particle-based view. We calculated the percentage of combined

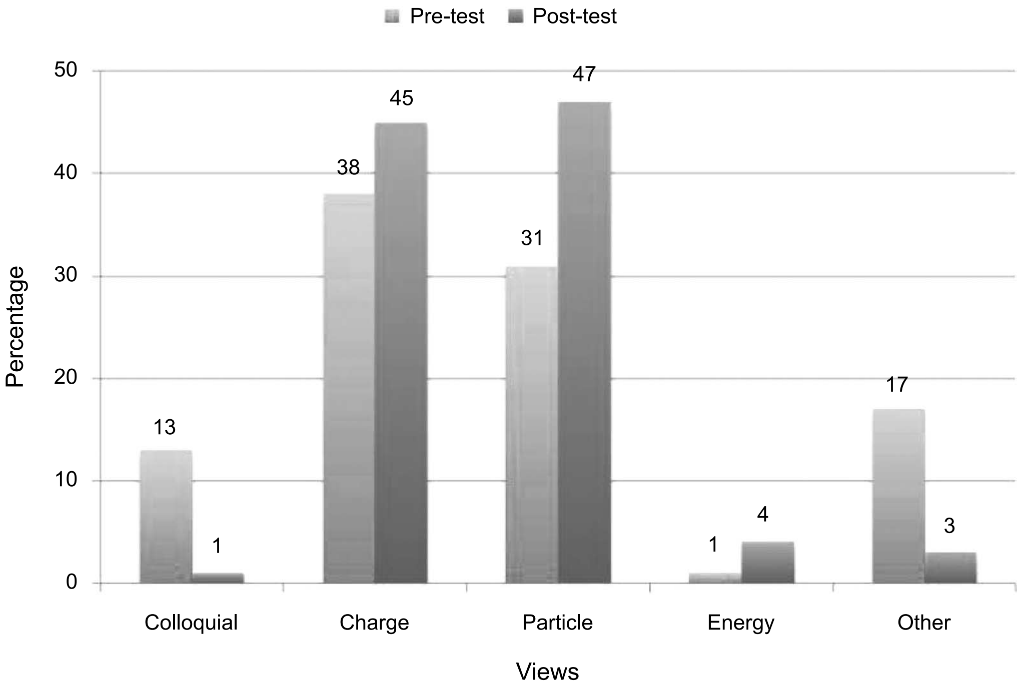


Figure 4. Comparison of student explanations in pre-test and post-test

responses to individual items as the ratio of the number of all combined responses to the number of all responses. Combined responses increased from 6% in the pre-test to 22% in the post-test.

To assess consistency of responses on the test, we looked at students' responses across items. Students may use different views depending on the items. For instance, a student may use the charge-based view to explain the item Balloon and the particle-based view to explain the item Escope. We coded student responses as relatively consistent when they used the same type of views to respond to three out of the four items. The percentage of explanation consistency was calcaluted by dividing the number of students who used relatively consistent explanations by the number of total students participated. Consistency increased from 26% to 42%. This finding suggests that students were progressing in the coherence of their ideas. Both the increase in consistency and the increase in combined responses show the benefit of the knowledge integration framework used to guide curriculum design.

Student Trajectories for Induction

To clarify the trajectory for induction (a key concept in electrostatics), we looked at students' performance on item Balloon in the pre- and post-tests and on three embedded notes (Figure 5). Two embedded notes occur before the balloon and wall visualization (note pre) and one note occurs after the visualization (note post).

