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**Author**
Chiu, Jennifer Lopseen

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# Supporting Students' Knowledge Integration with Technology-Enhanced Inquiry Curricula

by

Jennifer Lopseen Chiu

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Committee in charge:

Professor Marcia C. Linn, Chair
Professor Sophia Rabe-Hesketh
Professor Michael J. Clancy

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# Abstract

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Dynamic visualizations of scientific phenomena have the potential to transform how students learn and understand science. Dynamic visualizations enable interaction and experimentation with unobservable atomic-level phenomena. A series of studies clarify the conditions under which embedding dynamic visualizations in technology-enhanced inquiry instruction can help students develop robust and durable chemistry knowledge. Using the knowledge integration perspective, I designed *Chemical Reactions,* a technology-enhanced curriculum unit, with a partnership of teachers, educational researchers, and chemists. This unit guides students in an exploration of how energy and chemical reactions relate to climate change. It uses powerful dynamic visualizations to connect atomic level interactions to the accumulation of greenhouse gases. The series of studies were conducted in typical classrooms in eleven high schools across the country. This dissertation describes four studies that contribute to understanding of how visualizations can be used to transform chemistry learning. The efficacy study investigated the impact of the *Chemical Reactions* unit compared to traditional instruction using pre-, post- and delayed posttest assessments. The self-monitoring study used self-ratings in combination with embedded assessments to explore how explanation prompts help students learn from dynamic visualizations. The self-regulation study used log files of students' interactions with the learning environment to investigate how external feedback and explanation prompts influence students' exploration of dynamic visualizations. The explanation study compared specific and general explanation prompts to explore the processes by which explanations benefit learning with dynamic visualizations.

These studies delineate the conditions under which dynamic visualizations embedded in inquiry instruction can enhance student outcomes. The studies reveal that visualizations can be deceptively clear, deterring learners from exploring details. Asking students to generate explanations helps them realize what they don't understand and can spur students to revisit visualizations to remedy gaps in their knowledge. The studies demonstrate that science instruction focused on complex topics can succeed by combining visualizations with generative activities to encourage knowledge integration. Students are more successful at monitoring their progress and remedying gaps in knowledge when required to distinguish among alternative explanations. The results inform the design of technology-enhanced science instruction for typical classrooms.

# Dedication

To my family, for your incredible love and support

To my mom, my favorite teacher

# Table of Contents

Abstract ... 1
Table of Contents ... ii
List of Figures ... iv
List of Tables ... vi
Acknowledgments ... vii

**CHAPTER 1: INTRODUCTION AND RATIONALE ... 1**
Developing Integrated Chemistry Understanding ... 2
Knowledge Integration ... 4
Dynamic Visualizations ... 5
Dynamic Visualizations and Knowledge Integration Design Patterns ... 9
Dissertation Overview ... 9

**CHAPTER 2: CHEMICAL REACTIONS CURRICULUM DESIGN ... 12**
Design-Based Research ... 12
TELS Chemical Reactions Design ... 12

**CHAPTER 3: EFFICACY STUDY OF THE CHEMICAL REACTIONS MODULE21**
Rationale ... 21
Study 1: Comparison Study ... 23
Study 2: Longitudinal Study ... 36
Discussion ... 37
Conclusion ... 39

**CHAPTER 4: THE ROLE OF KNOWLEDGE INTEGRATION IN LEARNING CHEMISTRY WITH DYNAMIC VISUALIZATION ... 41**
Rationale ... 42
Methods ... 46
Results ... 47
Discussion ... 52
Conclusions ... 55

**CHAPTER 5: THE IMPACT OF FEEDBACK ON STUDENT LEARNING AND REGULATION WITH DYNAMIC VISUALIZATIONS ... 56**
Rationale ... 56
Methods ... 58
Results ... 61
Discussion ... 66
Conclusion ... 67

**CHAPTER 6: EXPLANATION PROMPT SPECIFICITY AND LEARNING WITH DYNAMIC VISUALIZATIONS ........................................ 68**
Rationale ........................................ 68
Methods ........................................ 70
Results ........................................ 71
Discussion ........................................ 76
Conclusions ........................................ 78

**CHAPTER 7: LOOKING ACROSS THE STUDIES, WHAT CONTRIBUTES TO LEARNING WITH DYNAMIC VISUALIZATIONS? ........................................ 79**
Summary of Findings ........................................ 79
Dynamic Visualization Design Principles ........................................ 85
Implications ........................................ 88

**REFERENCES ........................................ 90**

**APPENDIX A : OUTLINE OF THE ORIGINAL CSI UNIT ........................................ 101**

**APPENDIX B : PRETEST AND POSTTEST ASSESSMENTS ........................................ 102**

**APPENDIX C : SAMPLE ASSESSMENT RUBRICS ........................................ 106**

**APPENDIX D : EMBEDDED ANSWERS FOR CASE STUDIES ........................................ 115**

# List of Figures

Figure 2.1. Screenshot of the chemical reactions curriculum unit. 14

Figure 2.2. Benchmark assessment item used to guide curriculum development. 15

Figure 2.3. Activity structure of the current *Chemical Reactions* unit. 18

Figure 2.4. Example knowledge integration scoring rubric for pretest and posttest items. 20

Figure 3.1. Comparison study visualizations and explanation prompts. 25

Figure 3.2. Student pretest and posttest scores for honors, standard and comparison groups. 27

Figure 3.3. Total pretest and posttest scores for individual TELS students broken down by group. 27

Figure 3.4. Sample student responses to limiting reagent item. 31

Figure 3.5. Student BW's pretest and posttest responses to limiting reagent item. 34

Figure 3.6. RB and JG pretest and posttest responses to chemical representation and limiting reagent items. 35

Figure 3.7. Average knowledge integration scores for TELS pre, post, and TELS and non-TELS delayed year-end assessments. 37

Figure 4.1. Explanation First and Rating First treatment groups. 47

Figure 4.2. Average self-rating scores by treatment group and self-rating prompt. 49

Figure 4.3. Knowledge integration explanation scores by treatment group. 50

Figure 4.4. Average explanation scores and self-rating values for the Rating First group. 51

Figure 4.5. Average explanation scores and self-rating values for Explanation First group. 51

Figure 5.1 External Feedback and Self-Evaluation No-Feedback conditions for revisiting study. 59

Figure 5.2. Pretest and posttest scores for Feedback and No Feedback groups. 61

Figure 5.3. Greenhouse item explanation scores by treatment group. 62

Figure 5.4. Graph of student revisits "from" and "to" each step by treatment group. 64

Figure 5.5. Number of revisits to visualizations in activity two and activities three and four by treatment group. 65

Figure 6.1. Specific-link and General-link treatment conditions. 70

Figure 6.2. Embedded explanation scores by treatment group. 72

Figure 6.3. Average self-ratings by treatment group and question. 73

Figure 6.4. Pretest and posttest knowledge integration scores for General- and Specific-link groups. 74

# List of Tables

Table 1.1. Summary of Empirical Chapters.......... 11

Table 3.1. Means, standard deviations, and effect sizes of pretests and posttests for Honors, Standard and Comparison groups. .......... 26

Table 3.2. Mean scores and standard deviations for pretest and posttest items by group. .......... 29

Table 3.3. Student responses to chemical representation item. .......... 30

Table 3.4. Sample student responses to heat and molecular motion item. .......... 32

Table 3.5. Pretest and posttest scores for embedded prompt analysis student pairs.......... 33

Table 4.1. Number of students, mean score, standard deviations, standardized slopes, t-values, and significance levels for pretests and posttests.......... 48

Table 4.2. Number of student pairs, average embedded rating values and explanation KI scores by treatment group .......... 49

Table 4.3. Pretest and posttest average self-rating means and standard deviations by group. ..... 52

Table 5.1. Mean scores, standard deviations, and effect sizes for pretest and posttests by treatment group. .......... 61

Table 6.1. Explanation scores by treatment and class. .......... 71

Table 6.2. Self-rating scores by treatment and class.......... 73

Table 6.3. Average pretest and posttest scores by treatment, teacher, and class .......... 75

Table 6.4. Average pretest score, gain, duration, duration with visualizations, revisits, and revisits from explanations for treatment groups and honors classes.......... 75

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# Chapter 1: Introduction and Rationale

This dissertation investigates how powerful visualization tools embedded within relevant, meaningful instruction designed to help learners integrate their knowledge can help students form and retain robust understandings of complex scientific phenomena. My research contributes to the educational dialogue by providing ways to make technology effective in real classrooms and offering ways that generative activities such as explanation help students monitor and refine ideas in technology-enhanced settings.

This research focuses on how computer visualizations can transform the way learners understand scientific phenomena. Dynamic visualizations enable learners to observe and experiment with phenomena at very small or large scales of time and space. Embedded within inquiry learning environments, these visualizations can help students develop coherent and robust understanding of phenomena, contrary to isolated ideas typically produced by traditional textbook-based curricula. In chemistry, these kinds of visualizations can be especially powerful because students struggle to make sense of chemical phenomena on the molecular level. This inability to connect molecular and observable levels of phenomena accounts for a wide range of student difficulties in chemistry (Johnstone, 1993). Dynamic visualizations can help students develop robust ideas about atomic interactions and use these molecular-level ideas to explain chemical phenomena. However, many students find these visualizations difficult to interpret, and need specific content and self-monitoring guidance to learn most effectively from dynamic visualizations.

My dissertation investigates how technology-enhanced inquiry instruction using explanations and powerful visualizations embedded within knowledge integration design patterns can help learners with diverse backgrounds connect ideas in chemistry and improve understanding of chemical reactions. Specifically, the following questions guided my research:

1. How can we design instruction using technology-enhanced dynamic visualizations to help students link ideas and gain an integrated understanding of chemical reactions?
2. How can explanation prompts help students monitor their understanding while working with dynamic visualizations?
3. How can internal and external feedback affect learning with dynamic visualizations?
4. How do students use general- and content-specific explanation prompts to add, evaluate, revisit and revise ideas while working with dynamic visualizations?

This chapter reviews relevant research to reveal how chemistry students can benefit from technology-enhanced curricula guided by knowledge integration principles. I first identify common student difficulties with learning chemistry. I synthesize literature suggesting that students struggle to visualize the atomic level and make connections to other levels of chemistry. Second, I explore how the knowledge integration learning perspective helps chemistry students construct more coherent and connected networks of ideas. Third, I review prior work demonstrating that powerful dynamic visualizations can help students add normative ideas about the molecular level. Fourth, I investigate how the combination of dynamic visualizations and knowledge integration instructional design patterns and principles can help students evaluate, develop and refine connections among their ideas in technology-enhanced environments, specifically through generation activities surrounding dynamic molecular visualizations.

# Developing Integrated Chemistry Understanding

Chemistry students at all levels have diverse ideas about chemical phenomena (Ben-Zvi, Eylon & Silberstein, 1986, 1987; Boo, 1998; Gabel, 1999; Gabel, Samuel & Hunn, 1987; Nakhleh, 1993; Krajcik, 1991; Yarroch, 1985). For instance, students have trouble understanding the particulate nature of matter -- that matter is made of atoms and molecules in constant motion, and that the properties of these particles determine but are not the same as properties of observable phenomena. Ben-Zvi, Eylon and Silberstein (1986) administered a questionnaire about the nature of matter mid-year to eleven tenth-grade chemistry classes in Israel. The questionnaire asked students to compare the properties of a metallic wire to the properties of an atom taken from the wire, and to compare the properties of the gas after the wire had been vaporized to an atom taken from the gas. Almost half (46.2%) of the students did not differentiate the properties of the substance and of the atom. Ben-Zvi et al. suggest that these students viewed particles as very small bits of the continuous substance. Students may recognize that matter consists of particles, but don't understand that the particles have different properties from the observable substance. These kinds of student ideas persisted after explicit instruction about the history and nature of the atomic model. Similarly, students asked to draw air on a molecular level in closed containers create cloud or continuous models of air (Krajcik, 1991). Other students believe that molecules themselves expand when heated (Gabel, Samuel & Hunn, 1987).

The ability to understand matter at an atomic and molecular level is fundamental to chemistry. It serves as a basis for explaining phenomena such as chemical reactions, phase change, stoichiometry and solution chemistry. Students have multiple intuitive ideas about the particulate level at all age levels, even after taking chemistry courses. For instance, Osborne and Cosgrove (1983) asked students to describe the contents of bubbles within a boiling pot of water. Students from ages 8 to 17 said that the bubbles were made of air, hydrogen or oxygen, contrary to scientifically accepted answers such as water vapor, steam, or water molecules. Bodner (1991) asked the same question of incoming chemistry graduate students who majored in chemistry in college. Almost 25% of over 130 students suggested that the bubbles consisted of air, oxygen, or hydrogen gas. Typical explanations included ideas about air dissolved in water or containers having packets of air that rise up when the water is heated.

Similarly, students have varied ideas about chemical reactions that can be traced to understanding the atomic level. Ben-Zvi, Eylon, and Silberstein (1987) demonstrated that high school chemistry students think of chemical reactions as an additive process rather than an interactive one. Students view a chemical reaction as adding together reactants to form products, such as $H_2$ adding to $O_2$ to form a molecule, instead of a process of bonds breaking and forming. When asked to draw what happens in on a molecular level during electrochemical reactions, 58% of the students drew static representations of the reactions, with only 38.5% indicating a dynamic process after targeted instruction. Boo (1998) interviewed 48 twelfth-grade students about four aspects of familiar chemical reactions: predicted change of reactants and products involved; overall change in energy; the process of change; and the driving force of the change. Most students were able to correctly predict the products of the reaction, however, most students did not have a coherent understanding of chemical bonding and energetics involved in reactions. Many students (48%) thought of the chemical bond as a physical entity and only 10% of the students identified the driving force of a reaction as the decrease in free energy or increase in entropy.

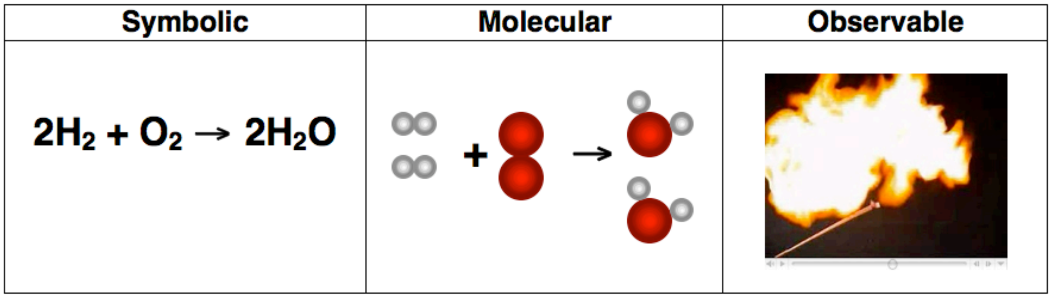


Figure 1.1. Chemical representations of the formation of water.

Research suggests that these difficulties stem from the different levels of representation in chemistry: the *observable* realm of visible phenomena; the *molecular* and *atomic* level; and *symbolic* chemistry, the equations, mathematics and stoichiometry describing phenomena (Figure 1.1; Johnstone, 1993). Students observe phenomena in labs, see molecular pictures of phenomena in textbooks, and use symbols in chemistry to solve math-like problems. Experts easily connect and traverse these different levels, but students often have isolated or partially connected ideas (Kozma, 2003). For instance, students can solve problems with symbolic equations yet have very little understanding of what the symbolic equations mean on a molecular level. Yarroch (1985) interviewed high school students and found that most students could correctly balance chemical equations, but only half could draw an accurate molecular representation of the reaction. Students had difficulty connecting subscripts and coefficients to the molecular level, often representing $3H_2$ as six atoms together instead of three separate molecules. Students associate symbolic representations with algorithmic procedures, do the "math" of stoichiometry and molar calculations, but fail to make connections to the macroscopic or molecular representations of chemical phenomena (Nakhleh, 1993).

Understanding the molecular level poses challenges because students can't "see" or interact with atoms and molecules. Instruction about the molecular level typically uses analogies, models, and static pictures and requires students to visualize these unseen levels. Students have natural intuitions about macroscopic phenomena from nature and daily life, but have no such anchoring ideas about atoms and molecules and the submicroscopic level (Johnstone, 1993). Thus, students promote ideas based on their intuitive experiences such as the continuous forms of matter, instead of integrating more scientifically normative ideas such as the particulate form of matter (Ben-Zvi, Eylon & Silberstein, 1986; Gabel, Samuel & Hunn, 1987). Students also have existing ideas about symbolic representations from other domains like mathematics (Yarroch, 1985), which enables them to integrate math-like ideas into their repertoire (Krajcik, 1991).

Textbooks can promote these fragmented views of chemistry. Textbooks predominantly use the symbolic level for instruction (Gabel, 1999), and present visualizations of macroscopic examples to explain molecular concepts that can ultimately confuse students. Theile and Treagust (1994) investigated the use of analogies in ten textbooks recommended by the state for use in Australian secondary chemistry classrooms. They defined analogies as a mapping between similar features of a student world ‘analog’ to help explain a conceptual target, or chemistry topic. For example, a rotating propeller serves as an analogy of the region of an electron’s influence. The textbooks presented analogies most often to help students visualize molecular concepts. However, textbooks linked 45% of the analogies to the target concept by simple mapping, stating that the analog “is like” the target without additional explanation. Additionally, the limitations of the analogies were explained in only 9% of the cases. This calls upon the teacher to help students make connections between representations, but research suggests that even teachers have difficulty integrating the three levels of representation in their own thinking (Gabel, 1999).

## Knowledge Integration

This research views learning as a process of integrating ideas -- adding, sorting, evaluating, distinguishing and refining accounts of experiences, phenomena, and abstractions (Bransford, Brown & Cocking, 1999; Linn & Eylon, 2006; Smith, diSessa & Roschelle, 1993). To help students build and retain connections among scientifically relevant ideas and existing knowledge, I use the knowledge integration learning perspective (Linn, 1995; Linn, Davis & Bell, 2004). The knowledge integration perspective is based upon research that learners have rich, diverse, and often conflicting ideas about any scientific phenomena from various contexts and experiences (Davis, 2003; Davis & Linn, 2000; diSessa, 2000; Linn, Clark & Slotta, 2002; Slotta, Chi & Joram, 1995; Songer & Linn, 2006). Promoting learning through knowledge integration involves an instructional pattern that includes eliciting student ideas (e.g. existing observations about metal rusting) adding new ideas to build understanding (a molecular visualization of the chemical reaction), helping learners to refine and sort their repertoire of ideas (asking for explanations how the molecular view relates to their observations), and developing criteria for evaluating ideas (asking students to assess their understanding of metal rusting) (Linn & Eylon, 2006).

Linn and Eylon (2006) reviewed research from the last decade using developmental, sociocultural, cognitive, and constructivist perspectives. Although these research programs have different methodologies, terminologies, and theoretical commitments, Linn and Eylon found emergent trends across these perspectives that illustrate the importance of knowledge integration processes. Extensive research documents the wide variety of ideas that learners have about science, scientific inquiry, the nature of science, and science learning (i.e. diSessa, 1988; diSessa & Sherin, 1998; Driver, Newton & Osborne, 1996; Hammer & Elby, 2003; Hofer & Pintrich, 2002; Linn & Hsi, 2000; Metz, 1993; Minstrell, 1992; Pfundt & Duit, 1991; Redish, 2003). These varied ideas refer to descriptive, complex, analogical, or symbolic views held by the learner.

The knowledge integration instructional pattern seeks to build upon and leverage the rich repertoires of ideas and values that students develop. Knowledge integration instructional activities guide learners to add and distinguish ideas. When students use evidence to sort out the alternative ideas that they generate about scientific phenomena they engage in knowledge integration. To promote knowledge integration successful programs start by eliciting ideas about scientific phenomena. This process recognizes the individual backgrounds and experiences that students bring to learning contexts and enables learners to make connections from new instruction to their existing ideas. Successful programs also encourage learners to distinguish alternative ideas. This process helps learners see how existing ideas may conflict with new, normative ideas added during instruction. Knowledge integration activities also help learners construct coherent understanding by developing criteria for the ideas that they encounter. These criteria can be cultivated individually by deliberate and intentional learners or socially constructed in groups and communities of learners. Finally, successful programs help learners evaluate their understanding and connections among their ideas using these negotiated criteria, and sort out and refine their knowledge based on these evaluations.

Ideally, learners monitor and reflect upon their knowledge to find gaps or discrepancies in their understanding, and act to remedy these situations. This research program explores when students do monitor their progress and explores various ways to encourage monitoring.

I use the knowledge integration perspective in my research to leverage chemistry students' existing ideas about chemical reactions and help them make connections among ideas and representational levels in chemistry. For instance, when Yarroch (1985) elicited students' ideas about what $3H_2$ represents on a molecular level, students often produced drawings of six hydrogen atoms connected together. These students demonstrate understanding that accounts for six total atoms, but still have non-normative ideas of coefficients and subscripts representing numbers of molecules and atoms within molecules. The knowledge integration approach encourages adding normative ideas through carefully designed instruction that supports students to reconsider their initial ideas, such as pivotal cases (Linn, 2005). A very simple example might be having students compare molecular representations of $3CO_2$ to $2CO_3$. Students can then add normative ideas and actively distinguish the meaning of the different coefficients and subscripts, encouraging students to realize they may have conflicting ideas. By reflecting and sorting out their ideas, students can refine their ideas about what coefficients and subscripts represent on a molecular level.

This example demonstrates how a single student can have multiple, varied ideas about a single concept such as the molecular representation of a subscript. To leverage the repertoire of ideas held by students, instruction needs to help students not only add ideas, but have them distinguish among their ideas. For instance, instruction focused on adding ideas about $3CO_2$ may result in this student having a normative idea about coefficients and subscripts for the specific case of $3CO_2$. Students can regurgitate that there are 3 molecules of $CO_2$. However, when asked about $2CO_3$, students can still hold alternate ideas about $2CO_3$ (see Chapter 3). Students can add ideas about specific cases but without instruction to help them distinguish their ideas, their overall understanding remains fragmented and incoherent. Supporting students to distinguish among these cases helps students to consider their ideas about coefficients and subscripts for each chemical, helps students to see when their ideas about representations of one chemical may conflict with their ideas for another chemical, and encourages students to connect and refine their ideas about the representations. Helping students add *and* distinguish their ideas supports the development of connected and coherent networks of ideas.

## Dynamic Visualizations

Dynamic visualizations can improve chemistry learning by presenting the unseen, submicroscopic level to students, supporting students to make connections among levels in chemistry, and by spurring students to recognize and refine conflicting ideas. Visualizations refer to external representations commonly used for learning. Typical static visualizations used in science include graphics, models, diagrams, each with different characteristics and different affordances for learners. However, dynamic visualizations differ from static visualizations in that they display processes of scientific phenomena that change over time. Animations can be regarded as simple dynamic visualizations, defined as sets of frames where each new frame appears as an alteration of the previous one (e.g. Tversky, Morrison & Betrancourt, 2002) or a pictorial representation depicting motion of artificial objects (Moreno & Mayer. 2007). Animations can alter properties of objects such as shape or size, can translate objects from one place to another, and make objects appear and disappear (Lowe, 2004). Although the overall value of animation is positive (Hoffler & Leutner, 2007), studies on learning with these simple animations yields mixed results (Chang et al., in preparation; Tversky, Morrison & Betrancourt, 2002). These differences can be traced to outcome measures, variable research settings, and the nature of the animations themselves. Many studies compare animations to static visuals of observable phenomena, such as toilet tanks or brakes for very short durations of time with little to no interactivity (i.e. 30-180s; Mayer et al., 2005). These simple animations offer little more than static diagrams and often do not lead to large learning gains (Chang et al., in preparation).

However, more sophisticated dynamic visualizations such as instructional simulations and computational models enable students to interact and experiment with phenomena on scales that are not directly observable such as molecular dynamics (Pallant & Tinker, 2004), population dynamics (Van Labeke & Ainsworth, 2002), genetics (Buckley et al., 2004) or experiment with visualized concepts like force (White & Frederiksen, 1998), heat (Linn & Hsi, 2000), and electricity (Finkelstein et al., 2005). These visualizations differ from simple animations because students can change variables or settings of the underlying model and see different outcomes. Students can construct understanding by generating hypotheses about a phenomenon, test those hypotheses by interacting or experimenting with the dynamic visualization, and synthesize and refine hypotheses and understanding by reflecting upon the dynamic visualization. These dynamic visualizations often have multiple, linked representations such as dynamic graphs of output variables.

For instance, ThinkerTools (White & Frederiksen, 1998) allows students to build and interact with models of Newtonian physics. Students can create their own models and experiments by drawing objects and barriers and defining properties of those objects such as mass, elasticity and velocity. Students can give impulses to objects and see the resultant motion, accompanied by a time-implicit "dotprint" that shows how far the object moves per second. With these tools, students can discover that adding an impulse in the same direction of motion adds to the velocity, but adding an impulse in a different direction is the vector sum of the two impulses. Students can manipulate settings of the entire model such as gravity and friction, and experiment in extreme cases such as models with no gravity or friction. These capabilities allow students to compare extreme cases of variables that would be very difficult to perform in the real world, such as behaviors of objects in no gravity environments compared to objects in high gravity environments. ThinkerTools also provides measurement tools that enable students to make accurate measurements of observations, graphical representations of variables such as velocity, and analytical tools that enable students to pause, replay, or step through time in their experiments to revisit and refine their conclusions from the model.

Dynamic visualizations are particularly helpful for learning chemistry (Hoffler & Leutner, 2007). Dynamic visualizations allow students to interact with phenomena at the molecular level (Chang & Quintana, 2006; Pallant & Tinker, 2004; Williamson & Abraham, 1995). Dynamic visualizations facilitate connections and refinement of links among molecular, observable and symbolic levels in chemistry by providing multiple, linked representations of a phenomenon (Stieff, 2006; Stieff & Wilensky, 2003; Wu, Krajcik & Soloway, 2001). For example, *4M:Chem* (Kozma, 2003; Russell et al., 2000) presents four coordinated representations of chemical phenomena in a technology-enhanced environment. The representations include a video of an observable lab experiment, the corresponding chemical equation, a dynamic real-time graph, and a molecular animation. Color and timing of events link the representations, for instance, the color of $NO_2$ gas in the video corresponds to the color of the line of the graph and the molecules in the animation. 4M:Chem benefitted students in both lecture-style courses and smaller group settings. Analysis of verbal protocols of students working with the environment in small groups demonstrated that students used the dynamic visualizations to make connections among representations and help integrate isolated ideas. Specifically, students used the visualizations to identify when their ideas conflicted with the presented information and helped refine ideas about chemical equilibrium. For example, two students initially thought of equilibrium as a static state with equal quantities of substance. They initially thought equilibrium would occur when the graphs of the pressures crossed. However, they noticed that the color was still changing in the video and the molecular animation when the graphs crossed, which triggered them to reconsider their ideas about equilibrium as equal quantities. Eventually the student pair used the linked visualizations to think of equilibrium occurring when the pressures leveled off and the graphs remained constant, and came to understand equilibrium as a dynamic process.

Similarly, *eChem* (Wu, Krajcik, Soloway, 2001) guided students through construction of molecular models, 3-D visualizations, and comparisons of molecular and macroscopic representations as part of a 6-week chemical toxin curriculum. Students made significant gains from pretest to posttests that assessed conceptual understanding of molecular and observable levels and the ability to connect levels of representation. Like *4M:Chem*, transcripts of students working with *eChem* suggest that students used the visualizations to help them recognize conflicting ideas and facilitated refinement of ideas of chemical structure and bonding.

These rich and powerful dynamic visualizations enable students to construct understanding of complex phenomena by manipulating situations that are difficult or impossible to create in real classrooms. Chemistry learners can use these rich learning environments to build durable and robust knowledge about molecular levels. Ardac & Akaygun (2004) compared students using a multimedia environment including molecular visualizations, videos, drawings, and interactive assessments to students receiving regular instruction. Students using the visualization-based 2-week curriculum outperformed students with regular instruction from pretest to posttest. Fifteen months later, students in the treatment group still used molecular representations more often and more accurately than students with regular instruction.

Although the majority of recent studies demonstrate that dynamic visualizations benefit learning, some studies show that dynamic visualizations are no more effective than static visualizations (Tversky, Morrison & Betrancourt, 2002). Just as there are successful and unsuccessful texts, there are also successful and unsuccessful visualizations.

A meta-analysis of research over the past decade demonstrates the benefit of dynamic visualization on learning (Chang et al., in preparation). Studies that use interactive dynamic visualizations in classroom settings produce large effects on learning from pretest to posttest. Instruction using dynamic visualizations has an overall greater effect on learning compared to traditional text-based or lab-based instruction.

Although research demonstrates an overall benefit of dynamic visualization on learning, refinements to visualizations and instruction surrounding visualizations can enhance effectiveness (Chang et al., in preparation). Learners can be distracted by perceptually salient parts of the visualization and focus on aspects that may or may not be conceptually relevant. Likewise, learners may focus on particular aspects of visualizations and neglect to investigate the visualization comprehensively. For instance, Lowe (2004) found that students working with an interactive visualization of weather patterns tended to focus on changes in position rather than changes in form of the weather isobars. Learners tended to interact with the visualizations in ways that isolated aspects of space or time, noticed small local changes but neglected to put together or coordinate patterns across the entire visualization.

Just like passively listening to a lecture, learners can passively observe dynamic visualizations. Research suggests that people overestimate their understanding of visualized systems (Rozenblit & Keil, 2002). This can lead to students thinking they understand visualizations when they only focus on superficial aspects. This literature offers clarification to research suggesting that visualizations are cognitively overwhelming for learners (Paas, Renkl & Sweller, 2003). Instead of visualizations overwhelming the processing capacity of learners' cognitive systems (Moreno & Mayer, 2007), learners may simply think they understand and fail to investigate the visualization in a more careful manner. Focusing on reducing cognitive load by making interactions with visualizations easier may not be beneficial for long-term, complex learning. Research demonstrates that instruction fostering easy, quick, and error-free learning may have immediate results, but that kind of instruction often fails to support long-term learning or transfer (Bjork, 1994; 1999; Roediger & Karpicke, 2005).

Interactivity can encourage active engagement with visualizations, but interactivity requires students to have metacognitive skills to learn from dynamic visualizations most effectively. Students need to be aware of important concepts upon which to focus and know how to monitor their understanding to appropriately manipulate the visualization to address gaps in knowledge. For instance, students using a chemical reaction visualization may focus on the impact of heat, manipulate settings to understand that relationship, think they understand it and move on to the next step in the unit. If students aren't aware of other aspects such as bonding, or have a false sense of understanding of the impact of heat, students won't fully utilize the functionalities of replaying or experimenting with other variables. This kind of learner expertise can have a large impact on how students interact with and how much students learn from dynamic visualizations (Lowe, 2004).

Multiple dynamic representations within a single visualization can place similar challenges on learners. Ardac & Akaygun (2004) found that students had difficulty making connections across different representations of the same chemical phenomena. They suggest explicitly prompting students to explain connections across representations and making sure that students reflect upon their understanding. This aligns with other research suggesting the importance of supporting the connection of multiple representations within dynamic visualizations (Ainsworth, Bibby & Wood, 2002; Bodemer et al., 2005).

Suggested improvements to visualizations to support learners making connections among representations include linking similar features of representations with similar colors or other ways to make these implicit connections salient (Kozma, 2003). Although these suggestions may highlight certain aspects of representations, they do not actively support students constructing meaningful knowledge. Learners can still focus upon surface features such as color or shape, passively observe a visualization, and continue without reflecting or recognizing conflicting ideas.

These various perspectives all point to the benefit of combining visualizations with instruction that helps students integrate their understanding and develop self-monitoring skills (Clark et al., 2008; Gobert, 2005; Kali & Linn, 2008). Instruction can help students build upon their existing ideas and engage with relevant aspects of visualizations. Instruction can help students make connections within and across visualizations, and link to ideas outside of the visualizations. Instruction can help students realize that they may not fully understand the visualization and support students to revisit the visualization to remedy gaps in their understanding. Instruction can help students realize that their existing ideas may conflict with new, added ideas, and encourage students to distinguish and refine the connections among their ideas.

This dissertation explores how dynamic visualizations embedded within instruction that encourages knowledge integration processes can improve chemistry learning. These studies report the overall efficacy of this approach and investigate how knowledge integration processes benefit learning with dynamic visualizations.

## Dynamic Visualizations and Knowledge Integration Design Patterns

Embedding dynamic visualizations within knowledge integration instructional patterns can benefit students using dynamic visualizations by encouraging students to build upon their existing knowledge, add scientifically normative ideas, recognize when their ideas conflict and engage students in reflection and refinement of their understanding. Linn and Hsi (2000) reported on studies with visualizations embedded within carefully designed inquiry projects that resulted in powerful and robust effects on integrated understanding. The visualizations of heat flow in combination with the surrounding instruction and instructional technologies of the Computer as Learning Partner project (such as real-time graphing, concept-mapping and argumentation builders) encouraged knowledge integration by *making science accessible, making thinking visible, helping students learn from others* and *promoting autonomy.* These design metaprinciples of scaffolded knowledge integration have been shown to engage students in knowledge integration processes (Linn, Davis & Eylon, 2004). The projects *made science accessible* by scaffolding investigations of everyday phenomena, like the difference between touching metal and wood. The projects *made thinking visible* by enabling students to interact with invisible, abstract concepts such as heat. The projects *helped students learn from others* by building upon students' existing understanding and providing a shared representation around which students could negotiate meaning. Finally, the projects *promoted autonomy* by engaging students in reflection and critique of ideas with visualizations.

In total, this chapter points to the benefit of learning chemistry with instruction that embeds visualizations within knowledge integration patterns. Chemistry students come to class with diverse experiences and ideas about chemical phenomena, need help visualizing atomic and molecular levels, and support to make connections among new scientific ideas at various levels with existing ideas. Research suggests that powerful dynamic visualizations can help students add normative ideas about the molecular level. Instruction based on the knowledge integration framework promotes interconnected and coherent knowledge. Embedding dynamic visualizations within knowledge integration patterns (such as encouraging explanations and self-assessment) can improve learning with visualizations by helping learners build connections among ideas.

## Dissertation Overview

This dissertation investigates how *Chemical Reactions,* a curriculum that combines dynamic molecular visualizations and knowledge integration patterns, can help students make connections among ideas and levels in chemistry.

First, this dissertation explores if this approach can help students make connections among ideas and improve chemistry learning. If so, what kinds of connections do students make and how robust are those connections over time? Chapter 2 discusses the curriculum design and iterative refinement of *Chemical Reactions,* along with methods common to the empirical studies. The first empirical study (Chapter 3) investigated the overall impact of the *Chemical Reactions* curriculum on student understanding. The findings demonstrate that students made connections among their ideas, and significantly improved their understanding even months after instruction. Portions of this chapter have been published in Linn et al., (2006).

Building upon these results, the second study (Chapter 4) investigated why the unit was so successful. The second study explored how students distinguished their ideas in the unit and how the knowledge integration pattern contributed to self-monitoring. Results demonstrated that dynamic visualizations can be deceptively clear, and that explaining encouraged students to identify gaps in their knowledge and distinguish existing ideas from new ideas in the visualizations. Additionally, explanations helped students develop more sophisticated criteria about their understanding.

These findings clarified that self-assessment and explanations engaged students in knowledge integration, namely, by developing criteria and distinguishing ideas. However, the results raised the possibility that external feedback could improve self-assessment and self-monitoring, especially for novice learners. The third study (Chapter 5) explored the role of feedback with develop criteria for and monitor their understanding. The results demonstrated that simple, immediate feedback can actually hinder self-monitoring and encouraged the development less sophisticated criteria. These results were consistent for learners with both high prior knowledge and low prior knowledge. However, generative activities like explanation encouraged all students to revisit new ideas and revise their understanding. Portions of Chapters 4 and 5 have been published in Chiu & Linn (2008) and Chiu & Linn (in press).

The fourth study (Chapter 6) used these results to investigate how the specificity of explanations can encourage different kinds of learners to distinguish ideas. The results suggest that general explanation prompts can encourage learners with low and high prior knowledge to distinguish ideas.

Chapter 7 discusses the overall impact of the empirical studies together with respect to desirable difficulties and constructivist activities, and provides directions for instruction with visualizations as well as refinements to design principles. Table 1 summarizes the empirical research chapters in terms of research questions, key methods and findings.

Table 1.1. Summary of Empirical Chapters

| Chapter | Research Questions | Key Methods | Key Findings |
|---|---|---|---|
| 3: Efficacy study of Chemical Reactions | • How can a technology-enhanced chemistry unit featuring dynamic molecular visualizations embedded within knowledge integration patterns help students connect concepts and representations of chemical reactions?<br>• How can embedded prompts promote connections between dynamic molecular representations and scientific ideas?<br>• How robust are these connections over time? | • Compared pre-, post and delayed assessments for students in TELS and students with traditional instruction<br>• Analyzed embedded assessments to understand how students made connections with visualizations | • TELS students made significant improvements compared to traditional instruction<br>• Students used embedded explanation prompts to build connections<br>• TELS students significantly outperformed students on delayed posttests |
| 4: The Role of Knowledge Integration in Learning Chemistry with Dynamic Visualization (Self-monitoring study) | • How do explanations help students monitor their understanding while using dynamic visualizations?<br>• How do students assess their own learning before and after generating explanations? | • Self-rating prompts before and after generating explanations<br>• Pretest and posttest self-ratings | • Visualizations can be deceptively clear<br>• Explanations help students realize gaps in their understanding<br>• Prompting self-assessment led to more accurate self-ratings |
| 5: The Impact of Feedback on Student Learning and Monitoring with Dynamic Visualizations | • How does external feedback compare to self-assessment without feedback to support learning and self-regulation with visualizations?<br>• What kinds of activities help students regulate their learning in terms of navigation through the unit? | • Compared groups with feedback to groups without feedback<br>• Embedded assessments, pre- and posttests<br>• Log data analysis | • Explanations spurred students to revisit visualizations<br>• Feedback encouraged simple criteria, less self-monitoring |
| 6: Explanation Prompt Specificity and Learning with Dynamic Visualizations | • How do general- and specific-link explanation prompts affect the number of connections and kind of ideas that students connect using dynamic visualizations?<br>• How do general- and specific-link explanation prompts influence how students evaluate their understanding and act upon these judgments in technology-enhanced environments? | • Compared general and specific prompt conditions<br>• Embedded self-ratings and assessments<br>• Pre- and posttests<br>• Log data analysis | • Students used general prompts to reflect upon visualizations, specific prompts to make specific conditions<br>• Students rated themselves as more knowledgeable in general condition<br>• No differences on posttest score |

# Chapter 2: Chemical Reactions Curriculum Design

This chapter describes the design and iterative refinement of the *Chemical Reactions* Technology-Enhanced Learning in Science (TELS) unit. The *Chemical Reactions* module serves as the basis for each of the studies presented in this dissertation. I also explain the development of the knowledge integration assessments and scoring used in each of the empirical chapters.