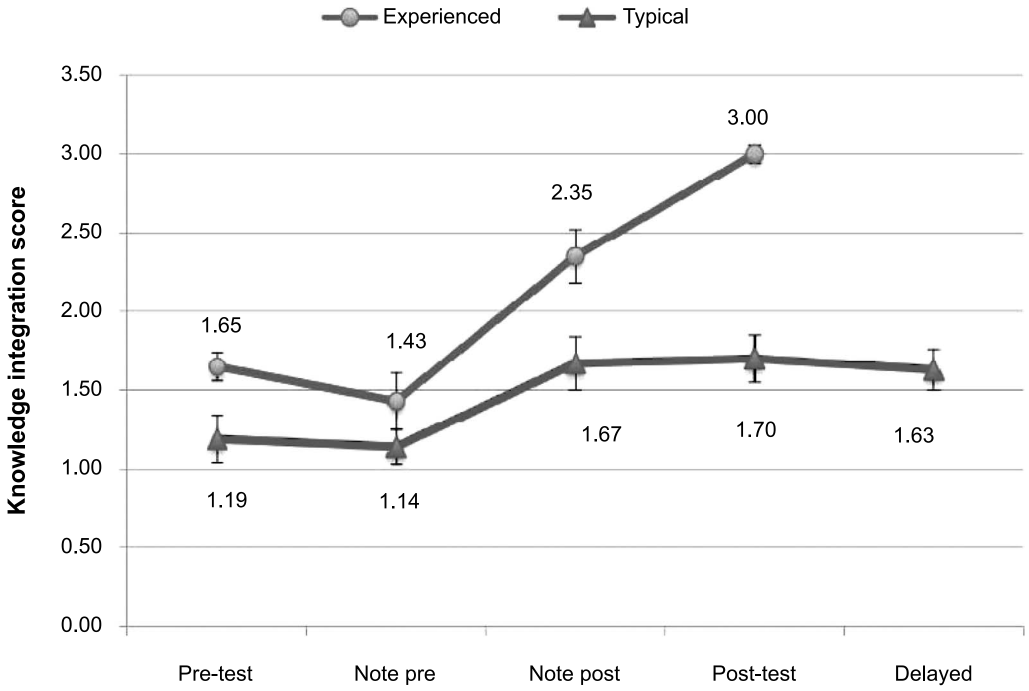


Figure 5. Student performance on induction across tests. Numbers are mean knowledge integration scores. Each error bar stands for one unit of the standard error

We also included the results of the item Balloon from the delayed test for the typical group.

Students in both groups scored significantly higher on the post-test than the pre-test induction item (typical group, effect size = 0.65; experienced group, effect size = 2.76; see Table 4). The quality of embedded notes on induction was statistically improved for both groups after the visualization activity (typical group, effect size = 0.79; experienced group, effect size = 1.20). This finding suggests that both groups profited from the visualization when they wrote their embedded notes in class. By the post-test, students in the typical group retained their ideas while those in the experienced group had actually progressed further, connecting their ideas to other electrostatics topics (knowledge integration score of 3, see Figure 5).

Based on students' responses, we also developed an emergent framework (Table 5) to examine patterns of student explanations on *induction*.[5] Some students used a particle-based view employing the idea of movement-of-electrons and the idea of interaction-between-particles. The movement-of-electrons idea highlights the realignment of electrons during induction process. The interaction-between-particles idea is a general idea used to explain electrostatics. Some students used a charged-based view employing the idea that charged-attract-neutral (an idea specific to induction) and the more general idea of interaction-between-charges/charged-objects.

The overall response pattern after the visualization is statistically different from that before the visualization ($\chi^2 = 90.9$, df = 5, $p < 0.001$). More than half of

Table 5. Students' explanations of induction

Views	Ideas	Sample student responses
Particle-based reasoning	Movement-of-electrons: the motion of electrons contributes to the attraction between the balloon and the wall.	Induction is caused by electrons moving within the objects. If the balloon has a positive charge close to the wall, then the wall's electrons will move towards the outer edge of the wall to the balloon. If the balloon has a negative charge close to the wall, then the wall's electrons will move away from the balloon to the other side of the wall.
	Interactions between particles: electrons attract positive ions and repel electrons and vice versa.	When an object is positively charged, it attracts the electrons from the neutrally charged wall. When an object is negatively charged, it attracts the protons from the neutrally charged wall.
Charge-based reasoning	Interactions between charges or charged objects: opposite charges attract each other, like charges repel each other.	Induction is when a neutral object becomes temporarily charged, if the balloon is negative then the portion in the field of the wall will be positive and vice versa.
	Charged attract neutral: a charged object attracts a neutral object.	The wall is neutral, and the balloon is (negatively/positively) charged. Thus, the two will attract. We have proved that charged objects attract non-charged objects, and the balloon follows this rule.
Other views/ no response	Balancing the quantity of particles/charges: particles/ charges want to transfer to other places to balance the distribution.	The balloon has more electrons than protons. The balloon wants to transfer its electrons so it is attracted to the neutrally charged wall.
	No new information or other ideas.	I don't understand the question. The attraction force overpowers the repulsion force because the wall is positively charged. The wall cannot do anything to stop the upcoming of the menacing balloon.

the students used particle-based ideas (movement-of-electrons and interactions-between-particles) to explain induction after working with the visualization, compared to only 9% before the visualization. The percentage of students who gave no response/non-normative ideas or the popular alternative idea balancing-the-quantity-of-particles/charges dropped from 44% to 30%. The percentage of students who only used charge-based concepts (interaction-between-charges/charged-objects and charged-attract-neutral) dropped from 49% to 19%.

Trajectory Case Studies on Induction

Our results show that both groups of students benefited from dynamic visualizations even though they started with varied prior knowledge. Consistent with knowledge integration framework, many students held multiple explanations including existing and new ideas (e.g., diSessa, 1993). The students incorporated their prior knowledge in the process of learning new ideas from dynamic visualizations. The following two case studies on induction illustrate this point.

Case 1: Integrating new and existing ideas. Responding to a prediction prompt before seeing the balloon and wall visualization (the sixth step in Activity 3, henceforth Step 3.6 in the unit), Jack and Kate (pseudonyms are used in the paper) stated that 'the wall is neutrally charged and charged materials will attract to neutrally charged objects.' Here, they used a charge-based view (charged-attract-neutral) to explain their predictions. After working with the visualization, the students explained:

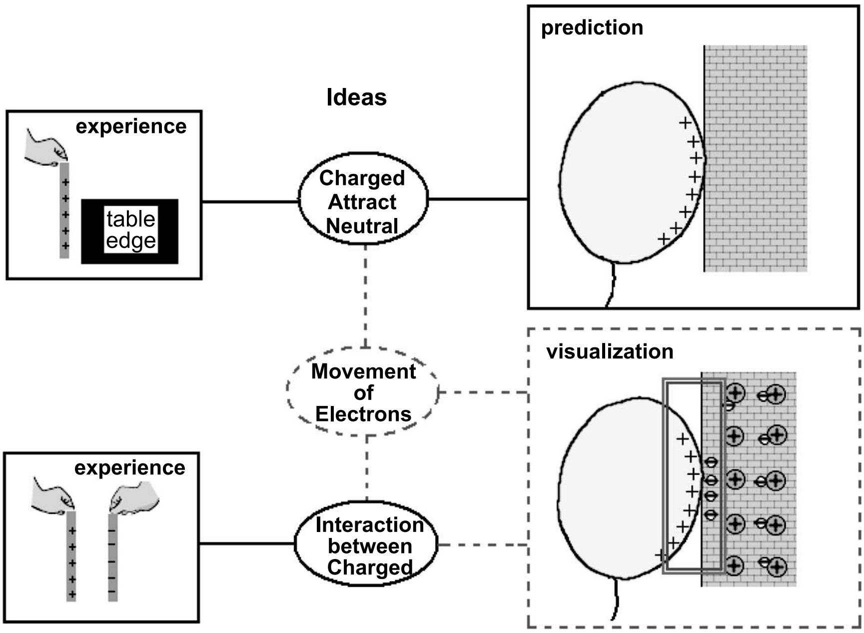
> Induction is caused by *electrons moving within the objects* [1]. When a charged object approaches a neutral object, *the charged object forces the electrons to move* [2] so *the area where the charged object touches the neutral object becomes oppositely charged* [3], *forcing the two objects to attract each other* [4]. (Italics and numbers added by the authors)

This statement not only contains multiple connections between ideas, but also indicates dual views. Statements [1] and [2] indicate that the students incorporated the idea of movement-of-electrons, a particle-based view. Statements [3] and [4] suggest that the students employed the idea of interaction-between-charges/charged-objects, a charged-based view, to account for induction.

Jack and Kate incorporated a new idea from the visualization into their repertoire of ideas. Prior to the balloon and the wall visualization, they learned two relevant ideas from the hands-on experience (Figure 6, Case 1). They learned the idea charged-attract-neutral from their observation of the interaction between charged and neutral objects, as indicated by their response to the second question in Step 2.4: 'We observed that they (charged tapes) were both attracted to the normal object (a neutral object such as a table edge).' They also learned the idea interaction-between-charges/charged-objects from the hands-on experiment they did with charged materials. In their response to the fourth question in Step 2.4, they stated: 'The tapes attract each other if they are oppositely charged.'

When making predictions before they saw the visualization, they applied the charged-attract-neutral idea since they recognized that the wall as a whole is neutral. When the group used the visualization, they observed that the electrons are moving towards or away from the charged balloon. The new idea movement-of-electrons was meaningfully added as indicated by Statements [1] and [2]. Furthermore, they noticed that the area on the wall closer to the balloon has a net charge opposite to the balloon (highlighted in double-lined box in Figure 6, Case 1). Their attention to a specific region (i.e., attending to the edge of the wall closer to the balloon instead of the whole wall) was possibly cued by the visualization showing that the balloon moved towards the left edge of the wall and some electrons in this region moved towards or away from the charged balloon. This attention to the specific region was reinforced by their prior knowledge. Instead of attributing the net attraction to the distance effect, they concluded by using the interaction-between-charges/charged-objects idea to explain that the edge of the wall could be interpreted as being

Case 1: The new idea is incorporated into existing ideas



Case 2: The new idea refines existing ideas.