## Design-Based Research

Design-based research investigates learning in context by systematic design and refinement of generalizable principles for effective classroom instructional interventions (e.g. Design-Based Research Collective, 2003). Design-based research builds from what Brown (1992) and Collins (1992) refer to as *design experiments*, which situated experiments within classrooms to test theories of learning in educational settings. Brown (1992) argued that it is difficult or impossible to isolate factors such as the teacher, students, assessments, curriculum, and classroom ethos. In order to fully understand learning in classroom environments, the entire operating system must be used and carefully engineered to reveal insights into cognition in classroom settings.

Ideally, design-based research methods combine developing theories of learning and designing learning environments (Design-Based Research Collective, 2003). Theory informs the design of the learning environment, and the output of the design research informs the learning theory. Developing learning environments entails iterative cycles of design, implementation, analysis, and refinement (Cobb, 2001). Design-based research should lead to generalizeable principles from which other practitioners and designers can build, and focus upon the interactions within the operating system that refine our understanding of authentic learning.

For example, the BGuILE project guided students through an inquiry-based investigation of natural selection (Sandoval & Reiser, 2004). The curriculum underwent multiple cycles of design, enactment, evaluation and refinement to support students' development of explanations with the technology-based scaffolds. While creating a successful inquiry project, the BGuILE researchers were also able to investigate the role of scaffolds on students' understanding of scientific explanations (Sandoval, 2003).

Throughout this dissertation research, I have employed design-centered methods and conducted design-based experiments in authentic classrooms. I use design experiments to investigate, employ and refine general principles concerning instruction surrounding dynamic visualizations (e.g. Kali & Linn, 2008) and characterize how generative activities help students learn and monitor their understanding with visualizations.

## TELS Chemical Reactions Design

I led the design of the *Chemical Reactions* curriculum module within a partnership that followed the Technology-Enhanced Learning in Science (TELS) design process. The partnership model (Shear, Bell & Linn, 2004) implemented by the TELS center brought together teachers, researchers and scientists to develop curricula to be used in authentic settings while investigating important theoretical issues. *Chemical Reactions* is a five-day curriculum unit (approximately 5-6 hours of class time) that resulted from the TELS partnership and process. The design process of *Chemical Reactions* included testing the curriculum in classrooms and iterative refinement based on results.

## Technology

The TELS partnership unites two technology platforms: the Web-based Inquiry Science Environment (WISE) from the University of California, Berkeley, and Molecular Workbench from the Concord Consortium. WISE is based on over twenty years of computer-based science learning and provides a learning environment to help students develop deep understandings of science (Linn, Davis & Bell, 2004; Slotta & Linn, 2009). The WISE interface gives designers diverse pedagogical tools to put knowledge integration principles into practice (Slotta, 2004). WISE includes pedagogical tools such as online brainstorms and discussions, explanation scaffolding, model building, drawing, and online journals. The TELS partnership combines the WISE environment with powerful dynamic visualizations from the Concord Consortium (Pallant & Tinker, 2004; Xie & Tinker, 2006). The visualizations within the TELS center explore such topics as natural selection, mitosis, airbag safety, and plate tectonics.

My dissertation focuses on the combination of WISE with Molecular Workbench, an environment that offers tools to visualize the collective motions of atoms and molecules based on estimations of classical dynamics and applicable forces. Each run of Molecular Workbench calculates Newtonian approximations of inter-atomic forces to decide how and where atoms will move and bond. Students can interact with these visualizations by changing such variables as heat or concentration. By manipulating these dynamic visualizations of chemical reactions, students have the potential to develop a deeper conceptual understanding of the underlying chemical phenomena. The pedagogical tools offered through WISE enable students to build, refine, and reflect upon their understanding of the visualizations (Figure 2.1).

## Designing to promote knowledge integration

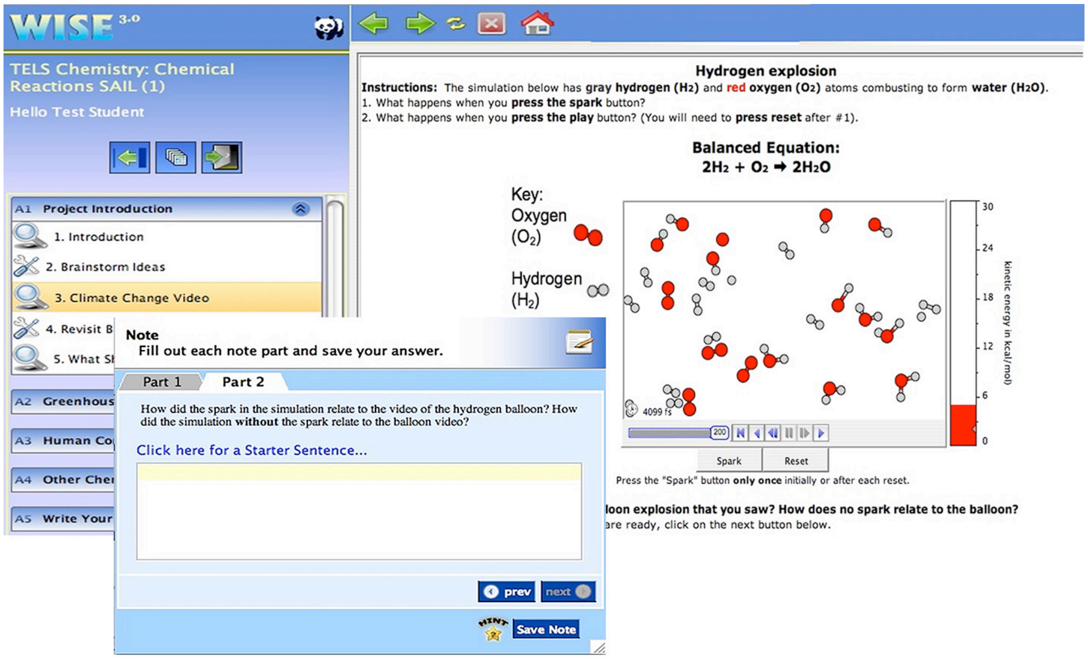
To help students make connections among ideas in chemistry, the curriculum uses design principles and patterns for knowledge integration (Linn & Eylon, 2006) and the scaffolded knowledge integration (SKI) instructional framework (Linn, Davis & Eylon, 2004). The scaffolded knowledge integration framework offers principles for designing effective instruction in science. The framework presents four *metaprinciples* (make science accessible, make thinking visible, help students learn from others and promote autonomy and lifelong learning) that promote knowledge integration within instructional design. These metaprinciples are based upon the results of multiple research contexts and programs (Linn & Hsi, 2000). The four metaprinciples of SKI guided design of *Chemical Reactions* in the following ways:

*Making Science Accessible* enables students to build on previous knowledge, connect new knowledge to preexisting knowledge, and appreciate the relevance of science to their lives. This unit makes science accessible by situating the curriculum within the context of climate change, energy use, and greenhouse gases.

*Making thinking visible* contributes to knowledge integration by modeling and critiquing how ideas are connected and organized in new knowledge networks. Providing multiple representations of scientific phenomena can make thinking visible by highlighting how aspects of the phenomena interact. This study makes thinking visible by providing interactive visualizations of chemical reactions and coordinating these visuals with other representations of chemical reactions. Students also draw their own models of chemical reactions and the greenhouse effect.

The unit *helps students learn from others* by confronting them with the beliefs of others, encouraging students to develop criteria and refine their own understanding. This curriculum implements this design principle in online discussions tools where students discuss climate change and are guided to comment on other students' posts. Students then view a video and subsequently refine or add posts to the online discussion. Students also use the functionalities of the WISE environment to critique each other's final essays at the end of the project. Students create an essay, post it in the online space, and then are guided in the critique of another groups' essay. The students then revise their own essay with the other group's feedback as well as any insights they might have learned from the process of critique. Additionally, students work in dyads to promote collaboration and peer discussion about the instructed concepts. Specific to *Chemical Reactions*, we have found that these collaborations are particularly beneficial (Gerard et al., 2009). Students who come from different levels of expertise help each other learn. The student with less knowledge about the chemistry concepts often has quite proficient computer skills, or engages with the visualizations and notices different aspects than the student with more chemistry knowledge. Students often ask each other to explain concepts or visualizations, which benefits both the explainer and the explainee. These kinds of interactions foster knowledge integration.

*Promoting autonomy and lifelong learning* involves helping students refine their knowledge by encouraging monitoring and reflection. By incorporating reflective embedded prompts, this curriculum encourages the students to monitor their learning. These prompts occur before and after the students encounter the molecular visualizations, and also after adding other new information such as sources of greenhouse gases. Additionally, throughout the module students build towards a letter to their congressperson. At the end of each activity students reflect



**Hydrogen explosion**

**Instructions:** The simulation below has **gray hydrogen ($H_2$)** and **red oxygen ($O_2$)** atoms combusting to form **water ($H_2O$)**.
1. What happens when you **press the spark** button?
2. What happens when you **press the play** button? (You will need to **press reset** after #1).

**Balanced Equation:**
**$2H_2 + O_2 \rightarrow 2H_2O$**

Press the "Spark" button **only once** initially or after each reset.

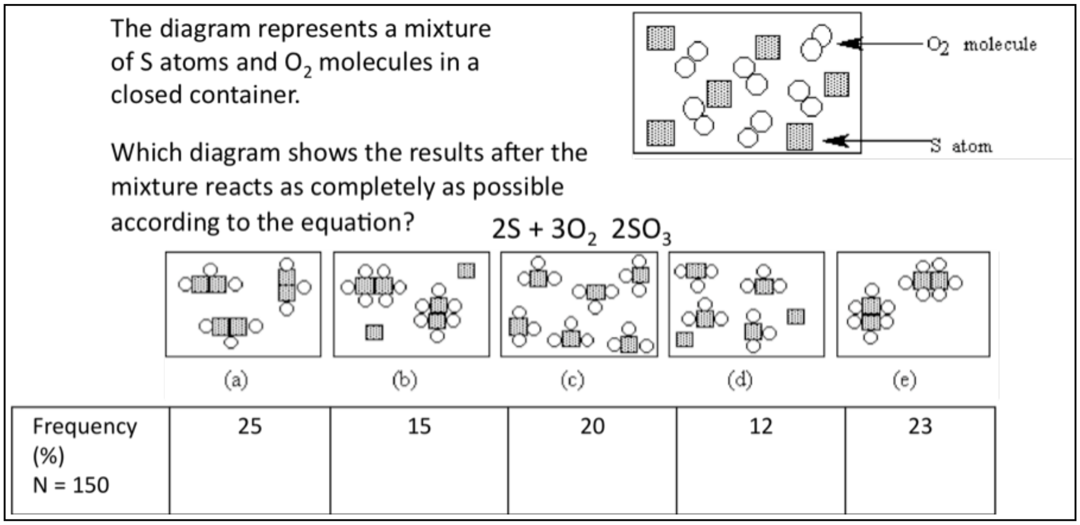
**loon explosion that you saw? How does no spark relate to the balloon?**
are ready, click on the next button below.

Fill out each note part and save your answer.

How did the spark in the simulation relate to the video of the hydrogen balloon? How did the simulation **without** the spark relate to the balloon video?

Click here for a Starter Sentence...

Figure 2.1. Screenshot of the chemical reactions curriculum unit.



The diagram represents a mixture of S atoms and $O_2$ molecules in a closed container.

Which diagram shows the results after the mixture reacts as completely as possible according to the equation?

$2S + 3O_2\ 2SO_3$

| | | | | | |
|---|---|---|---|---|---|
| Frequency (%)<br>N = 150 | 25 | 15 | 20 | 12 | 23 |

Figure 2.2. Benchmark assessment item used to guide curriculum development.

on what they have learned using a persistent journal, where they are encouraged to build upon their understanding and make connections among the science of chemical reactions and everyday consequences such as climate change. In the final activity, students use the journal combined with research from outside sources to create and revise a letter to their congressperson.

## Curriculum focus

The week-long *Chemical Reactions* module helps students understand chemical reactions, limiting reactants and conservation of mass. It helps students link molecular, observable, and symbolic representations. The curriculum development team began by looking at assessments administered to students in local schools and identifying concepts of which students could improve their understanding. Students scored particularly poorly on one item that asked students to choose a molecular representation of products of a reaction with a fixed amount of reactants (Figure 2.2). This item resonated with prior research on student difficulties in chemistry, as well as the teachers, researchers, and scientists involved with the project. We decided to focus on the topic of chemical reactions because it is a fundamental concept in chemistry, later concepts build upon student understanding of chemical reactions, and powerful chemical reaction visualization capabilities were available to us through Molecular Workbench.

From there, we decided to contextualize the unit within climate change. I used to be a chemistry teacher, and many of my students would ask me what chemistry has to do with their everyday life. I used that to shape my teaching to include more relevant connections for students, especially when the course became more math-oriented with stoichiometric calculations. Climate change is a very publicized topic, has direct connections to chemical reactions and students' everyday lives, and opens doors for sophisticated discussions about energy, types of chemical reactions, and social implications.

The first version of the project guided students on an investigation of how chemical reactions relate to global warming, with specific focus on how combustion reactions contribute greenhouse gases (Appendix A). By researching, graphing, and predicting levels of greenhouse gases, students appreciated the importance of chemical reactions. Dynamic visualizations of chemical reactions on a molecular level clarified the science of combustion and its relationship to greenhouse gases and energy use. Students manually created chemical reactions by rearranging atoms and molecules to form desired products to understand symbolic representations of these processes on a molecular scale. Students interactively balanced equations and presented and critiqued reports about various greenhouse gases to consolidate their ideas. The entire project was centered around a "CSI: Chemistry Scene Investigators" theme with agents that led them through their investigation.

Based on student data, teacher input, and classroom observations of the initial enactments, the curriculum unit was refined to streamline the overall guiding theme and visualizations, increase alignment between visualizations and the curriculum, and increase students' refinement and reflection upon their ideas. In the second version of the curriculum, I refined the "CSI" theme to a more general "Chemical Reactions" theme. Feedback revealed that although the theme may have been motivating, some of the high school students found the "CSI" theme distracting. I also refined the first two activities to take out the graphing of atmospheric carbon dioxide, which tended to take time away from the students interacting with the chemistry content. Students would spend time getting acquainted with graphing tools when the overall learning goal was that carbon dioxide levels have increased through time. Because most students have familiarity with that data from the media, I decided to take that activity out and instead use a graph taken from the IPCC publication to start a discussion at the beginning of the activity. Student data led me to take out the mathematical focus of balancing equations and instead focus upon the conceptual connections among balanced equations and what they mean on a molecular level. I revised this aspect of the curriculum because students were balancing equations in the unit without making connections to the molecular and observable representations.

The current version of *Chemical Reactions* guides students through an exploration of chemical reactions, limiting reactants and conservation of mass in the context of climate change (Figure 2.3). Students investigate how chemical reactions relate to climate change by focusing on how combustion reactions release energy that we use for our everyday needs, yet these reactions contribute greenhouse gases. In the first activity, students elicit their ideas about climate change by participating in an online class discussion about chemical reactions and climate change. Students are asked right away about what they have heard in the media and about their initial thoughts on climate change. After posting to the discussion, students watch a video about the science of the greenhouse effect and concerns about climate change. Students then revisit their posts and comment on other groups' posts building upon the information presented in the video. Throughout the unit, students are building an essay to send to their local congressperson about the chemistry of climate change. For each activity, students make notes in a persistent journal about what they have learned and how that relates to climate change.

The second activity guides students to make connections among symbolic and molecular representations in the context of hydrocarbon reactions. The activity begins by presenting the collective need for energy and having students manually combust ethane and methane molecules in visualizations to form carbon dioxide and water. Students add ideas about limiting reactants and stoichiometry by linking these visualizations to balanced equations. At the end of the activity students make connections from the carbon dioxide that is formed in these kinds of combustion reactions to the production of carbon dioxide by cars, power plants, and other sources that students hear about in the media.

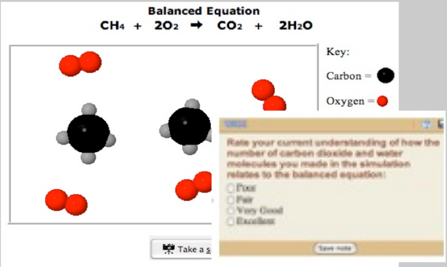
In the third activity, students investigate other chemical reactions that have similar energy output through dynamic visualizations of chemical reactions on a molecular level. Students explore hydrogen as an alternate fuel, linking videos of hydrogen exploding to hydrogen combustion visualizations. Using the visualizations, students can see on a molecular level the consequences of activation energy with an exothermic reaction and make connections to hydrogen combustion on an observable level. The visualizations in this activity help students add and refine ideas about energy and chemical bonding by having students experiment with heat and molecular motion. At the end of the activity, students build upon their notes from the last activity, reflect upon the current activity and make connections to climate change and how these alternate chemical reactions can possibly ameliorate greenhouse gas pollution.

In the fourth activity, students explore how carbon dioxide relates to the global climate. Students interact with visualizations of the greenhouse effect that include infrared radiation, sunlight and clouds to experiment with levels of carbon dioxide and atmospheric energy retention. These visualizations help students distinguish between the greenhouse effect and climate change and understand how products of combustion reactions have consequences on a global scale. Again, students reflect and make notes in their persistent journal about how the greenhouse effect works and how chemical reactions can relate to the climate.

The final activity guides students to put their ideas together in a letter to their congressperson. Students explore various initiatives on outside webpages, such as corporate average fuel economy standards or more sustainable energy sources such as wind or solar. From there, students create an essay to their congressperson by looking over past work in the unit and building from their persistent journal. Students post their essay in an online forum and receive feedback from another student pair. After revising their essay based on the peer feedback, students have the option to submit their essay to their congressperson’s website.

**Activity 1**
Elicits and builds upon student ideas of the greenhouse effect through video and online discussions.

**Activity 2**
Learners relate ideas about hydrocarbon combustion reactions, stoichiometry, and limiting reactants to the greenhouse effect through molecular visualizations of hydrocarbon combustion.

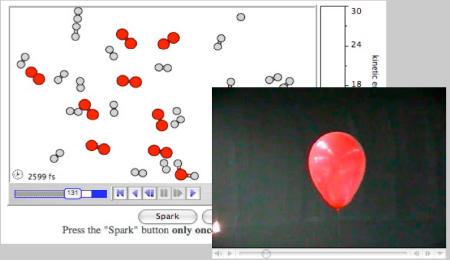


$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$

Rate your current understanding of how the number of carbon dioxide and water molecules you made in the simulation relates to the balanced equation:

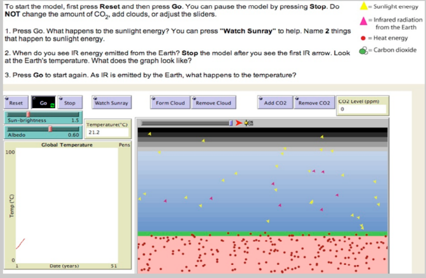
☐ Poor
☐ Fair
☐ Very Good
☐ Excellent

**Activity 3**
Uses dynamic models of hydrogen combustion to guide students' research on alternatives to hydrocarbons for energy, and videos to help students make connections to macroscopic phenomena.