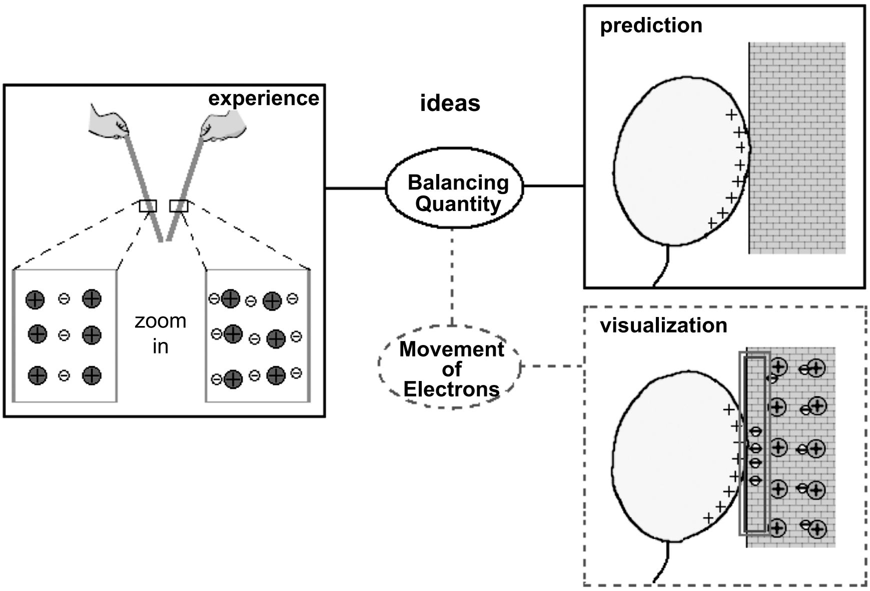


Figure 6. Diagrams of the interactions between student ideas and visualization. The double-lined box within the visualization box refers to the specific area to which students may attend. Ellipses refer to student ideas; lines refer to connections; dotted ellipses refer to new ideas; dotted lines refer to new connections

charged.[6] At the same time, they still held the charged-attract-neutral idea since they acknowledged that the wall as a whole was neutral (the term appeared twice in their statement above). As a result they linked the interaction-between-charges/charged-objects and the charged-attract-neutral ideas together in that they used the former to explain the latter. This link involved the addition of the movement-of-electron idea, a new idea illustrated in the dynamic visualization (see Figure 6).

Case 2: Refining existing ideas. Students often think that both positive and negative ions can move in all materials (e.g., Otero, 2004). After viewing the visualization, students grappled with the popular alternative idea about balancing-the-quantity-of-particles/charges. For instance, before seeing the balloon visualization, Sarah and Richard predicted that a negatively charged balloon would be attracted to the wall 'since the balloon is negatively charged, the balloon's electrons try to transfer into the neutral wall.' They also predicted that a positively charged balloon would be attracted to the wall because 'now the positive particles will try to transfer into the wall.' The students held the balancing idea before seeing the visualization. When asked from an atomic perspective, how do materials become charged through rubbing against each other, they wrote 'friction causes an interaction between the particles of the two objects; therefore, the number of electrons becomes uneven among the two.' They asserted that both positively and negatively charged particles could transfer to other materials. The students predicted the attraction between the charged balloon and the neutral wall and believed that both positive and negative particles could transfer to even out (Figure 6, Case 2). While explaining the visualization, they noticed that only negatively charged particles moved. They summarized:

> When an object is negatively charged it attracts to a neutral object because its electrons try to transfer into the neutral object. When an object is positively charged, it also attracts to a neutral object because the electrons in the neutral object want to transfer into the positively charged object.

After adding the idea of movement-of-electrons, they recognized that only the negative particles could move *in this context*. Although the students viewed particles anthropomorphically, saying they 'try' and 'want' to transfer, they made progress. They linked the movement-of-electrons idea with the balancing idea and concluded that the balancing process is made possible through the movement of electrons. As is common when new ideas are added, the students refined but did not replace the balancing idea.

These two case studies of student understanding on induction illustrate how dynamic visualizations, combined with other activities in the unit, can help the integration or refinement of ideas. In both cases, the students added the new idea movement-of-electrons to their repertoire by working with the dynamic visualization. They integrated this idea with their existing ideas in different ways. In the first case, the students shifted from simply using the charged-attract-neutral idea to connecting two existing ideas (interaction-between-charges/charged-objects and charged-attract-neutral) through the new idea movement-of-electrons. The visualization helped them sort out existing and new ideas. In the second case, the students used the movement-of-electrons idea to refine the balancing idea. They added constraints about the types of particles that can move.

In summary, the two case studies reinforce the pattern of knowledge integration that arises when students study the unit that emphasizes developing coherent understanding. The cases resonate with the findings for combined explanations and consistency of explanation usage. The activities have the capability of reinforcing the emphasis on knowledge integration.

Conclusion

Our analysis shows how students integrate the three views of electrostatics (charge, particles, and energy views) in the technology-enhanced inquiry unit. The knowledge integration design allowed students to explore the visualizations and identify ways that their ideas differed from those in the visualizations. The reflection questions helped students reconcile these views. Students gained about one knowledge integration level as the result of instruction, which was a significant improvement in terms of their knowledge organization. Specifically, after the unit the experienced students were successful in connecting across views of electrostatics, while the typical students started to make connections. Delayed tests show that typical students were able to sustain their understanding over a period of two months. In addition, since most of the knowledge integration items present scenarios using everyday observations (e.g., fluffy hair, plastic wrap cling, and electrostatic shocks), the scores also indicate that the students were able to tie electrostatics ideas to everyday observations.

In terms of specific explanations, the pre-tests, post-tests, and embedded notes show that many students integrated the charge-based and the particle-based views to account for their observations. The post-test responses also show that very few students incorporated the energy related ideas. Energy is a fundamental but difficult topic in learning physics (Liu & McKeough, 2005; Papadouris, Constantinou, & Kyratsi, 2008). Only one day of the five-day unit addresses the energy-based view and integrates it with the other views. The unit sought to connect to prior knowledge of potential energy and kinetic energy using the example of a freefalling object but many students were puzzled by the concepts. To make the connection ideally, students should have a prior knowledge of mechanics and experience making connections between energy and the behavior of individual particles. They need to connect these ideas to everyday observations. These results suggest that the instruction about the energy view should be refined and that the unit would benefit from additional activities on energy to help students better integrate this view. Such expansions are challenging given the numerous topics in the state standards and the use of state pacing guides (see Linn, 2010).

In addition, this research shows that students need opportunities to refine their ideas about balancing charges. One possible direction is to add a virtual experiment where students make predictions and test their ideas about the impact of the magnitude and charge status of objects on their interactions.

Knowledge Integration Framework

One aim of design study research is to strengthen the theoretical framework guiding the work (Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003). The knowledge integration framework aligned the curriculum, assessment, and pedagogy in this research (Lee et al., 2009). The framework takes account of the diversity of student ideas, and offers ways to help students sort out these ideas. The integration process was supported by opportunities for students to generate their ideas, to distinguish their ideas from the normative ideas in the visualizations or experiments, to learn to use evidence to support their claims, and to develop arguments that connected ideas.

This unit was designed to guide connections between everyday observations, charge-based views, particle-based views, and energy-based views through multiple levels of representations (particle visualizations, charge animations, and everyday situations) (Kozma & Russell, 1997, 2005; Shen & Confrey, 2007). For instance, to understand electrostatic induction, it is helpful to connect observations of attracting balloon and wall, interactions between two types of charges, and movements of atomic particles.

The study shows how dynamic visualizations can help students link their everyday observations with atomic-level explanations. The visualization provides an animated analogy between observed phenomena and unseen processes and clarifies the nature of the atomic-level phenomena. The visualizations have the benefit of making scientific ideas visible and make the abstract particle-level explanation more salient. They showcase the charging status by showing plus or minus signs or the different quantity of positive or negative ions, and the charging process by simulating the movement of the particles.

The diversity of ideas held by students raises challenges for instructional design that a knowledge integration perspective can address. We started by documenting the kinds of connections students make and identifying connections that act as obstacles to learning because they are difficult to distinguish from normative ideas. For example, the balancing idea makes sense superficially but needs refinement to focus on electrons under certain conditions. Another example is the connection to the energy-based view which we will explore more thoroughly in the next phase of revision.

By stressing the connections between everyday experience and scientific explanations, the unit allowed students to apply ideas in complex settings. One key condition may be that the instructor elicited ideas gained from previous experience that needed to be distinguished from the new ideas. Perhaps students would otherwise just separate school and everyday events and ignored possible connections between them. Another key condition may be that the instructor used multiple everyday situations. Students may achieve broader integration of ideas by using diverse contexts. In addition, these relevant contexts made instructors more accessible to students.

Open-ended assessment items allowed the researchers and the teachers to appreciate the kinds of connections students make when they grapple with complex examples of electrostatics. The detailed scoring rubrics capture this process by rewarding normative connections and showing shifting patterns of the types of connections. Our data support that students can offer more complex explanations after working with the technology-enhanced electrostatics unit. This trend, however, does not prevent them from forming more coherent accounts at the instrument level (i.e., the percentage of students who consistently used similar types of explanation across items increased).

In summary, this paper reports on how two groups of students, one typical and one experienced, both benefited significantly from an online unit on electrostatics that uses dynamic visualizations to link different aspects of electrostatics and combine charge, particle, and energy views with everyday life experience. The analyses illustrate how students add and link ideas about electrostatics in general and about the concept of induction specifically. The impact of the unit is large for both learning contexts. The dynamic visualizations employed in the unit show substantial benefit for student understanding.

Acknowledgments

This material is based upon work supported by the National Science Foundation (NSF) grant REC-0334199, Center for Learning and Teaching on Technology Enhanced Learning in Science (TELS). Any opinions, findings and conclusions expressed in this paper are those of the authors and do not necessarily reflect the views of the NSF. The authors appreciate the helpful comments and edits from Suparna Kudesia and other TELS research group members and the feedback provided by the anonymous reviewers of the journal.

Notes

1. Comparing to the previous version (Casperson & Linn, 2006), one major change in terms of topic coverage is that the new unit focuses on static electricity and only briefly mentions electric circuit. A unified treatment of electrostatics and electric circuits needs additional instructional time (Sherwood & Chabay, 1999). Another major difference is that the previous unit emphasizes literacy and historical development of the knowledge on electricity whereas the current unit incorporates hands-on experience and the connections between scientific views and students' everyday life.
2. The video can be accessed from the website of the Petroleum Equipment Institute (http://www.pei.org/). The chemical aspect of refueling fires (e.g., combustion) is not addressed in this unit. It is addressed in the WISE unit—Will Gasoline Powered Vehicles Become a Thing of the Past?
3. The Wright map (Wilson, 2005) of the results shows that the electrostatics item difficulties are well spread out along the logit units. Fit statistics are within the range of 0.75–1.33, indicating that the Rasch partial credit model fits the data well. The EAP/PV reliability coefficient is 0.77.
4. When computing F, we used the average of item Balloon and item Silk to represent the knowledge integration scores in pre-, post-, and delayed tests, since only these two items are measured in the delayed post-test. We used results from students ($N = 23$) who took all the three tests.