Press the "Spark" button **only onc**

**Activity 4**
Dynamic visualizations of the greenhouse effect help students add ideas about the mechanisms of the greenhouse effect, and how this relates to chemistry and global warming.



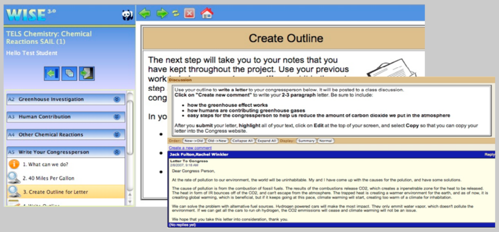
To start the model, first press **Reset** and then press **Go**. You can pause the model by pressing **Stop**. Do **NOT** change the amount of $CO_2$, add clouds, or adjust the sliders.

1. Press Go. What happens to the sunlight energy? You can press **"Watch Sunray"** to help. Name **2** things that happen to sunlight energy.

2. When do you see IR energy emitted from the Earth? **Stop** the model after you see the first IR arrow. Look at the Earth's temperature. What does the graph look like?

3. Press **Go** to start again. As IR is emitted by the Earth, what happens to the temperature?

**Activity 5**
Students synthesize their ideas throughout the project in a letter to their congressperson about chemical reactions and their impact on the global climate.



Create Outline

The next step will take you to your notes that you have kept throughout the project. Use your previous work

Use your outline to **write a letter** to your congressperson below. It will be posted to a class discussion.
**Click on "Create new comment"** to write your **2-3 paragraph** letter. Be sure to include:

- **how the greenhouse effect works**
- **how humans are contributing greenhouse gases**
- **easy steps for the congressperson to help us reduce the amount of carbon dioxide we put in the atmosphere**

After you **submit** your letter, **highlight** all of your text, click on **Edit** at the top of your screen, and select **Copy** so that you can copy your letter into the Congress website.

**Jack Fulton,Rachel Winkler**

**Letter To Congress**
2/8/2007, 9:18 AM

Dear Congress Person,

At the rate of pollution to our environment, the world will be uninhabitable. My and I have come up with the causes for the polution, and have some solutions.

The cause of pollution is from the combustion of fossil fuels. The results of the combustions release CO2, which creates a inpenetrable zone for the heat to be released. The heat in form of IR bounces off of the CO2, and can't escape from the atmosphere. The trapped heat is creating a warmer environment for the earth, and as of now, it is creaiting global warming, which is beneficial, but if it keeps going at this pace, climate warming will start, creating too warm of a climate for inhabitation.

We can solve the problem with alternative fuel sources. Hydrogen powered cars will make the most impact. They only emmit water vapor, which doesn't pollute the environment. If we can get all the cars to run on hydrogen, the CO2 emmissions will cease and climate warming will not be an issue.

We hope that you take this letter into consideration, thank you.

(No replies yet)

Figure 2.3. Activity structure of the current *Chemical Reactions* unit.

## Knowledge Integration Assessments and Scoring

The pretests and posttests assessed the students' knowledge of the learning goals of the unit:

1. Students make and explain connections between molecular, symbolic and observable representations of balanced equations.
2. Students use conservation of mass to balance equations and understand limiting reagents on a molecular scale.
3. Students make connections among the dynamic and interactive nature of chemical reactions (e.g. chemical reactions involve bonds breaking and forming), and make connections among temperature, molecular speed and chemical reactions.
4. Students distinguish the greenhouse effect from climate change, and understand the impact of chemical reactions on the global climate.

Like the curriculum unit, the assessments underwent refinement according to student data and to align with the revised curriculum. Pretests and posttests from all versions of the project included constructed response items that had students drawing molecular representations of symbolic equations, and explaining relationships among levels and concepts, such as heat and molecular motion. Refinement to the assessments included replacing mathematically balancing equation items with items that assessed balanced equations and limiting reactants on a molecular scale. In some cases, assessments were slightly adjusted with specific studies to measure particular constructs. For example, as part of the self-monitoring study presented in Chapter 4, I revised pretests and posttests to include student self-ratings of the concepts to measure students' abilities to judge their understanding. Those adjustments are mentioned within the context of the study. On the first version of the assessments, two test items remained exactly the same from pretest to posttest. The other six items the chemicals or chemical formulas changed, but the structure of the question remained the same. On subsequent assessments pretest and posttests were identical. Pretest and posttest items can be found in Appendix B.

## Analysis

All assessments were scored with the same rubric based on the knowledge integration framework, which identifies the numbers of connections that students make among ideas (Linn et al., 2006). Higher numbers of connections between scientifically relevant ideas resulted in higher KI scores, and signified a more robust knowledge of scientific principles and concepts. For example, question 2 on the pretest asked students to draw a molecular representation of the chemical equation $2H_2 + O_2 \rightarrow 2H_2O$ (Figure 4). In order for the students to transition between the symbolic form of a chemical equation to a molecular representation, students must have a good understanding of the following ideas: coefficients and subscripts on a molecular scale, conservation of mass, and the dynamic nature of a reaction (indicated by chemicals changing form). The rubric coded for the number of connections between these concepts. If the student drew a correct molecular picture of the synthesis of water, the student would have demonstrated a strong connection between all ideas and would receive a score of 4. In contrast, if the student demonstrated no integration of any ideas, then the response would receive a score of 1.

The rubric distinguishes between complete, robust connections between concepts and partial connections between concepts. If a student demonstrated a complete connection, then the connection would have been used consistently throughout the answer. A student demonstrated a

**Question: If a grey circle represents hydrogen, a white circle represents oxygen, and a bond is represented with a line, draw a molecular picture of the following balanced equation: $2H_2 + O_2 \rightarrow 2H_2O$.**
(Possible ideas to integrate: Conservation of mass, molecular understanding of subscripts and/or coefficients, dynamic nature of reaction)

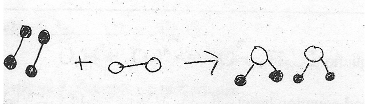
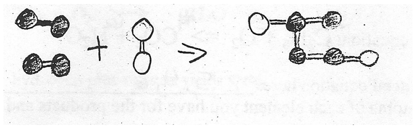
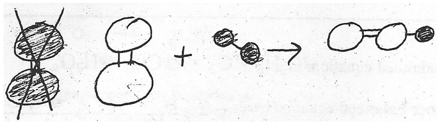
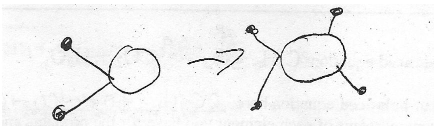
| ***Score*** | ***Description*** | ***Student Example*** |
|---|---|---|
| 4 | Complex link: Two or more scientifically valid links among ideas. |  |
| 3 | Full link: Complete connection among ideas. Students understand how two scientific concepts interact. |  |
| 2 | Partial link: Partial connections among ideas, students consider relevant ideas but not consistent throughout response (i.e. correct molecules but incorrect number) |  |
| 1 | No link: Students have non-normative links or ideas in a given context. |  |
| 0 | No answer/Irrelevant: Students do not engage in given science context. | I don't know |

Figure 2.4. Example knowledge integration scoring rubric for pretest and posttest items.

partial connection between concepts if the student showed inconsistent use of the concept throughout the answer. For instance, the student's response that earned a score of 3 in Figure 2.4 drew the correct molecular structure for $2H_2$ but instead of $2H_2O$ drew a molecule of $H_4O_2$. This student demonstrated full connection to conservation of mass, but a partial connection to coefficients and subscripts. This response was not credited for a complete connection to subscripts and coefficients because this knowledge had not yet been fully integrated into their repertoire.

The scoring guide did not penalize students for aspects of chemical reactions and representations not addressed in the curriculum. For instance, the scoring guide only distinguished basic chemical structure. If students grasped the concept that coefficients relate to the number of molecules and subscripts refer to the number of atoms within molecules, then they received full credit for their response. Other structural concepts such as bond angles and number of bonds (double, triple, etc.) did not affect the overall scoring of the item. Likewise, the rubric did not include topics of energy not covered within the unit. If students did make robust connections to scientifically relevant ideas independently (including scientific concepts other than energy), then the response would receive credit for a robust connection to other knowledge. Scoring rubrics can be found in Appendix C.

# Chapter 3: Efficacy Study of the Chemical Reactions Module

This chapter discusses the design, implementation and efficacy of a new technology-enhanced chemistry curriculum. The curriculum features dynamic visualizations embedded within instruction that encourages knowledge integration. The goal of the unit is to help students connect ideas about chemical reactions on molecular, symbolic, and observable levels.

This chapter reports on two studies: a comparison study between the new curriculum and typical instruction, and a longitudinal study that compared student performance months after implementation of the unit. The comparison study offers insight into how instruction featuring dynamic visualizations can help students add ideas about the molecular level and build connections among ideas at various levels, in contrast to traditional instruction. The longitudinal study offers insight into the transformative power of instruction featuring visualizations. These two studies together investigate the following questions:

1. How can a technology-enhanced chemistry unit featuring dynamic molecular visualizations embedded within knowledge integration patterns help students connect concepts and visualizations of chemical reactions?
2. How can embedded prompts promote connections between dynamic molecular visualizations and scientific ideas?
3. How robust are these connections over time?

To foreshadow the results, the unit helped students form connections among representations and develop complex understandings of chemical reactions as compared to typical instruction. Students participating in the unit outperformed students receiving typical instruction from pretest to posttest and made further gains by the time of the delayed posttest. Detailed analysis of embedded prompts illustrated the types of connections students made within the curriculum and suggests that these connections provided a generative basis for future course activities. These results show how dynamic molecular visualizations in a technology-enhanced curriculum helped students add and connect ideas about chemical reactions on molecular, symbolic and observable levels.

## Rationale

Various types of knowledge are embedded within and distributed across chemistry representations (Seufert, 2003). For each representation, students need to identify the relevant scientific ideas and understand how these ideas are expressed within the representation. For example, to understand a single representation such as $H_2O$, a student must understand what the H, 2, and O signify, what a subscript signifies, and why these three items are connected together within this representation.

For students to understand the relationship among molecular, symbolic and observable levels in chemistry, students need to understand each individual idea, find connections between ideas or phenomena depicted at each level, and distinguish differences and similarities among ideas. For instance, students trying to make connections between a molecular representation of a water molecule and the chemical formula, $H_2O$, need to find connections between the subscript "2" and the number of hydrogen atoms bonded to the oxygen.

Dynamic visualizations in technology-enhanced curricula provide novel ways to augment student learning in science by providing rich representations of scientific phenomena on levels previously unavailable to students (Pallant & Tinker, 2004; Barab, Hay, Barnett & Keating, 2000; see Chapter 1). These visualizations present information interactively, which can help students form a better understanding of scientific phenomena (Edelson, 2001). For example, visualizations of chemical reactions allow students to watch simulations of reactions with atoms forming and breaking bonds dynamically. Students can manipulate such variables as heat and concentration and observe resultant behaviors of atoms and molecules. These visualizations provide a rich environment for students to add ideas about chemical reactions on a molecular level (e.g. Schank & Kozma, 2002), and support students to connect, critique, and refine links among ideas.

Although using technology-enhanced curricula with dynamic visualizations can increase students' connections between representations, researchers warn that these representations can confuse students (Boo & Watson, 2001; see Chapter 1). Students who lack the skills necessary to hold and manage multiple, visually presented ideas may form superficial connections or become overwhelmed trying to process visualizations (Seufert, 2003). Students who have partial understanding may gain confidence in their ideas because the visualization reinforces their impressions (Chiu & Linn, in press). To help students make sense of these visualizations, instruction should guide students to conduct detailed analyses of the ideas added with visualizations and distinguish these ideas from existing, relevant ideas (Ardac & Akaygun, 2004; Wu, Krajcik & Soloway, 2001).

## Knowledge Integration and Design of Instruction

Knowledge integration (Linn, Eylon & Davis, 2004) emphasizes this process of eliciting the students' repertoire of ideas and motivating them to sort out the various connections among the ideas to identify the most valid and useful connection.

The knowledge integration instructional pattern starts with eliciting student ideas about a particular phenomenon (for example, asking "How do chemical reactions relate to the environment?"). Learners then have opportunities to add new ideas to these existing ideas to strengthen understanding (i.e. through a molecular visualization of a chemical reaction). Learners sort and distinguish their ideas and reconcile new ideas with their existing repertoire of ideas (i.e. giving an explanation of how chemical reactions relate to the environment). Specifically, they develop criteria for evaluating ideas (i.e. evaluating their own explanation or understanding and acting upon those judgments by seeking evidence to support or refute their ideas). Finally, learners reflect and consolidate their ideas and build a more coherent view. According to the knowledge integration perspective, students who actively sort out their ideas and develop criteria for distinguishing among ideas gain a more coherent, integrated understanding. This study uses the knowledge integration framework to guide design of the curriculum and assessments (see Chapter 2).

Instruction designed for knowledge integration can help students form more coherent knowledge networks. Linn and Eylon (2006) synthesized results from numerous design studies to describe basic instructional design patterns that leverage from knowledge integration processes to promote understanding. Design patterns engage students in these processes to promote knowledge integration. For instance, the *predict, observe, explain* design pattern has students predict outcomes of phenomena, observe and distinguish predictions from these new observations, and formulate and explain connections between predicted and actual outcomes of the phenomena.

Instruction using knowledge integration design patterns and processes can help students learn from dynamic visualizations. Because students tend to isolate ideas in chemistry and fail to distinguish ideas that they gain through dynamic visualizations, instruction guided by the knowledge integration perspective can be especially beneficial for learning with dynamic visualizations. For example, eliciting exiting ideas can help students activate relevant prior knowledge. Students can add normative ideas through dynamic visualizations. Instruction can help students develop criteria for their understanding of concepts presented with visualizations, and see where their existing ideas may conflict with these new added ideas. As a result, instruction can support students to distinguish these ideas, make connections among relevant ideas and refine links to existing knowledge. Instead of simply adding ideas, knowledge integration encourages students to reflect upon their understanding and revisit information to help distinguish their ideas.

Embedded explanation prompts offer promise as a way to encourage knowledge integration and scaffold connections among ideas in technology-enhanced curricula. Embedded in curricular activities, these prompts ask explicit questions to help students integrate and refine their ideas. In the Web-based Inquiry Science Environment (WISE), Davis and Linn (2000) found that careful use of embedded prompts increased students' integration of middle school science concepts. Embedded prompts can enhance the impact of visualizations by asking students about connections between representations. These prompts can help guide students to generate connections between aspects of the visualizations and ideas about symbolic or observable phenomena.

The studies reported in this chapter evaluated the impact of a new technology-enhanced chemistry curricular unit, *Chemical Reactions*, which combined dynamic visualizations with instruction based on knowledge integration design principles and patterns. The comparison study used pretest, posttest, and delayed posttest assessments to compare students using *Chemical Reactions* to students receiving traditional textbook-based instruction. The comparison study used embedded prompts to both encourage knowledge integration and determine how students integrate their knowledge with visualizations. The longitudinal study used pretests, posttests and delayed posttests to replicate the findings of the comparison study and determine the long-term impact of the *Chemical Reactions* unit.

# Study 1: Comparison Study

## Comparison Study Methods

### *Participants*

A total of 70 students in an urban high school participated in the honors study, standard run, and comparison groups of the *Chemical Reactions* curriculum. Students attended the 10th grade and came from a variety of ethnic and economic backgrounds. The school includes over 50% students from underrepresented populations in science.

Approximately 21 honors chemistry students participated in the honors implementation of the TELS *Chemical Reactions* curriculum unit. For the standard run, approximately 24 general chemistry students participated in the instruction and approximately 25 general chemistry students served as a comparison group, completing the assessments while studying the typical curriculum. The honors class had not yet covered topics of balancing equations, the standard and comparison classes had covered most topics of chemical reactions, balancing equations, and limiting reactants. This was the students' first experience with the TELS interface.

## *Teacher & Implementation*

The same teacher taught all the chemistry classes. The teacher was using WISE for the first time, and learned about WISE at the TELS summer retreat. As part of TELS professional development, a researcher was present in the classroom for at least the first day to help with technical issues.

The teacher selected pairs of students within each class to work through the entire project together, as typical in WISE projects (Linn and Hsi, 2000). Technical difficulties arose during the pilot run of the curriculum when the students loaded the molecular visualizations. Finding solutions to these problems caused the unit to stretch over multiple weeks. The classroom test of the curriculum did not encounter technical trouble and lasted one week.

## *Data Sources*

### *Pretests and posttests*

The teacher administered a paper pretest and posttest to individual students for both the honors and standard runs. The teacher gave the pretest two days before the units began, and gave the posttest following the conclusion of the project. The pretests and posttests assessed the students' knowledge of the learning goals of the unit (Chapter 2).

To control for test taking, the teacher gave identical pretests and posttests to the comparison chemistry classes not running the TELS curriculum. These comparison assessments occurred on the same days as the TELS assessments for the test run. Students in this comparison group received traditional lecture and text-based chemistry instruction instead of the TELS curriculum.

### *Embedded prompts*

Student responses to embedded prompts about the visualizations were analyzed to illustrate the types of connections students made using the visualization/prompt combination (Figure 3.1). Case studies of five student groups chosen to represent a range of prior knowledge based on pretest scores were qualitatively analyzed. The kinds of connections students made were identified (i.e. superficial connections based on color or robust connections based on concepts).

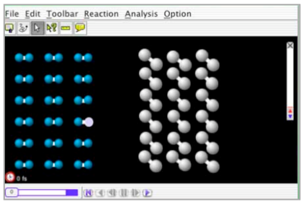
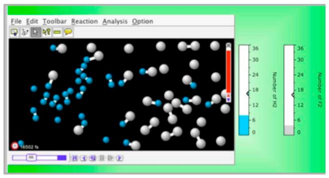
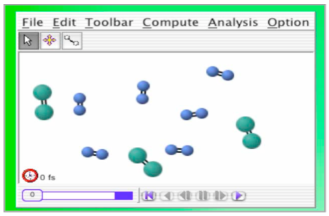
| Activity | Description | Visualization | Prompt Question |
|---|---|---|---|
| 1 | Students manipulate a visualization of a combustion reaction, heat and cool the reaction. |  | Describe what happened to the highlighted hydrogen atom during the reaction. ("When the reaction first started, the H atom…") |
| 2 | Students view the same visualization of a combustion reaction, this time with instantaneous displays of number and concentration. |  | How do the graphs and simulation relate to the balanced equation? |
| 3 | Students manually break and form bonds with different numbers of reactant molecules to form product molecules. |  | How did making water molecules in Molecular Workbench relate to the balanced equation of 2H2 + O2 -> 2H2O? |
| 4 | Students are introduced to limiting and excess reactants through the same exercise as 3. | | Given a certain number of reactant molecules, how does the balanced equation affect the number of product molecules you are able to make? |

Figure 3.1. Comparison study visualizations and explanation prompts.

## Comparison Study Results and Discussion

### *Implementation Results*

The teacher chose her honors chemistry class to pilot test the *Chemical Reactions* curriculum. Since the honors study encountered technical difficulties the teacher postponed the completion of the project several weeks until the technology department at the school could address the issue. This extended length of time may have impacted the pretest to posttest gain by the honors group.