5. When we categorized student explanations based on Table 5, each student response was treated as one unit. For example, if a student presented two explanations (e.g., movement-of-electrons [ME] and interaction-between-charges/charged-objects [IC]), we counted each as half. The reader should not equate the mixture of explanations with knowledge integration connections of ideas. Even within one type of explanation (say, ME), students may present several ideas and make connections among them, hence receiving high knowledge integration scores.
6. The distance effect refers to the mechanism that the attraction between the excessive charges on the balloon and the opposite charges in the wall is greater than the repulsion between the excessive charges on the balloon and the like charges in the wall since the distance between the excessive charges on the balloon and the opposite charges in the wall is smaller than that between the excessive charges on the balloon and the like charges in the wall.

References

Benseghir, A., & Closset, J. L. (1996). The electrostatics–electrokinetics transition: Historical and educational difficulties. *International Journal of Science Education, 18*(2), 179–191.

Bjork, R. A. (1994). Memory and metamemory considerations in the training of human beings. In J. Metcalfe & A. Shimamura (Eds.), *Metacognition: Knowing about knowing* (pp. 185–205). Cambridge, MA: MIT Press.

Bransford, J., Brown, A., & Cocking, R. (2000). *How people learn: Brain, mind, experience, and school committee on developments in the science of learning.* Washington, DC: National Academy Press.

Casperson, J. M., & Linn, M. C. (2006). Using visualizations to teach electrostatics. *American Journal of Physics, 74*(4), 316–323.

Chabay, R. W., & Sherwood, B. A. (1999). Bringing atoms into first-year physics. *American Journal of Physics, 67*(12), 1045–1050.

Chang, H.-Y., & Shen, J. (2008, June). *How can student logs inform the design of interactive, dynamic visualizations for science learning?* Symposium presented at the 8th International Conference of the Learning Sciences (ICLS) 2008. Utrecht, the Netherlands.

Clark, D. B., & Jorde, D. (2004). Helping students revise disruptive experientially supported ideas thermodynamics: Computer visualizations and tactile models. *Journal of Research in Science Teaching, 41*(1), 1–23.

Clark, D. B., & Sampson, V. (2007). Personally-seeded discussions to scaffold online argumentation. *International Journal of Science Education, 29*(3), 253–277.

Clark, D. B., & Sampson, V. (2008). Assessing dialogic argumentation in online environments to relate structure, grounds, and conceptual quality. *Journal of Research in Science Teaching, 45*(3), 293–321.

Clement, J. (1993). Using bridging analogies and anchoring intuitions to deal with students' preconceptions in physics. *Journal of Research in Science Teaching, 30*(10), 1241–1257.

Cobb, P., Confrey, J., diSessa, A. A., Lehrer, R., & Schauble, L. (2003). Design experiments in educational research. *Educational Researcher, 32*(1), 9–13.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Hillsdale, NJ: Lawrence Erlbaum.

Cuthbert, A. F., & Slotta, J. D. (2004). Designing a web-based design curriculum for middle school science: The WISE 'Houses In The Desert' project. *International Journal of Science Education, 26*(7), 821–844.

Davis, E. A. (2003). Prompting middle school science students for productive reflection: Generic and directed prompts. *Journal of the Learning Sciences, 12*(1), 91–142.

Davis, E. A. (2004). Knowledge integration in science teaching: Analyzing teachers' knowledge development. *Research in Science Education, 34*(1), 21–53.

diSessa, A. (1993). Towards an epistemology of physics. *Cognition and Instruction, 10*(2–3), 105–225.

Eylon, B. S., & Ganiel, U. G. (1990). Macro-micro relationships: The missing link between electrostatics and electrodynamics in students' reasoning. *International Journal of Science Education, 12*(1), 79–94.

Frederiksen, J., White, B., & Gutwill, J. (1999). Dynamic mental models in learning science: The importance of constructing derivational linkages among models. *Journal of Research in Science Teaching, 36*(7), 806–836.

Gilbert, J. K. (Ed.). (2005). *Visualization in science education (Vol. 1): Models and modeling in science education.* Dordrecht: Springer.

Gobert, J. D., & Pallant, A. (2004). Fostering students' epistemologies of models via authentic model-based tasks. *Journal of Science Education and Technology, 13*(1), 7–22.

Guruswamy, C., Somers, M. D., & Hussey, R. G. (1997). Students' understanding of the transfer of charge between conductors. *Physics Education, 32,* 91–96.