The standard group, consisting of regular chemistry students, worked through the curriculum in a week. As a result of technical difficulties from the honors run, the teacher had one backup computer with preloaded visualizations. Any students who had difficulty opening Molecular Workbench steps could use the backup computer when needed.

### *Pretest and Posttest Results*

To understand how dynamic visualizations and prompts can help students form more integrated views of chemical reactions, this section looks at student results from pretest and posttest assessments. Overall pretest and posttest scores measure how the entire curriculum helped students form more connected understandings of chemical reactions. Effect sizes were calculated using the pooled standard deviation (Cohen, 1988; Rosnow & Rosenthal, 1996). Mean scores, standard deviations and effect sizes for the honors, standard, and comparison group are presented in Table 3.1.

The honors group gained around 5 points from pretest to posttest ($t = 5.44$, $df = 20$, $p < 0.05$). Students in the standard group gained around three points from pretest to posttest ($t = 3.94$, $df = 23$, $p < 0.05$. Mean scores for students in the comparison group did not significantly increase ($t = 1.518$, $df = 24$, $p = 0.14$). Figure 3.2 displays pretest and posttest scores for the honors, standard, and comparison groups of students.

Honors students achieved larger gains from pretest to posttest than the other two groups, with a large standardized effect size. Standard students scored higher on both pretests and posttests than the other two groups. The standard group gained from pre to post, but with a medium effect, smaller than the gain for the honors group. Students in the comparison group who took the pretest and posttest gained little, with a small effect size.

Pretest scores for the honors and standard group are consistent with the performance differences one would expect from students further along in chemistry courses as compared to students in their first semester of chemistry. In addition, the students selected for honors chemistry made more gains from the unit that those in the standard group, possibly because they were more efficient learners (see Figure 3.2). Although the comparison group started with lower pretest scores than standard students, students in the standard run made significant gains while the comparison group scores did not significantly increase. This suggests that students involved in the TELS unit were able to make more connections than those students with typical instruction.

Table 3.1. Means, standard deviations, and effect sizes of pretests and posttests for Honors, Standard and Comparison groups.

| | Pretest | | Posttest | | Effect Size |
|---|---|---|---|---|---|
| | M | SD | M | SD | |
| Honors group (n=21) | 11.1 | 5.3 | 16.4 | 4.3 | 1.09 |
| Standard group (n=24) | 20.5 | 6.3 | 23.2 | 6.3 | 0.43 |
| *Comparison group (n=25)* | *16.3* | *5.5* | *17.4* | *5.7* | *0.20* |

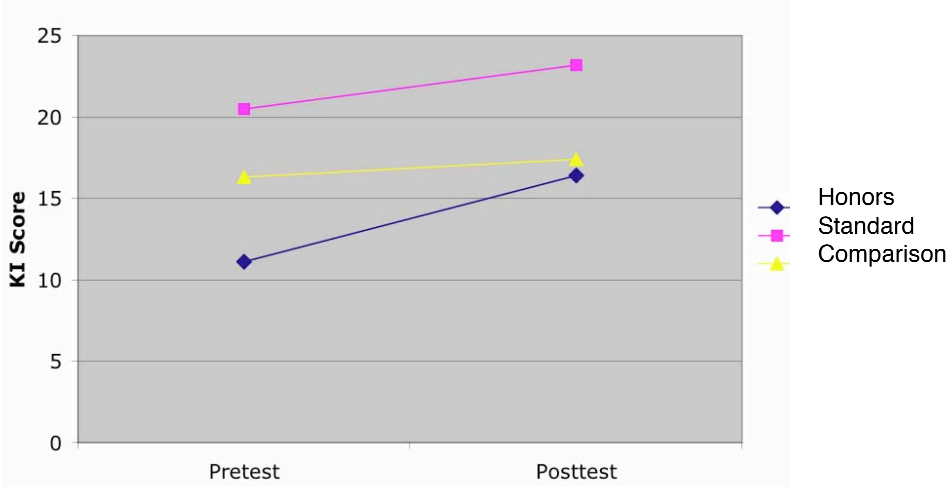


Figure 3.2. Student pretest and posttest scores for honors, standard and comparison groups.

The posttest scores were regressed with pretest scores and group as explanatory variables ($r^2$= 0.68, F(3,66) = 49.98, *p*< 0.001). Pretest score and group had significant effects on posttest scores (Pretest: b = 0.79, *p*=0.001; Honors b=2.91, *p*=.011; Standard b= 2.68, *p*=.014). After controlling for pretest scores, honors and standard groups both individually differed from the comparison group, significant at the .05 level. There was no significant difference between the honors and standard groups after controlling for the pretest (*p*=0.86). This suggests that *Chemical Reactions* helped students make connections among their ideas, independent of where they started on the knowledge integration scale (Figure 3.3).

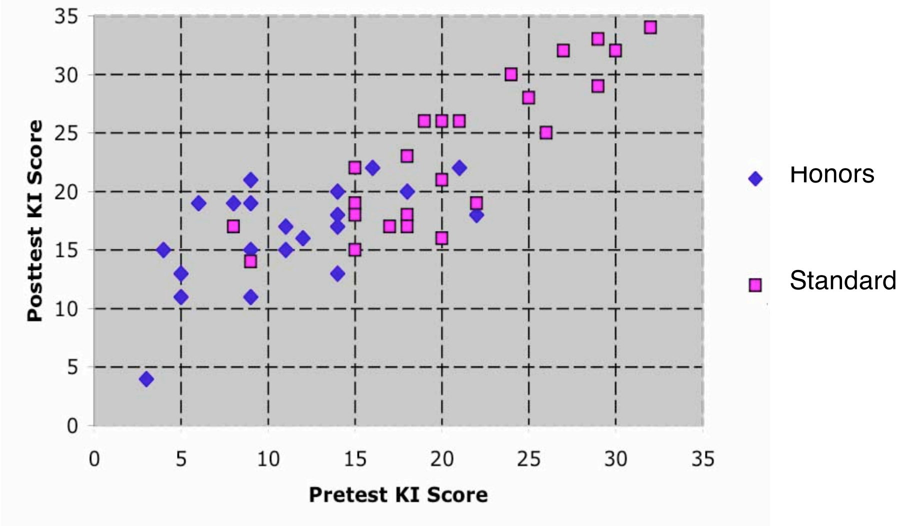


Figure 3.3. Total pretest and posttest scores for individual TELS students broken down by group. Students in the honors group did not have prior instruction on chemical reactions, whereas students in the standard group had prior instruction on chemical reactions.

### *Performance on individual items*

To refine the findings, item level effect sizes were calculated between pretest and posttest assessment for the honors, standard, and comparison groups (Table 3.2). Effect sizes were largest for items testing student knowledge of connections between symbolic and molecular representations, limiting reactants, and the connection between heat and molecular motion. These assessment items covered concepts introduced by the visualizations. Effect sizes were smaller for items that tested a more mathematical knowledge of balancing equations for students in the standard implementation.

### *Chemical representations*

Students in the honors and standard groups made small improvements linking the symbolic and molecular representations for items 1 and 2 where they were asked to draw molecular representations of chemical equations and write equations for molecular representations. The comparison group had even smaller effect sizes.

These questions did not require students to explain their answers or articulate specific differences between concepts or representations. Students involved in *Chemical Reactions* made substantial gains in linking the symbolic and molecular representations for single chemical formulae, with regard to the comparison group (items 3 and 4). For example, item three asked students to explain the differences between molecular representations of $2NO$ and $NO_2$ using symbolic representations. To score well, students needed to explain connections between coefficients and subscripts and what they signified on a molecular level. Both honors and standard students improved their scores for this item, while comparison students did not. On the pretest, some students were able to identify correct symbolic formulae, but most students across groups were not able to explain the connections between the symbolic and molecular representations. On the posttest, honors and standard groups were able to articulate connections between the two representations (Table 3.3). To illustrate, student AP stated the two formulae and identified numbers of coefficients and subscripts on the pretest. On the posttest, AP made connections from the coefficients to the number of molecules.

Item four asked students to draw slightly different symbolic representations in molecular form. In order to receive a high score, students needed to provide clear drawings of connections between representations. Increases in students' scores of items 3 and 4 may reflect students' developing ability to distinguish and articulate specific connections between symbolic and molecular representations.

Table 3.2. Mean scores and standard deviations for pretest and posttest items by group.

| Concept | Item | Group | Pretest | | Posttest | | Effect Size |
|---|---|---|---|---|---|---|---|
| | | | M | SD | M | SD | |
| Chemical Representations | 1 | Honors | 2.81 | 1.47 | 3.14 | 1.42 | .23 |
| | | Standard | 3.75 | 1.29 | 3.96 | 1.20 | .19 |
| | | *Comparison* | *3.24* | *1.27* | *3.16* | *1.46* | *-.06* |
| | 2 | Honors | 2.86 | 1.60 | 3.48 | 1.60 | .39 |
| | | Standard | 3.63 | 1.50 | 4.08 | 1.10 | .34 |
| | | *Comparison* | *2.84* | *1.52* | *3.24* | *1.62* | *.25* |
| | 3 | Honors | 1.29 | 1.27 | 2.14 | 1.20 | .69 |
| | | Standard | 2.21 | 1.29 | 2.75 | .90 | .49 |
| | | *Comparison* | *1.56* | *.92* | *1.60* | *1.00* | *.04* |
| | 4 | Honors | 1.95 | 1.60 | 2.90 | 1.48 | .62 |
| | | Standard | 2.21 | 1.29 | 2.75 | .90 | .49 |
| | | *Comparison* | *2.56* | *1.23* | *2.92* | *.99* | *.32* |
| Balancing Equations | 5 | Honors | .71 | 0.85 | 1.10 | 0.83 | .46 |
| | | Standard | 2.46 | 1.25 | 2.71 | 1.68 | .17 |
| | | *Comparison* | *1.88* | *1.13* | *1.96* | *1.21* | *.07* |
| | 6 | Honors | .52 | .51 | 1.05 | .50 | 1.05 |
| | | Standard | 2.33 | .82 | 1.96 | .95 | -.42 |
| | | *Comparison* | *2.12* | *.97* | *2.00* | *1.04* | *-.12* |
| Limiting Reagents | 7 | Honors | .67 | .91 | 1.29 | .97 | .66 |
| | | Standard | 1.38 | .35 | 2.25 | 1.68 | .57 |
| | | *Comparison* | *1.08* | *.64* | *1.24* | *.66* | *.25* |
| Heat and Molecular Motion | *8* | Honors | .33 | .66 | 1.33 | .73 | 1.44 |
| | | Standard | 1.50 | .89 | 1.83 | 1.00 | .35 |
| | | *Comparison* | *1.04* | *.68* | *1.28* | *.74* | *.34* |

Table 3.3. Student responses to chemical representation item.

**Question:** In the following two figures, striped circles represent nitrogen and white circles represent oxygen. What is the difference between figures A and B? Explain your answer using the chemical formulas and the words subscript and coefficient.

Figure A

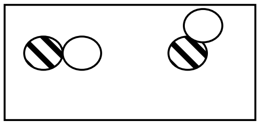
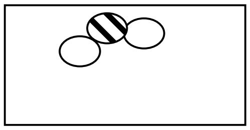


Figure B



| Student | Pretest (score in parentheses) | Posttest |
|---|---|---|
| AP | "The difference between figure A and figure B is Figure A's has a coefficient of 2 and no subscripts [2NO written on picture], whereas Figure B has no coefficients and has two subscripts, ($N_2O_3$). (2) | "The difference between these two formulas is in Figure A there is a written coefficient of "2" [2NO written on picture], whereas, Figure B has a given coefficient of "1" [$NO_2$written on picture]. Figure A also does not contain a subscript, whereas, Figure B has one subscript which is 2. So therefore, there are two molecules of nitrogen oxide in Figure A and one molecule of nitrogen oxide in Figure B." (4) |
| QB | "In A, $N_2O$ is the equation. In B. There are double bonds, so its $N_2O_3$" (1) | "Figure A is 2NO. They are different b/c there's 2 O's, not just $O_2$. Figure B is $NO_3$." (2) |
| KR | "2NO has two nitrogen & 2 oxygen. $NO_2$ has 1 nitrogen and two oxygen." (3) | "This is 2NO. There are to of each molecule therefore a coefficient is needed. This $NO_2$. There is 1 Nitrogen branching 2 oxygen off of it. Therefore you use 2 as a subscript."(4) |

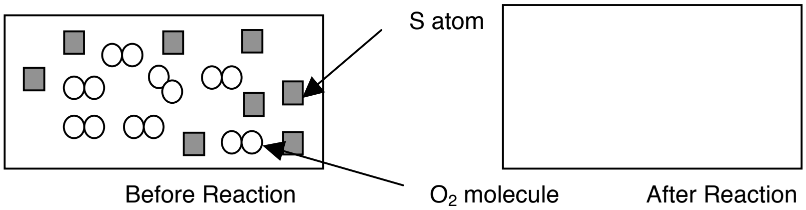
In Activity 3 in the curriculum, *Chemical Reactions* students used scaffolded visualizations to form product molecules out of a certain number of reactant molecules by rearranging atoms and breaking and making bonds between atoms. This activity was designed to help students develop connections between the molecular and symbolic representations. Although the students did not significantly improve their abilities to switch between chemical equations in symbolic and molecular forms, they did improve their ability to explain the connections between coefficients and subscripts in symbolic and molecular representations. These scaffolded visualizations may help students make and articulate connections between the symbolic and molecular representations.

### *Limiting reagents*

Instructed students made progress in understanding limiting reagents as measured by item 7. This item gave students a certain amount of reactant molecules in a closed container and asked students to draw the contents of the container after a certain reaction occurred. In order for students to score well, they needed to integrate their knowledge of the structure of molecules, conservation of mass, the dynamic nature of reactions, and limiting reagents. Scores on the limiting reagent increased for both honors and standard groups, but not for students in the comparison group classes. In general, students for both honors and standard groups progressed from giving irrelevant, non-normative ideas to responses with normative ideas. The comparison students stayed at the irrelevant, non-normative level. For example, many students drew molecular representations of some part of the balanced equation, failing to integrate concepts of conservation of mass, limiting reagents, or the dynamic nature of reactions on the pretest (Figure 3.4). On the posttest, more students made connections to these concepts. For instance, student RB drew a molecular representation of the chemical equation on the pretest. On the posttest, RB drew only product molecules, recognizing the chemicals had changed form during the reaction. In addition, RB made connections to conservation of mass by drawing the same amount of atoms before and after the reaction, and also made connections to limiting reagents by leaving some chemicals unreacted.

Scaffolded visualizations introduced the concept of limiting reagents in activity three of this unit. Increases in scores to item 7 suggest that these visualizations may have helped students form more integrated understandings of limiting reagents and chemical reactions on a molecular and symbolic level.

**Question:** The following diagram represents a mixture of S molecules and $O_2$ molecules in a closed container.



If only the molecules in the closed container above react according to the equation

**$2S + 3O_2 \Rightarrow 2SO_3$**,

draw the container after the reaction in the space above.

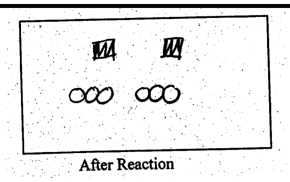
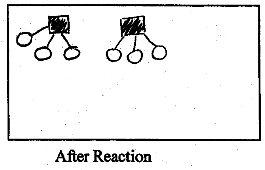
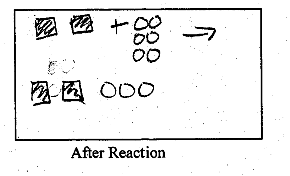
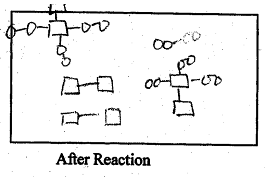
| Student | Pretest | Posttest |
|---|---|---|
| CB |  |  |
| RB |  |  |

Figure 3.4. Sample student responses to limiting reagent item.

### *Heat and molecular motion*

Item 8 asked students to explain what impact adding heat has on the rate of a chemical reaction in a closed container. Students needed to integrate the concepts of heat increasing molecular motion and the interactive nature of chemical reactions to receive a high score. Scores from item 8 increased for students in the honors group. The effect size of the standard group was the same as the comparison group, although the scores were greater for the standard group. On the pretest, many students made connections to other knowledge not relevant to the question. On the posttest, students made more connections to heat increasing molecular motion and made more connections to the interactive nature of chemical reactions forming and breaking bonds (Table 3.4).

Students interacted with dynamic molecular visualizations by manipulating heat and watching the effect of adding heat to a chemical reaction. Since scores for honors students significantly increased, this may suggest that the scaffolding for these visualizations did not help students farther along in chemistry courses as much as students with less chemistry experience.

### *Mathematically balancing equations*

Items 5 and 6 probed students' ability to balance equations in symbolic form. This study included these assessment items in the hope that developing students' conceptual understanding of balanced equations would also develop students' ability to balance equations mathematically. Only the scores of the honors group significantly increased for item 5 (see Table 3.2). The standard group did not significantly increase their scores on items 5 or 6. Prior instruction (or lack of prior instruction) combined with relatively little instruction from the curriculum offers a possible explanation for these results. Honors group students had not covered balancing equations in class. Many of their responses to these questions on the pretest were either blank or

Table 3.4. Sample student responses to heat and molecular motion item.

**Question:** Refer to the closed container and the reaction in the previous question. If you add heat to the system what happens to the reaction rate?

a. Speed of the reaction increases
b. Speed of the reaction decreases
c. Speed of the reaction does not change

Explain what happens to the molecules when you add heat.

| Student | Pretest | Posttest |
|---|---|---|
| SP | "a. I think speed of reaction increases because heat serves as a catalyst." (2) | "a. It speeds up the reaction because heat act as a catalyst and makes breaking and bonding easily for oxygen so they can form new bonds quickly." (3) |
| EY | "b. speed of the reaction decreases because the energy starts to burn out and slows it down." (1) | "a. the speed of the reaction increases because heat gives off energy and it makes it go faster" (2) |
| AH | "a. The molecules become larger." (1) | "a. When heat is added to molecules their speed of reaction increases." (1) |

"I don't know." Very low initial pretest scores may have caused the significant increase in the honors group's scores. Effect sizes were small for the standard group who already covered balancing equations in class. Standard students scored well on these items and there was little room for improvement. The comparison group declined from pretest to posttest, which suggests that the posttest question might have been more difficult than the pretest question. The scaffolded visualizations did not explicitly address a mathematical approach to balancing equations, and these activities did not seem to help students algorithmically balance equations.

### *Case Studies of Embedded Prompt Trajectories*

Selected students' responses based on pretest and posttest achievement scores provide a range of what kinds of connections students make using embedded prompts and visualizations. This section examines three student pairs from the standard group. The selection of pairs highlights the range of scores from pretest to posttest (Table 3.5): groups collectively scoring below the class average on the pretest with little or no increase in score on the posttest (Pair 2); groups scoring below the class average on the pretest with much increase on the posttest (Pair 3); and groups scoring above the class average on the pretest with increase on the posttest (Pair 1).

This analysis presents a synthesis of the groups' responses, including embedded prompts and related pretest and posttest responses. Complete responses from all groups to the four embedded prompts can be found in Appendix D.

### *Pair 1: BW and AS*

BW and AS participated in the standard implementation of the *Chemical Reactions* curriculum. Both BW and AS scored above the class average on the pretest (29 and 32, respectively). BW and AS demonstrated strong connections from the visualizations to normative chemistry ideas. For example, when asked about the relationship between Molecular Workbench visualizations and the related balanced equation, they responded:

> "They are related because in order to have no atoms left over in the workbench, we had to get a certain amount of oxygen atoms and hydrogen atoms. This number is the same as the ratios in the balanced equation (2 H2, 1 O2, and you end up with 2 H2O molecules)."

BW and AS demonstrated a strong connection between what they have experienced in

Table 3.5. Pretest and posttest scores for embedded prompt analysis student pairs.

| | Student 1 | Pretest Score | | Posttest Score | Student 2 | Pretest Score | | Posttest Score | Group |
|---|---|---|---|---|---|---|---|---|---|
| Pair 1 | BW | 29 | < | 33 | AS | 32 | < | 34 | Standard |
| Pair 2 | DC | 18 | = | 18 | JM | 15 | < | 18 | Standard |
| Pair 3 | JG | 18 | < | 23 | RB | 15 | < | 22 | Standard |

the visualizations and the concept of balanced equations on a molecular scale. They made connections between chemical reactions and balanced equations through the underlying concept of ratios, and emergent connections between the balanced equation and limiting reagents.

Both BW and AS improved from pretest to posttest, connecting heat and molecular motion, conservation of mass, and limiting reagents. For example, BW drew two $SO_3$ atoms on the pretest, demonstrating no connection to conservation of mass or limiting reagents. However, on the posttest BW includes the remaining S atoms and $O_2$ molecules, conserving the number of both sulfur and oxygen atoms (Figure 3.5). The scaffolded visualizations may have helped BW and AS integrate new ideas of conservation of mass and limiting reagents into their repertoire.

### *Pair 2: DC and JM*

DC and JM participated in the standard implementation. Both DC and JM scored below the class average on the pretest (18 and 15, respectively). DC and JM's answers to the prompts demonstrated superficial connections from the visualizations to other concepts. For example, when asked about how the balanced equation affects the numbers of product molecules that are made, DC and JM stated:

> "You start off with 2purple [sic] molecules, and two blue, bonded molecules. You end up with One purple, and two blu, all bonded."

Here, DC and JM made superficial connections between the color and number of molecules involved in the activity, but no connections to more scientific ideas. The scaffolding did not seem to help DC and JM make robust connections to the ideas underlying the visualizations. Instead, DC and JM add superficial information from the visualizations into their repertoire.

DC and JM made very little, if any, gains on the posttest (18 and 18, respectively). Both remained under the class average on the posttest.

### *Pair 3: JG and RB*

Both JG and RB started with the same pretest scores as pair 4 (18 and 15, respectively) and took part in the standard TELS run. Contrary to pair 4, JG and RB demonstrate connections from the visualizations to chemistry concepts in their responses. For instance, JG and RB respond to prompt 4 by saying:

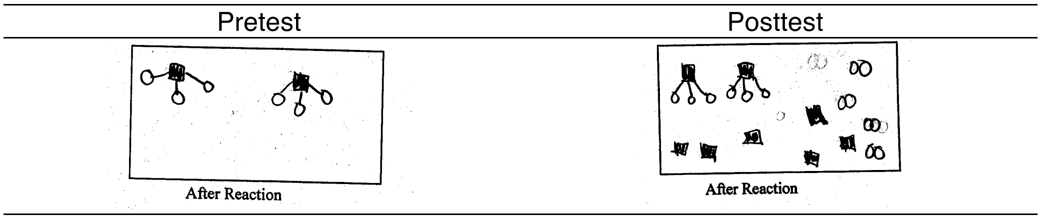


Figure 3.5. Student BW's pretest and posttest responses to limiting reagent item.

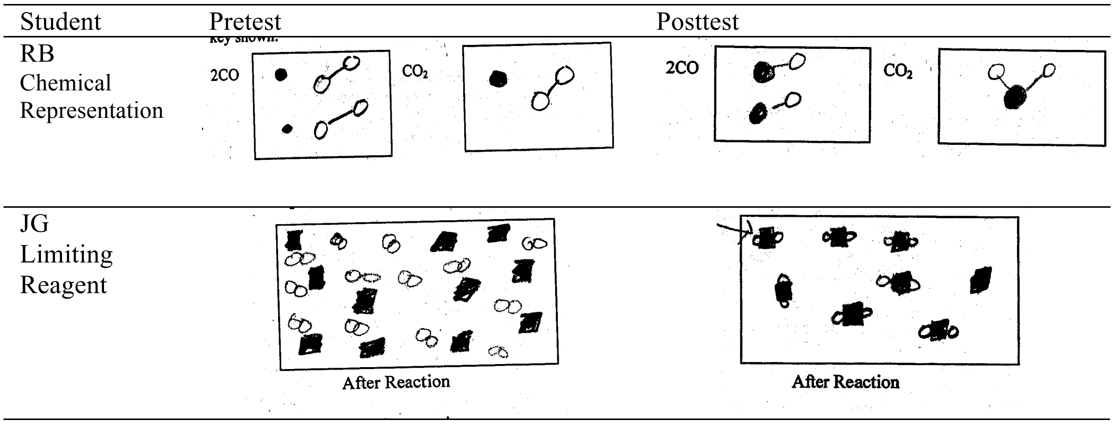


Figure 3.6. RB and JG pretest and posttest responses to chemical representation and limiting reagent items.

> “The balanced equation effected the product molecules by allowing a certain amount of molecules to bond with each other. When some molecules bond with others, some molecules are left alone.”

JG and RB demonstrate emerging connections from the visualizations to the concept of limiting reagents. These kinds of emerging conceptualizations were present in other responses, such as the interactive nature of reactions in their response to prompt 1. The scaffolding seemed to help JG and RB add new information about the visualizations, refine and sort their ideas to make connections to underlying scientific ideas.

Contrary to pair 2, JG’s and RB’s scores increased from pretest to posttest (23 and 22, respectively). Both JG and RB demonstrated an increase in their understanding of the connections between the symbolic and molecular representations, conservation of mass, limiting reagents, and the dynamic nature of reactions on the posttest. For example, in item 7, JG simply drew different numbers of S atoms and $O_2$ atoms on the pretest (see Figure 3.6). On the posttest, JG drew seven $SO_2$ molecules and one S atom. Although JG did not draw the structure of the product molecule correctly ($SO_2$ instead of $SO_3$), he drew different chemicals than the reactants, demonstrating an understanding of the dynamic nature of chemical reactions. Also, JG conserved the total number of both S and O atoms, showing a robust connection to the concept of conservation of mass. Because JG draws a solo S atom left over, he also demonstrates a connection and an understanding of limiting reactants. Overall, both JG and RB demonstrate increased connections between representations and concepts on the posttest.

### *Case Studies Summary*

Across the studied pairs, the dyads that were able to use the embedded prompts to make connections from the visualizations to relevant concepts increased their score from pretest to posttest. These groups demonstrated more integrated understandings of symbolic and molecular representations, conservation of mass, limiting reagents and the nature of chemical reactions. Scores for groups for which the scaffolding did not help them add, refine and sort their ideas did not increase from pretest to posttest.

# Study 2: Longitudinal Study

## Longitudinal Study Methods

### *Participants and Implementation*

The replication study participants (n=93) included students from another teacher and school who ran the same version of *Chemical Reactions* as the Test group in Study 1. These students were mostly tenth grade students and also came from a variety of ethnic and economic backgrounds. 61% of the students in this school are socioeconomically disadvantaged, and the student body consists of over 75% of students from underrepresented populations in science.

The same teacher taught all of the students who participated in the *Chemical Reactions* unit. Similar to the teacher used in Study 1, this teacher was also using WISE for the first time, and participated in the development and design of the unit during summer retreats. At least one researcher was present in the classroom during the entire implementation.

### *Data Sources*

Pretests and posttests were identical to those used in Study 1. In addition to the pre- and posttests, the TELS center administered benchmark assessments to all students participating in the TELS program, as well as a comparison group of students who did not participate in TELS but came from the same schools and teachers (n=408). The benchmark assessments were given to students in the last month of the academic year, months after the TELS unit was completed. Identical items across pretests, posttests and delayed posttests were analyzed to investigate the robustness of students' ideas and connections over time (Lee & Linn, 2008).

All assessments were scored with the same rubric based on the knowledge integration framework. Item scores were averaged to reveal the trajectory of the number of connections and ideas in student responses.

## Longitudinal Study Results

Students using the *Chemical Reactions* unit significantly increased from pretest to posttest, replicating results from Study 1. Additionally, TELS *Chemical Reactions* students significantly increased from the posttest to the delayed posttest (Figure 3.7; Lee & Linn, 2008). TELS *Chemical Reactions* students outperformed non-TELS students on the year-end assessments ($t(499) = 4.59$, $p < .001$).

For instance, an item used on all of the assessments asked students about what happens to the reaction rate if heat is added to a chemical reaction that occurs in a closed system (Table 3.4). On average, students had a partial understanding of one concept on the pretest ("The molecules have more heat"). On the posttest, students on average had a partial link, with one relevant concept stated ("When you add heat, molecules move around more"). On the delayed posttests, students on average had a full link between two scientifically relevant ideas ("When you add heat to a reaction, the molecules move faster and atoms break and form bonds").

These results suggest that *Chemical Reactions* helps students form durable, connected knowledge that students could build upon with subsequent instruction. After learning about chemical reactions in the TELS unit, students went on to study stoichiometry, equilibrium, and acid-base reactions with traditional instruction. With a better understanding of chemical reactions on a molecular scale, students could use these future topics to reinforce and add connections to their understanding, since they all are related to chemical reactions.

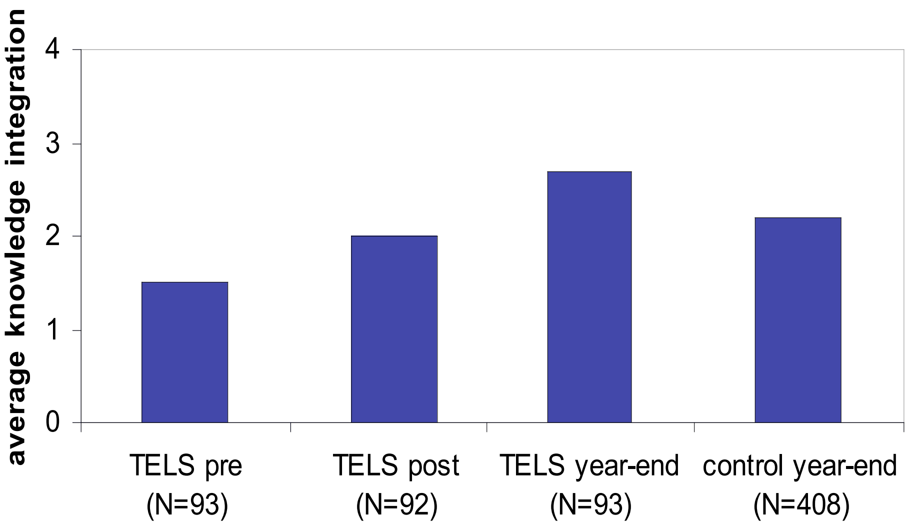


Figure 3.7. Average knowledge integration scores for TELS pre, post, and TELS and non-TELS delayed year-end assessments.
*Figure courtesy of (Lee & Linn, 2008)*

# Discussion

## Findings Overview

This study investigated how molecular visualizations combined with embedded prompting can help students form integrated understandings of chemical reactions. Pre and posttest results indicate that the students involved with the *Chemical Reactions* curriculum unit formed connections between symbolic and molecular representations, and connections to concepts such as conservation of mass and limiting reagents. Both the honors and standard groups significantly differed from the comparison group. Students studying the unit outperformed students revising material and retaking the same tests.

These findings reinforce research demonstrating technology-enhanced instruction can help students integrate symbolic, molecular, and observable representations for an improved understanding in chemistry (Ardac & Akaygun, 2004; Greenbowe, 1999; Wu, Krajcik & Soloway, 2001). The combination of embedded and outcome measures specifically show that interactive visualizations contribute to understanding of the relationship between symbolic, molecular, and observable representations since students in the comparison group made no gains on these dimensions.

Regression analysis found no differences between honors and standard groups, controlling for pretest score. Students both before and after learning about chemical reactions with different levels of prior knowledge made similar improvement in numbers of relevant ideas and connections. These results replicated across contexts. Students studying the same project at another school had similar learning gains.

Importantly, and contrary to findings by others, student dyads with both low and high prior knowledge as determined by the pretest were able to use the visualizations and embedded prompts to make relevant connections between representations (ChanLin, 2001; Gobert, 2005;

Hegarty, Kriz & Cate, 2003). Furthermore, students in both honors and standard chemistry made progress. The honors students made larger gains possibly due to the longer interval between pretest and posttest that was necessitated by school based technical difficulties. The longer interval allowed for more distributed practice that might have enhanced outcomes. Alternatively, the honors students might be more efficient learners. Overall, these findings provide evidence that the knowledge integration patterns add value to the visualizations by enabling students across the performance spectrum to succeed.

Students' scores from the longitudinal study not only increased from pretests to posttests, but also significantly increased from posttests to delayed posttests months after the implementation of the unit. These findings suggest that the *Chemical Reactions* unit helped students integrate subsequent instruction to relevant networks of ideas after the unit ended. TELS students also outperformed a non-TELS control group on these year-end delayed posttests, demonstrating that the unit has a lasting impact as compared to traditional instruction months after implementation.

## Student Use of Molecular Visualizations

In spite of the documented success of the unit, classroom observations revealed that students had difficulty sorting out information presented in the visualizations, consistent with other research (Chang et al., in preparation; Tversky, Morrison & Betrancourt, 2002). Students asked their partners or their teacher what purpose the visualizations served, what they were supposed to do with the visualizations, and how the visualizations related to the unit. Because the visualizations loaded slowly students usually grappled with the surrounding text before interacting with the visualizations. Many students struggled to use the text especially before they viewed the visualizations. These observations informed revisions to the project. For instance, based on these findings the supporting text was moved to appear with the visualizations. In addition, scaffolds were added to make the links more explicit.

These findings suggest the need for further exploration of how the design of visualizations impacts student learning. *Chemical Reactions* started with complex visualizations and guided students to revisit the same complex visualizations with different goals. In this way, students become familiar with the overall visualizations by addressing certain pieces of the visualization at different times, and then put those pieces together. Other studies show benefit of having students start with simple visualizations and build more complexity within the visualizations as the students proceed through the learning experience (e.g., McElhaney & Linn, 2008).

The case studies of responses to the embedded prompts illustrate how the knowledge integration scaffolding of the visualizations helped students to make relevant connections from the visualizations to chemistry concepts. Students who followed the scaffolds and made connections to the visualizations gained from pretest to posttest, while dyads that did not make connections to these visualizations did not gain from pretest to posttest. Although some students were able to use the embedded prompts to make relevant connections between representations, many students struggled to make meaningful connections with these scaffolds. This points to the difficulty of making these kinds of connections even with explicit instructional guidance. These results suggest the need for comparison studies of the supporting instruction around visualizations. For example, future research can investigate how different types of instructional guidance helps students make different kinds of connections to visualizations.

### Longitudinal Classroom Findings

Students in the standard group were able to build upon the connections they made within the unit during subsequent instruction and perform effectively on the delayed posttest. These findings suggest that helping students connect and refine their ideas results in durable knowledge. Interviews with the teachers pointed to the importance of visualizations for students' understanding of subsequent concepts. The teacher reported that the ability to visualize the molecular level was particularly powerful for students who had very limited exposure or understanding of chemical reactions on a molecular level (e.g. Figure 2.4). Instead of isolating the symbolic, molecular, and observable levels like typical instruction, these visualizations and the surrounding instruction within the unit helped students make connections among these levels. Teachers reported that they referred back to the molecular visualizations when talking about subsequent concepts such as chemical equilibrium. The visualizations allowed the teacher and students to build their interactions from a common reference point or model.

The open-ended assessment items made students' thinking visible to the teacher and the researchers. The teacher expressed surprise about the students' lack of connection among the symbolic and molecular levels. For instance, many students struggled with drawing a molecular representation of $CO_2$. Standard multiple-choice or text-based assessment items typically do not make this kind of student thinking readily accessible to teachers. The teacher was able to use this information to increase emphasis on the links between molecular and observable phenomena.

### Knowledge Integration Design Patterns and Visualizations

The *Chemical Reactions* unit used the knowledge integration pattern to elicit ideas, add ideas, distinguish ideas, and reflect to help scaffold students' interactions with the visualizations. Eliciting and adding ideas was successful for all learners. Distinguishing ideas was more successful for some than others as shown in the case studies. In addition, the delayed test shows that the reflection activities were successful in enabling learners to retain their ideas. Overall, the knowledge integration pattern was found to be particularly successful to help students form and retain connections among their ideas.

The knowledge integration instructional pattern may be particularly helpful for students because it poses *desirable difficulties* that enhance learning (Bjork 1994; 1999). Desirable difficulties slow the learning process, may increase errors during learning, but result in more durable learning. Generation activities, such as explanation and drawing used in the module, can help students connect and distinguish their existing ideas from concepts presented in the visualizations. These types of activities can help students build more coherent and durable understanding from visualizations, especially when students interact with a visualization on a superficial level. In particular, the developing criteria, sorting, refining and reflecting processes of the knowledge integration pattern seem to introduce desirable difficulties. Future research will investigate the relationship between desirable difficulties and knowledge integration with instruction featuring visualizations.

## Conclusion

This study investigated how a technology-enhanced chemistry curriculum unit featuring dynamic molecular visualizations could help students connect ideas and representations of chemical reactions. Our findings demonstrate that dynamic visualizations embedded within knowledge integration instructional patterns resulted in increased connections among students' ideas about chemical reactions. Contrary to many studies showing that visualizations confuse learners, the findings in this study demonstrate ways to make visualizations comprehensible and effective. Expert scientists use molecular visualizations are to advance their research. It is gratifying to find ways to make this form of information useful for students. Specifically, the embedded explanation prompts helped students form connections among the molecular levels depicted in the visualizations and the symbolic levels of chemical reactions. The longitudinal findings suggest that the curriculum helped students form robust and durable networks of ideas to which students could connect subsequent instruction.

These studies raised questions to explore in greater detail. How did the explanation prompts help students make these robust connections? Since students retain these connections over time, and subsequently build from these connections, how does the knowledge integration pattern contribute to self-monitoring? The next chapters investigate these questions in greater depth.

# Chapter 4: The Role of Knowledge Integration in Learning Chemistry with Dynamic Visualization

In this chapter I investigate how the knowledge integration perspective contributes to learning with visualizations. Self-monitoring skills are particularly important for learning from dynamic visualizations (see Chapter 1). This chapter explores ways that the knowledge integration pattern can encourage students to monitor and regulate their learning in authentic classroom contexts. I focus on critical self-assessment where learners actively distinguish ideas, evaluate ideas, and reflect upon their own understanding. These processes require students to make informed decisions about their knowledge and take action to remedy gaps or conflicts within their understanding (i.e. Georghiades, 2004).

Building upon the results presented in Chapter 3, I wanted to explore how generating explanations can help students learn more effectively from visualizations and monitor their understanding. Other research demonstrates that generative activities such as explaining create desirable difficulties for learning (Bjork, 1994; 1999). These activities appear to slow the learning process but result in more robust learning. I hypothesized that the success of *Chemical Reactions* may be partly due to embedding the visualizations in a knowledge integration pattern.