Harrington, R. (1999). Discovering the reasoning behind the words: An example from electrostatics. *American Journal of Physics, 67*(7), 58–59.

Kali, Y. (2006). Collaborative knowledge-building using the Design Principles Database. *International Journal of Computer Support for Collaborative Learning, 1*(2), 187–201.

Kali, Y., Linn, M. C., & Roseman, J. E. (Eds.). (2008). *Designing coherent science education.* New York: Teachers College Press.

Kali, Y., Orion, N., & Eylon, B. (2003). The effect of knowledge integration activities on students' perception of the earth's crust as a cyclic system. *Journal of Research in Science Teaching, 40*(6), 545–565.

Kozma, R. B., & Russell, J. (1997). Multimedia and understanding: Expert and novice responses to different representations of chemical phenomena. *Journal of Research in Science Teaching, 34*, 949–968.

Kozma, R. B., & Russell, J. (2005). Students becoming chemists: Developing representational competence. In J. Gilbert (Ed.), *Visualization in science education* (pp. 121–146). London: Kluwer.

Lee, H.- S., Linn, M. C., Varma, K., & Liu, O. L. (2010). How do technology-enhanced inquiry science units impact classroom learning? *Journal of Research in Science Teaching, 47*(1), 71–90.

Lee, O., Eichinger, D., Anderson, C., Berheimer, G., & Blakeslee, T. (1993). Changing middle school students' conceptions of matter and molecules. *Journal of Research in Science Teaching, 30*(3), 249–270.

Lewis, E., & Linn, M. (2003). Heat energy and temperature concepts of adolescents, adults, and experts: Implications for curricular improvements. *Journal of Research in Science Teaching, 40*(Suppl. 2003), S155–S175.

Linn, M. C. (2006a). The knowledge integration perspective on learning and instruction. In R. K. Sawyer (Ed.), *The Cambridge handbook of the learning sciences* (pp. 243–264). New York: Cambridge University Press.

Linn, M. C. (2006b). WISE teachers: Using technology and inquiry for science instruction. In E. A. Ashburn & R. E. Floden (Eds.), *Meaningful learning using technology: What educators need to know* (pp. 45–69). New York: Teachers College Press.

Linn, M. C. (2010). Designing standards for lifelong science learning. *Journal of Engineering Education, 99*(2), 103–105.

Linn, M. C., Clark, D. B., & Slotta, J. D. (2003). WISE design for knowledge integration. In S. Barab (Ed.), *Building sustainable science curriculum: Acknowledge and accommodating local adaptation* [Special issue]. *Science Education, 87,* 517–538.

Linn, M. C., Davis, E. A., & Bell, P. (Eds.). (2004). *Internet environments for science education.* Mahwah, NJ: Lawrence Erlbaum.

Linn, M. C., Davis, E. A., & Eylon, B.-S. (2004). The scaffolded knowledge integration framework for instruction. In M. C. Linn, E. A. Davis, & P. Bell (Eds.), *Internet environments for science education* (pp. 47–72). Mahwah, NJ: Lawrence Erlbaum.

Linn, M. C., & Eylon, B.-S. (2006). Science education: Integrating views of learning and instruction. In P. A. Alexander & P. H. Winne (Eds.), *Handbook of educational psychology* (2nd ed., pp. 511–544). Mahwah, NJ: Lawrence Erlbaum.

Linn, M. C., & Hsi, S. (2000). *Computers, teachers, and peers: Science learning partners*. Mahwah, NJ: Erlbaum.

Linn, M. C., Lee, H.-S., Tinker, R., Husic, F., & Chiu, J. L. (2006). Teaching and assessing knowledge integration in science. *Science, 313,* 1049–1050.

Liu, O. L., Lee, H.- S., Hofstetter, C., & Linn, M. C. (2008). Assessing knowledge integration in science: Construct, measures and evidence. *Educational Assessment, 13*(1), 33–55.

Liu, X., & McKeough, A. (2005). Developmental growth in students' concept of energy: Analysis of selected items from the TIMSS database. *Journal of Research in Science Teaching, 42*(5), 493–517.

Mazur, E. (2004). *Electrostatic interactions*. Retrieved September 11, 2008, from http://www.harvard.edu:8182/images/material/299/82/26v2.10.pdf

McDermott, L. C., & Shaffer, P. S. (1993). Research as a guide for curriculum development: An example from introductory electricity, Part I: Investigation of student understanding. *American Journal of Physics, 60*(11), 994–1003.

McIntyre, P. J. (1974). Students' use of model in their explanations of electrostatic phenomena. *Science Education, 58*(4), 577–580.

Miller, C. S., Lehman, J. F., & Koedinger, K. R. (1999). Goals and learning in microworlds. *Cognitive Science, 23*(3), 305–336.

National Research Council. (2000). *Inquiry and the national science education standards: A guide for teaching and learning*. Washington, DC: National Academy Press.

Osborne, R. J. (1983). Towards modifying children's ideas about electric current. *Research in Science & Technological Education, 1*(1), 73–82.

Otero, V. K. (2004). Cognitive processes and the learning of physics part 1: The evolution of knowledge from a Vygotskian perspective. In E. F. Redish & M. Vicentini (Eds.), *Proceedings of the international school of physics 'Enrico Fermi' course CLVI, Italian Physical Society* (pp. 409–445). Amsterdam: IOS Press.

Pallant, A., & Tinker, R. F. (2004). Reasoning with atomic-scale molecular dynamic models. *Journal of Science Education and Technology, 13*(1), 51–66.

Papadouris, N., Constantinou, C. P., & Kyratsi, T. (2008). Students' use of the energy model to account for changes in physical systems. *Journal of Research in Science Teaching, 45*(4), 444–469.

Park, J., Kim, I., Kim, M., & Lee, M. (2001). Analysis of students' processes of confirmation and falsification of their prior ideas about electrostatics. *International Journal of Science Education, 23*(12), 1219–1236.

Richland, L. E., Bjork, R. A., Finley, J. R., & Linn, M. C. (2005). Linking cognitive science to education: Generation and interleaving effects. In B. G. Bara, L. Barsalou, & M. Bucciarelli (Eds.), *Proceedings of the 27th Annual Conference of the Cognitive Science Society* (pp. 1850–1855). Mahwah, NJ: Lawrence Erlbaum.

Roschelle, J. (1995). Learning in interactive environments: Prior knowledge and new experience. In J. H. Falk & L. D. Dierking (Eds.), *Public institutions for personal learning: Establishing a research agenda* (pp. 37–51). Washington, DC: American Association of Museums.

Seethaler, S., & Linn, M. C. (2004). Genetically modified food in perspective: An inquiry-based curriculum to help middle school students make sense of tradeoffs. *International Journal of Science Education, 26*(14), 1765–1785.

Shen, J., & Confrey, J. (2007). From conceptual change to transformative modeling: A case study of an elementary teacher in learning astronomy. *Science Education, 91*(6), 948–966.

Shen, J., Gibbons, P. C., Wiegers, J. F., & McMahon, A. (2007). Using research based assessment tools in professional development in current electricity. *Journal of Science Teacher Education. 18*(3), 431–459.

Shepardson, D. P., & Moje, E. B. (1994). The nature of fourth graders' understanding of electric circuits. *Science Education, 78*(5), 489–514.

Sherwood, B. A., & Chabay, R. W. (1991). Electrical interactions and the atomic structure of matter: Adding qualitative reasoning to a calculus-based electricity and magnetism course. In M. Caillot (Ed.), *Proceedings of the NATO advanced research workshop on learning electricity or electronics with advanced educational technology* (pp. 23–35). Berlin: Springer-Verlag.

Sherwood, B. A., & Chabay, R. W. (1999). A unified treatment of electrostatics and circuits. Retrieved May 9, 2010, from http://citeseerx.ist.psu.edu/viewdoc/summary?

Shipstone, D. M. (1988). Pupils' understanding of simple electrical circuits: Some implications for instruction. *Physics Education, 23*, 92–96.

Siegel, S., & Castellan, N. J. (1988). *Nonparametric statistics for the behavioral sciences* (2nd ed.). New York: McGraw-Hill.

Slotta, J. D., & Linn, M. C. (2009). *WISE science.* New York: Teachers College Press.

Stevens, S. Y., Delgado, C., & Krajcik, J. (2010). Developing a hypothetical multi-dimensional learning progression for the nature of matter. *Journal of Research in Science Teaching, 47*(6), 687–715.

Thacker, B., Ganiel, U., & Boys, D. (1999). Macroscopic phenomena and microscopic processes: Student understanding of transients in direct current electric circuits. *American Journal of Physics, 67*(7), 525–531.

Varma, K. (2006). *Examining the impact of targeted professional development.* Poster presented at the TELS advisory board meeting at the annual meeting of the American Educational Research Association, San Francisco, CA.

Wandersee, J. H., Mintzes, J. J., & Novak, J. D. (1994). Research on alternative conceptions in science. In Gabel, D. L. (Ed.), *Handbook of research on science teaching and learning, a project of the national science teachers association* (pp. 177–221). New York: Macmillan.

White, B., Frederiksen, J., & Spoehr, K. (1993). Conceptual models for understanding the behavior of electrical circuits. In M. Caillot (Ed.), *Learning electricity and electronics with advanced educational technology* (pp. 77–95). New York: Springer-Verlag.

Wilson, M. (2005). *Constructing measures: An item response modeling approach.* Mahwah, NJ: Lawrence Erlbaum.

Wu, H., Krajcik, J. S., & Soloway, E. (2001). Promoting understanding of chemical representations: Students' use of a visualization tool in the classroom. *Journal of Research in Science Teaching, 38*(7), 821–842.

Xie, Q., & Tinker, R. (2006). Molecular dynamics simulations of chemical reactions for use in education. *Journal of Chemical Education, 83*(1), 77–83.