I study two approaches to encourage integration of ideas: judgments of learning and prompted explanations. Both of these approaches provide a way to measure and support monitoring of connections and ideas. When students make judgments of their learning they evaluate their level of understanding and practice assessing their own progress. I prompt students to explain in order to capture the level of understanding students achieve at various points in their learning as well as to spur students to recognize what they do not understand.

This chapter focuses on how students integrate scientific visualizations with symbolic and everyday events. I review the literature and show how research has elucidated the ways that explanations and scientific visualizations contribute to understanding of chemistry. I report on investigations of how explanations impact judgments of learning and help students more accurately assess their understanding. I elicit judgments of learning and focused explanations to help students monitor their understanding of chemical reactions. Specifically, I wanted to explore how students could develop self-knowledge and self-regulation skills through this combination of visualizations followed by explanation prompts. To explore self-monitoring surrounding this combination, I investigated how students assessed their learning before and after generating explanations. I sought to describe how learners monitored their understanding and clarify how explanations may contribute to learning with dynamic visualizations.

To foreshadow the results, this study found that students typically overestimate their understanding of visualizations. Encouraging students to explain and rate their understanding helped students realize gaps in their knowledge and more accurately judge their learning. These results suggest that visualizations can be *deceptively clear*, and highlight the importance of combining visualizations with generation activities to help students develop self-assessment and self-regulatory skills.

# Rationale

## Encouraging Knowledge Integration

The knowledge integration perspective calls for conscientious, intentional learning (Linn & Eylon, 2006). Metacognition, or “thinking about thinking”, is crucial to successful knowledge integration. Although researchers use slightly different descriptions of metacognition (Georghiades, 2004; Schoenfeld, 1992), most agree that metacognition involves some form of self-knowledge and self-regulation (Brown, 1987; Flavell, 1987; Schraw, 1998; Zimmerman, 1990). Metacognitive expertise involves knowledge about oneself as a learner, such as knowing what you do or don’t know, as well as knowing how you learn through tasks and processes (Brown, 1987). Metacognitive self-regulation includes planning, monitoring, testing, revising, and evaluating one’s activities (Baker & Brown, 1984).

Engaging in the full knowledge integration pattern requires metacognitive expertise. Eliciting students’ existing ideas brings prior knowledge about a subject or concepts to the forefront. Learners can then add new, normative ideas to these existing frameworks through, for example, instruction. Learners must then develop criteria to examine new ideas and links that they have formed to their prior knowledge. In order to develop criteria for their ideas, learners evaluate their understanding to sort and distinguish more productive and relevant ideas from less productive ideas. Learners use self-knowledge to judge their understanding, and then monitor and regulate their learning to sort and distinguish ideas. For instance, students could add ideas about conservation of mass in chemical reactions but realize that they don’t understand how conservation of mass connects to their existing ideas about reactions on a molecular level. Learners can act upon this realization and decide to use metacognitive strategies such as reviewing information or extra practice to refine connections. Students then reflect upon these connections among ideas, examine alternatives, and possibly revise or test their new connections. Metacognitive acts of reflection, self-testing, considering other ideas and hypotheses contribute to knowledge integration.

Engaging learners in the knowledge integration pattern results in connected, durable, and complex understanding (Lee et al., 2009). I argue that while traditional instruction usually adds ideas and perhaps elicits prior knowledge, it does not focus on developing criteria, sorting, refining and reflecting on ideas (Chang et al., in preparation). Leaving these crucial pieces out of instruction, particularly technology-enhanced instruction featuring dynamic visualizations, can leave students with disconnected and isolated ideas.

Research demonstrates that supporting students’ development of self-knowledge and self-regulatory skills can improve student performance across many domains (Palincsar & Brown, 1984; Scardamalia & Bereiter, 1991; Schoenfeld, 1985). These metacognitive processes are especially important and beneficial for inquiry science learning in technology-enhanced environments (Quintana, Zhang & Krajcik, 2005; White & Frederiksen, 1998; 2005) and chemistry (Rickey & Stacy, 2000).

Activities that help students develop metacognitive skills include modeling thinking processes for students and scaffolding students to engage in these processes (Collins, Brown & Holum, 1991). Computer environments can promote metacognitive expertise by prompting students to participate in planning, monitoring, regulation, and refection processes (Quintana, Zhang & Krajcik, 2005). For instance, students can be prompted to reflect upon their current thinking or to reflect upon their project success (Davis & Linn, 2000). Computer environments can also model these types of processes by providing metacognitive agents whose role is to provide planning, monitoring, and synthesizing advice (White & Frederiksen, 2005).

To develop and detect self-knowledge and self-regulation skills, I use prompts for explanations and self-evaluations. By explicitly asking students to explain and assess their understanding, I purposefully guide students through activities that help develop criteria for their understanding and sort and refine links among their ideas. Prompts to assess understanding are designed to help students develop self-knowledge and awareness about themselves as learners. Prompts to explain understanding encourage learners to actively sort, refine, and reflect upon their understanding.

## Eliciting Explanations

When students actively participate in their own knowledge construction by generating conjectures and testing them, they form a robust, coherent, and integrated network of ideas (Linn & Eylon, 2006). Self-explanation, the spontaneous generation of explanations by oneself when learning new information, helps students learn in many contexts. Explanations that connect ideas about scientific phenomena can help students integrate new, productive ideas with existing knowledge (Chi, Bassok, Lewis, Reimann, & Glaser, 1989). Successful students explain their ideas to themselves more often than less successful students (Chi et al., 1989). Successful problem-solving students tended to generate explanations that connected one problem-solving step to another, connect the example to ideas presented in the textbook, and use their explanations to integrate new ideas. This relationship between self-explanations and successful problem solving has been replicated in physics (Ferguson-Hessler & de Jong, 1990) and computer science (Bielaczyc, Pirolli, & Brown, 1995; Pirolli & Recker, 1994). Explicitly prompting students to explain, rather than looking for spontaneously generated self-explanations, has been found to help students learn from scientific texts (Chi, de Leeuw, Chiu, & Lavancher, 1994; Davis, 2003). Students prompted to explain by an experimenter gained significantly more on conceptual measures from pretest to posttest than students who read the same texts twice. Eliciting explanations can spur students to recognize conflicts, examine conflicting information and "self-repair" these differences (Chi, de Leeuw, Chiu, & Lavancher, 1994).

Encouraging metacognitive self-evaluation and self-regulation can be difficult in authentic classrooms. Students can respond to metacognitive prompts by repeating memorized phrases without analyzing possible gaps in understanding or checking for completeness of knowledge. For instance, a learner can reflect upon their understanding by saying that they have no questions or that they learned as best they could (e.g. Davis, 2003). However, well-designed prompts can also spur learners to question their understanding, realize inconsistencies in their ideas, and identify gaps in their argument. This study uses explanation prompts to help learners sort, refine, and reflect upon their knowledge (Chi et al., 1989; Rozenblit & Keil, 2002). Prompting for explanations is particularly well suited for authentic classrooms since students develop conceptual understanding as a product.

For example, Tien, Teichart and Rickey (2007) prompted students to reflect and explain connections between macroscopic observations and molecular models of salt and sugar dissolving in water. As part of the Model-Observe-Reflect-Explain (MORE) pedagogical approach, college-level general chemistry students described their initial models of molecules dissolving (model), carried out laboratory experiments (observe), reflected upon their observations and used their experiments to refine their ideas (reflect and explain). Of the 84 students participating at three different institutions, 35% had correct initial models of salt dissolution, 32% had accurate initial models of sugar dissolution, and 15% had correct models of both. After reflecting and explaining, a significantly greater proportion of students had correct models of the phenomena (80% salt, 52% sugar, 46% both) across institutions. Prompting students to reflect upon their ideas and explain connections among molecular and macroscopic representations helped students develop understanding of ionic and covalent dissolution.

Similarly, Davis and Linn (2000) investigated how self-monitoring versus activity prompts affected middle school students' explanations of thermodynamics concepts within the Knowledge Integration Environment (KIE). Specific activity prompts asked eighth-grade students to think about different aspects of a project, such as "the letter says we need to…" or "the major claims of the article include..." Self-monitoring prompts encouraged students to monitor their learning through planning e.g. "Thinking ahead: To do a good job on this project, we need to…") and reflecting upon the activity (e.g. "In thinking about how it all fits together, we're confused about…"). Self-monitoring prompts were better than activity prompts in supporting students' integration of scientific principles into explanations, and for linking scientific principles to real-life experiences. Additionally, students who reflected upon ideas and "checked their understanding" were more likely to develop an integrated understanding of the project. Thus, prompting for explanations may help learners sort, refine, and reflect upon their understanding.

## Encouraging Self-Assessment

Knowledge integration includes evaluating one's understanding. Studies show that learners both overestimate (Koriat, 1997) and underestimate (Hyde, Fennema, & Lamon, 1990) their abilities. Research suggests that learners who initially overestimate their understanding increasingly underestimate their abilities after repeated study and testing cycles (Koriat, Sheffer, & Ma'ayan, 2002). Students who are better able to assess their understanding tend to be more successful learners (Wiediger & Hutchinson, 2002). Studies have identified many factors contributing to learners' difficulties assessing their understanding, such as the nature of the assessment task, subject-matter knowledge, the surrounding learning environment, and motivation. For example, Zoller, Fastow, Lubezky and Tsaparlis (1999) studied how college chemistry students assess themselves on midterm exam questions. Zoller et al. found that students' self-assessments and professors' assessments did not significantly differ on questions that assessed straightforward cognitive skills, such as simple recall or recognition of facts. On open-ended items that required students to explain their understanding or rationale, students tended to overestimate their ability as compared to their professors.

Even if learners accurately identify when they do not understand, they may or may not spend more time to go back and learn the material. Studies demonstrate that learners will more often pick items to study that they deem as less well learned (Nelson, Dunlosky, Graf, & Narens, 1994), and will spend more time studying items that they think they will be less likely to recall (Mazzoni, Cornoldi, & Marchitelli, 1990). However, this may depend on the learning goals and study time of the student. Students with goals to minimize effort or studying time may choose to spend more time going over items that they consider as easier to understand, whereas students with goals of overall comprehension may spend more time focusing on items that they perceive as more difficult (e.g. Linn & Hsi, 2000; Thiede & Dunlosky, 1999).

Supporting students to assess their understanding can help students learn scientific inquiry (White & Frederiksen, 1998) and computer science (Bielaczyc, Pirolli, & Brown, 1995). However, these studies also demonstrate the intricacies of promoting self-assessment with learners. White and Frederiksen (1998) found that students involved in reflective self-assessment processes improved on inquiry measures as compared to students without the self-assessment prompts. However, students in the self-assessment group had differential gains on conceptual measures depending on achievement level. A variety of factors contribute to students' self-assessments and their resulting action or inaction can impact the effectiveness of these kinds of supports. Capturing how students evaluate their understanding in authentic classroom contexts can help researchers develop successful and meaningful ways to support students' self-monitoring skills.

Several studies show a connection between evaluating one's understanding and self-explaining. In the aforementioned Chi et al. study (1989), successful problem-solvers recognized when they did not understand more often than the less successful students. Some investigators report that successful students appear to be awakened by the realization that they do not understand and use this observation to seek ways to reconcile their ideas (e.g., Baker & Brown, 1984). Thus, improving students' abilities to evaluate their own understanding can help them identify weak links in their repertoire. Eliciting explanations may help trigger the refinement of ideas in the integration process.

## Dynamic visualizations

Combining dynamic visualizations with instructional prompting can encourage students to use explanation to sort and refine their repertoire of ideas. For example, transcripts of students working with *eChem* suggested that the visualizations facilitated self-explanations that helped refine links among ideas of chemical structure and bonding (Wu, Krajcik, & Soloway, 2001). Ainsworth and Loizou (2003) found that students learning about the circulatory system generated more self-explanations and higher quality explanations when prompted to explain static diagrams instead of text. In addition, the students in the diagram condition significantly outperformed students in the text condition on content assessments. They hypothesized that prompting explanations with diagrams helps maximize memory resources, encourages learners to integrate new information into their existing mental models, and may motivate students to actively process ideas.

These results suggest that students may need more guidance to monitor their understanding of dynamic visualizations within technology-enhanced environments (Tversky, Morrison, & Betrancourt, 2002). For instance, learners who made large conceptual gains in computer-based environments with text, diagrams, and animations monitored their understanding nearly twice as much as learners who made small conceptual gains (Azevedo, Guthrie, & Seibert, 2005). These monitoring activities included becoming aware that they did not understand (judgments of learning), expressing that they have learned something similar in the past (feelings of knowing), and questioning their understanding. In contrast, learners who did not make large gains spent little time self-monitoring and instead engaged in activities such as copying information, or looking through the environment without specific plans or goals.

Recent studies demonstrate the effectiveness of support within technology-enhanced environments to promote self-monitoring skills (Azevedo, 2005; Graesser, McNamara, & Van Lehn, 2005; White & Frederiksen, 2005) and call for scaffolding tools within science inquiry environments to support ongoing explanation and self-monitoring of understanding (Quintana, Zhang, & Krajcik, 2005). By supporting and guiding students' self-monitoring skills, computer-based learning environments can encourage integration of ideas from visualizations. Aleven and

Koedinger (2002) used an intelligent instructional software program, a “Cognitive Tutor,” to scaffold self-explanations for students studying high school geometry. They found that students with explanation support from the cognitive tutor outperformed students with only problem solving support. They suggest that facilitating self-explanations with the cognitive tutor helped learners integrate visual and verbal forms of information and discouraged students from developing superficial procedural knowledge.

# Methods

## Participants

Approximately 173 high school chemistry students completed the unit in the fall semester. Students attended two diverse public schools in California. Students at both schools previously covered most topics of chemical reactions, balancing equations, and limiting reactants. Students went through the unit in pairs.

Two teachers participated in the study. Teacher 1 ran the project with 5 classes, comprised of 2 honors and 3 regular classes. This teacher, affiliated with the TELS center, was a member of the design partnership. This was the teacher’s third experience running this project. The other teacher, Teacher 2, ran the project with 2 regular classes in another high school in the same district. The teacher had not previously run the *Chemical Reactions* unit but had run other TELS projects during the year.

## Self-Assessment Data Sources

Both teachers administered a paper pretest to individual students two days before the unit began, and a paper posttest the day immediately following the conclusion of the project. The unit took approximately one week of 55-minute classes to complete. These tests included thirteen free-response items that allowed students to create their own drawings and representations of chemical reactions. Items across tests were identical. The pretests and posttests asked *individual* students to rate their understanding of four different concepts: the greenhouse effect, limiting reactants, balanced equations and the effect of heat on chemical reactions. These self-assessments were multiple-choice, allowing students to rate their understanding as poor, fair, very good or excellent. The self-assessment questions were dispersed among the other questions.

During the curriculum, pairs of students explained their interactions with visualizations through embedded prompts after visualization steps. For example, after interactively making water molecules, a prompt asked students, “How did making water molecules in Molecular Workbench relate to the balanced equation?” Either before or after these explanations students assessed their own knowledge of the visualization and related concepts. Similar to the pretest and posttest, pairs of students rated their understanding of particular topics within the unit as poor, fair, very good, or excellent. These rating prompts targeted certain concepts; for example, after the same interactive water-making visualization, the rating prompt asked students, “Rate your understanding of how making water molecules in the visualization related to the balanced equation."

## Treatment

To investigate how students evaluate their learning surrounding visualizations and explanations, I changed the order of the self-ratings and explanation-generating prompts. I hypothesized that students would over-estimate their understanding after viewing the visualizations. In contrast, I hypothesized that generating explanations would help students identify difficulties and result in more accurate assessments of learning. I also hypothesized that both conditions would result in similar student progress.

Within each class, student pairs were randomly assigned to Explanation First or Rating First conditions. These two groups had the same curricular content, except the order of the explanation and rating steps were switched. The Explanation First group had explanation prompts immediately following visualizations and then rated their understanding in the next step. The Rating First group rated their understanding immediately following visualizations and then explained their understanding in the next step (Figure 4.1).

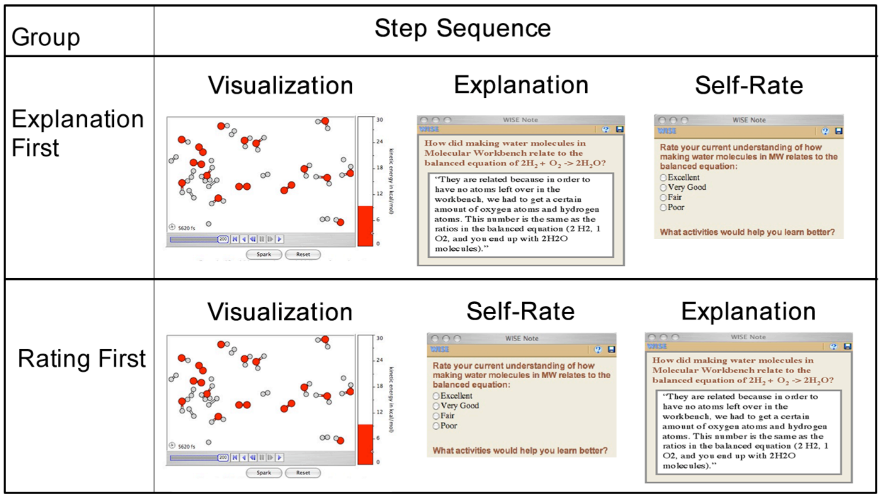
## Analysis

The scoring of pretests, posttests, and embedded explanation prompts followed the knowledge integration framework outlined in Chapter 2. I converted the pretest, posttest, and embedded student self-ratings into a numeric scale, where one = poor, two = fair, three = very good and four = excellent.

# Results

## Implementation

Teachers implemented the TELS curriculum in all classes with help from TELS



How did making water molecules in Molecular Workbench relate to the balanced equation of $2H_2 + O_2 \rightarrow 2H_2O$?

"They are related because in order to have no atoms left over in the workbench, we had to get a certain amount of oxygen atoms and hydrogen atoms. This number is the same as the ratios in the balanced equation (2 H2, 1 O2, and you end up with 2H2O molecules)."

Rate your current understanding of how making water molecules in MW relates to the balanced equation:

○ Excellent
○ Very Good
○ Fair
○ Poor

What activities would help you learn better?

Figure 4.1. Explanation First and Rating First treatment groups.

researchers. Students worked through the project in pairs assigned by the teachers. Researchers randomly divided student pairs into Rating First or Explanation First groups on the first day of the project run.

One teacher missed two days of running the unit. In these classes, a substitute teacher and researcher helped students finish the last two activities. Across both schools, 99% of student groups finished four activities, and 86% of student groups finished all five activities. All self-rating and explanation prompts occurred in the first four activities. Students who missed either the pretest or the posttest were removed from the analysis. Researchers also removed students with no record of completing the curriculum unit. No significant differences on the pretest were found between those students removed from the analysis and those with complete data.

## Pretest and Posttest Results

### *Integration of representations*

Overall, paired t-tests revealed significant gains from pretests to posttests across groups (Pretest: M(SD)=17.2 (6.7); Posttest: M(SD) = 26.8 (7.9); Effect size = 1.3, *t*(141) = 21.8, p = 0.001) replicating earlier results that the *Chemical Reactions* unit helps students make connections among representations in chemistry.

Regression analysis with pretest score, group, teacher, and honors status as explanatory variables and posttest score as the dependent variable indicated that pretests, group, teacher and honors status explained a significant proportion of variance in posttest scores ($R^2 = .58$, $F(4,137) = 47.5$, $p < .01$; (Table 4.1).). Students in the Explanation First group tended to score above the Rating First group, and Teacher 2 students tended to score above Teacher 1 students holding all other variables constant. However, regression analysis found no significant impact of teacher or group on posttest score. Holding all other explanatory variables constant, the honors classes did significantly differ from the non-honors classes on the posttest. Honors students' knowledge integration levels were about 3 points (or three connections) above non-honors students' knowledge integration levels on the posttest.

Table 4.1. Number of students, mean score, standard deviations, standardized slopes, t-values, and significance levels for pretests and posttests

| | n | *Pretest* *M (SD)* | *Posttest* *M (SD)* | *Standardized* Slope | *t* | *Significance* Level *p =* |
|---|---|---|---|---|---|---|
| Rating First | 73 | 17.1 (6.5) | 26.3 (7.5) | .89 | 1.02 | .31 |
| Explanation First | 69 | 17.3 (6.9) | 27.5 (8.3) | | | |
| Non-honors | 103 | 15.5 (6.4) | 24.9 (7.7) | 2.91 | 2.51 | .01 |
| Honors | 39 | 21.7 (5.1) | 32.2 (5.5) | | | |
| Teacher 1 | 98 | 17.9 (6.2) | 27.4 (8.4) | 1.64 | 1.59 | .11 |
| Teacher 2 | 44 | 15.5 (7.4) | 25.7 (6.6) | | | . |

### *Embedded Self-rating and Explanation-Eliciting Prompts*

The Rating First group consistently rated themselves as more knowledgeable than the Explanation First group (Table 4.2, Figure 4.2). To understand the significance of this observation, we used a 2-level ordinal logistic regression with the embedded self-ratings as the dependent variable and group, question, and the interaction between group and question as explanatory variables. The Rating First group was significantly more likely to rate themselves as more knowledgeable than the Explanation First group ($\beta$ = -1.49, z = -2.20, p = .03). No significant effect of question or interaction between question and rating was found on self-ratings.

Table 4.2. Number of student pairs, average embedded rating values and explanation KI scores by treatment group

| Rating Values | Rate 1<br>*M (SD)* | Rate 2<br>*M (SD)* | Rate 3<br>*M (SD)* | Rate 4<br>*M (SD)* |
|---|---|---|---|---|
| Rating First (*n*= 48) | 2.7 (.8) | 2.7 (.7) | 2.8 (.7) | 2.5 (.8) |
| Explanation First (*n*=43) | 2.4 (.7) | 2.4 (.9) | 2.4 (.7) | 2.3 (.7) |
| Explanation Scores | Question 1<br>*M (SD)* | Question 2<br>*M (SD)* | Question 3<br>*M (SD)* | Question 4<br>*M (SD)* |
| Rating First (*n*=48) | 2.0 (1.0) | 1.9 (.7) | 1.7 (.7) | 1.4 (.6) |
| Explanation First (*n*=43) | 2.2 (.8) | 1.8 (.8) | 1.5 (.7) | 1.2 (.5) |

Knowledge integration scores for the prompted explanations tended to decrease as students progressed through the curriculum for both groups (Figure 4.3). This indicates the increasing difficulty of the project and the level of connections that students are prompted to explain. On average, students made partial connections from the visualizations to traditional representations. For instance, in the second molecular visualization students started with two methane molecules and five oxygen molecules and were instructed to form carbon dioxide and water. The explanation prompt following the visualization (Question 2) asked students how

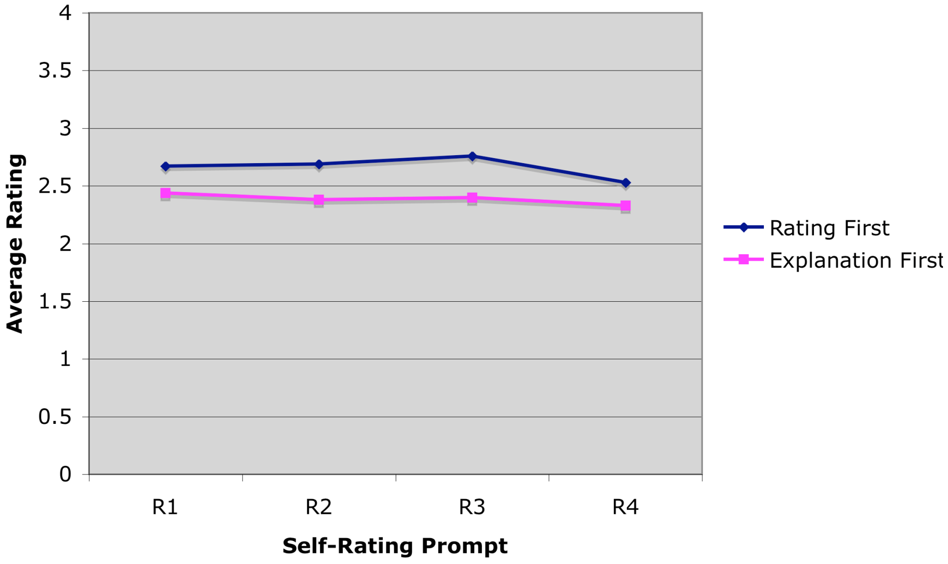


Figure 4.2. Average self-rating scores by treatment group and self-rating prompt.

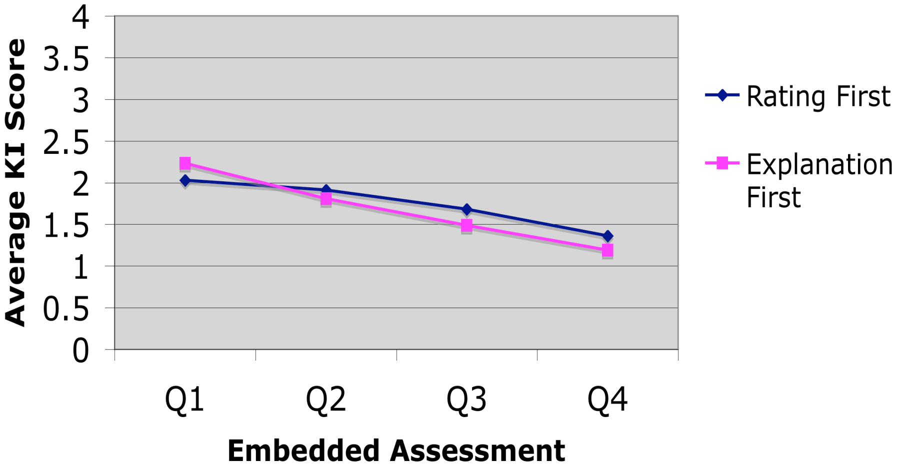


Figure 4.3. Knowledge integration explanation scores by treatment group.

excess reactants in the visualization related to the balanced equation, $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$. Most students correctly identified what was left over in the visualization (1 oxygen molecule or 2 oxygen atoms). Many students connected the “leftovers” with partial ideas about conservation of mass (“you can’t gain or lose atoms, so the extra oxygen molecule couldn’t be taken away”), ideas about balanced equations (“to balance the equation we don’t need one oxygen molecule”), and limiting reactants (“there is not enough to make more”). Some students were able to connect the ratios of the balanced equation to what they had left over (“With the equation above there was 1 o2 [sic] left because we had 5. We needed only 4 so we subtracted 4”). No significant differences between groups were found on knowledge integration scores.

Although the embedded knowledge integration scores decreased over the curriculum, student ratings in both groups remained relatively constant, suggesting that students did not see themselves as becoming less competent as they answered questions about more difficult concepts. The rating prompts asked students to rate their understanding of a particular concept within the larger topic of chemical reactions. For example, a self-rating prompt asked students to rate their understanding of limiting reactants. As the curriculum progressed, concepts became more difficult, the explanation scores decreased, yet the self-ratings in both groups stayed at roughly the same levels.

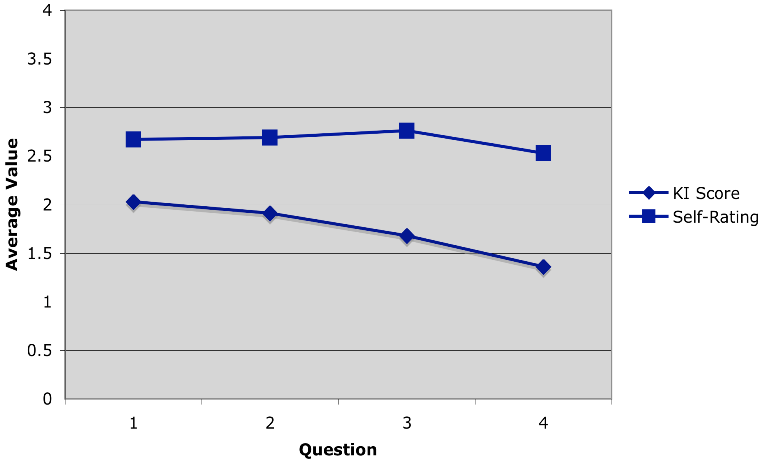


Figure 4.4. Average explanation scores and self-rating values for the Rating First group.

The Rating First group rated themselves as more knowledgeable than the Explanation First group (Figures 4.4 and 4.5). This indicates that the Rating First group's ratings were on average less accurate than the Explanation First group. Alternatively, ratings as the project progressed can be viewed as reflecting an internal sense of increased overall understanding of chemical reactions, instead of students rating each particular concept. Analysis of pretest-posttest self-ratings suggests this may also be the case, since students on average rated themselves as more knowledgeable and were more accurate.

*Pretest to Posttest Self-Ratings*

Students' self-ratings increased from pretest to posttest, mirroring increases of pretest to posttest scores (Table 4.3) To investigate the relationship between prior knowledge and self-

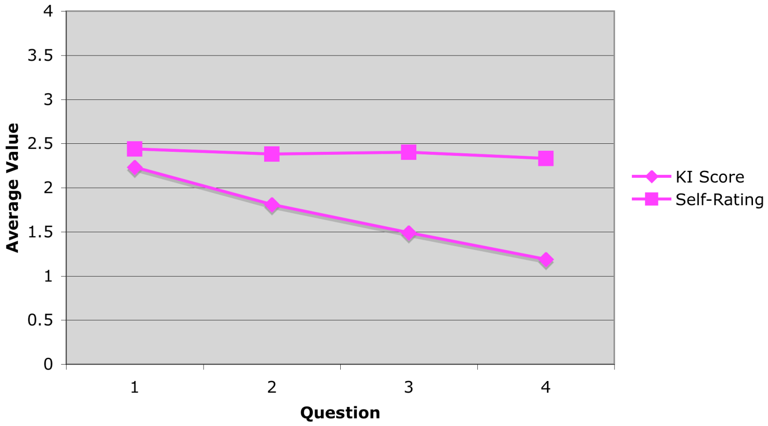


Figure 4.5. Average explanation scores and self-rating values for Explanation First group.

ratings, students were grouped into pretest levels using a median split on their pretest score. Regression analysis indicates that average pretest rating, pretest level, honors classes and explanation/rating group explained a significant amount of the variance in average posttest self-ratings ($R^2 = .48$, $F(4,125) = 28.6$, $p < .01$). The Explanation First group tended to rate themselves as less knowledgeable than the Ratings First group, and honors students tended to rate themselves as more knowledgeable than non-honors students, but no significant differences among groups and honors classes were found. Students scoring at or above the median on the pretest rated themselves as significantly more knowledgeable on the posttest than students scoring below the median on the pretest.

Table 4.3. Pretest and posttest average self-rating means and standard deviations by group.

| Group | n | *Pretest*<br>*M (SD)* | *Posttest*<br>*M (SD)* | *Standardized*<br>Slope | *t-value* | *Significance* Level<br>*p =* |
|---|---|---|---|---|---|---|
| Rating First | 73 | 1.91 (.65) | 2.52 (.60) | -.02 | -.30 | .77 |
| Explanation First | 69 | 1.81 (.65) | 2.47 (.65) | | | |
| Non-honors | 103 | 1.80 (.68) | 2.38 (.61) | .17 | 1.83 | .07 |
| Honors | 39 | 2.00 (.52) | 2.79 (.56) | | | |
| Below Median | 67 | 1.60 (.58) | 2.17 (.52) | .40 | 4.26 | .001 |
| Above Median | 75 | 2.08 (.63) | 2.78 (.56) | | | |

To estimate the ability of individual students' self-ratings to predict pretest and posttest scores, average ratings on the pretest were regressed with the pretest score as an explanatory variable, and average posttest ratings were regressed with the posttest score as an explanatory variable. Residuals of these regressions serve as an estimate of individual students' self-rating accuracy, where each individual error term represents the difference from the predicted value from the regression. Thus, a greater residual for an individual student represents less accuracy (more deviation from the predicted value) and a lower residual for an individual student represents more accuracy (less deviation from the predicted value). Negative residuals indicate that students underestimate their ability, and positive residuals indicate that students overestimate their ability.

Controlling for pretest ability, honors status, and project, students' residuals tended to decrease from pretest to posttest, indicating less inflated self-ratings on the posttest ($R^2 = .29$, $F(4,135) = 14.4, p < .001; \beta = .43, t = 6.89, p < .001$).

# Discussion

These results reveal the importance of self-monitoring for learning with dynamic visualizations. Overall, they suggest that visualizations are *deceptively clear* (Tinker, 2009). Embedding visualizations within the knowledge integration instructional pattern helps overcome this deceptive clarity by encouraging students to develop criteria for understanding. The pattern also helps students to recognize gaps in their knowledge. These results also point to design principles for instruction featuring dynamic visualizations.

## Deceptive Clarity

These findings help clarify why visualizations can be deceptively clear. A visualization can be so memorable that students become convinced they understand when they can recall only superficial features of what they have seen. Students rated themselves as more knowledgeable immediately after working with visualizations, and rated themselves as less knowledgeable after explaining connections from the visualizations. This supports the idea that students may develop a false sense of competence or an “illusion of knowing” from working with visualizations (Keil, 2006; Rozenblit & Keil, 2002). Students interact with the visualizations and believe that they understand the visualizations until they get to the explanation prompt.

Three possible reasons could explain students’ overestimations. First, students in the Rating First group may overestimate their knowledge because of the relative ease of accessing information learned from the visualization. In general, students report preferring visualizations to explanations (Corliss & Spitulnik, 2008). Also, students often feel that visualizations are the best way to learn, possibly because the visualizations give them a false sense of competence.

Second, students in the Explanation First group have both more time and specific instruction to reflect before they rate their understanding. The explanation prompt gives students the opportunity to reflect on their understanding and identify gaps in their knowledge that could make their rating more accurate (Davis, 2004; Davis & Linn, 2000). To illustrate, after the students investigate the dynamic molecular visualization of the hydrogen explosion, the explanation prompt asks students to relate the visualization to the macroscopic video of a hydrogen balloon exploding. One student pair in the Explanation First group responded that the visualization related to the balloon video “because it creates energy? I’m not completely sure.” This student group rated their understanding as fair in the corresponding prompt. In contrast, a student group in the Rating First group rated their understanding as very good, yet responded, “I have no idea.” Students in the Explanation First group may rate themselves as less knowledgeable than students in the Rating First group for reasons independent of the explanation item response. The greater time delay between the visualization and the rating prompt affords the Explanation First group an extended opportunity to think about the visualization and possibly appreciate its complexity (Dunlosky & Nelson, 1992).

Third, students may have more experience judging their own performances on written tasks than on their interactions with visualizations. Students who rate themselves immediately after interactions with visualizations may overestimate their abilities because students do not have commensurate prior experience assessing their interactions with visualizations. Thus, a mediating step such as an embedded explanation prompt may give students a more valid reference point to judge their understanding.

Despite the reasons for overestimation, students working with visualizations need help identifying what they do not understand and guidance to repair these deficits. This helps refine previous research that suggests that learners working with visualizations may be cognitively overwhelmed (Mayer, 2001; Paas, Renkl & Sweller, 2003). Instead, students may have different criteria for their understanding of visualizations as compared to other instructional activities. Students need help developing these kinds of self-monitoring skills to learn most effectively from dynamic visualizations.

## Knowledge Integration Patterns and Visualizations

These results suggest that the knowledge integration pattern contributes to learning with dynamic visualizations by helping students overcome deceptive clarity. The knowledge integration perspective adds value by helping students monitor their understanding through the development of criteria and refinement of their ideas and connections among ideas. Students interacting with visualizations may add ideas to their repertoire but these ideas may be irrelevant and non-normative. Students need help to identify when ideas may be less fruitful or conflicting, so that students can revisit and refine their understanding.

### *Prompting Explanations*

These findings suggest that prompting explanations encourages students to engage in knowledge integration by developing criteria, identifying gaps in their understanding, and distinguishing their ideas. The explanation prompt forces students to make their thinking visible, which "jars" them into realizing that they may not have understood the visualization as well as they previously thought. Giving an explanation requires students to develop criteria for their understanding that aligns with their criteria for explaining (e.g. "Am I capable of explaining? At what level/quality?") By having students generate explanations, students identify gaps in their understanding. The act of explaining seems to help students distinguish their ideas. All of this requires monitoring one's own knowledge.

Prompting explanations appear to work as desirable difficulties for learning with visualizations (Bjork, 1994; 1999). Prompting explanations aligns with research in technology-enhanced environments that call for increasing generative processing (Moreno & Mayer, 2007) or germane cognitive load (Paas, Renkl & Sweller, 2003) with visualizations.

Explanation prompts may also benefit learners using dynamic visualizations by focusing attention on specific aspects of the phenomena. The explanation prompts may guide learners to connect the most relevant ideas to relevant prior knowledge (Lombrozo, 2006). In addition, the act of generating an explanation forces learners to make their ideas explicit, which can help learners interpret dynamically presented material. To enhance student learning with visualizations, prompts can direct students to carefully observe and analyze what they see. For example, students observing a visualization of an explosion that at first glance depicts slow molecules that bounce around and suddenly speed up may think they understand. The curriculum can prompt students to inspect the visualization more closely and help them recognize that the reaction starts when one of the reactants spontaneously dissociates. The resultant free radicals attack the other reactant, releasing energy that causes additional dissociations and reactions. By experimenting with different dissociation and activation energies via visualizations students can gain a deep understanding of chemical reactions. Chapter 6 explores these issues in more detail.

Explanation prompts also seem to encourage students to use peers and teachers as well as information in the curriculum as resources. Classroom observations reveal that students often get useful information from their peers and that pairs of students will ask for help from the teacher. Dividing the classroom into pairs of students enables the teacher to have more tailored interactions with each learner, and allows time for the teacher to ask students to explain their own understanding (Slotta & Linn, 2009).

### *Prompting Self-Assessment*

Consistent with their knowledge gains, individual students across all groups rated themselves as more knowledgeable on the posttest than on the pretest. These self-assessments were conducted off-line on paper and pencil, surrounding typical chemistry representations and concepts. Although students rated themselves as more knowledgeable on the posttest, the residuals decreased from pretest to posttest. This suggests that students became more accurate at rating their understanding (or became more critical of their understanding) after completing the *Chemical Reactions* unit.

These changes in individual self-ratings are consistent with the nature of the instruction. Students spent an entire week investigating and explaining chemical reactions in depth with the TELS curriculum. In addition, students assessed their understanding (albeit in pairs) throughout the curriculum. This kind of instruction can help students not only make connections in chemistry but also develop metacognitive self-knowledge and encourage refinement, revision, and reflection upon understanding, similar to other studies using technology to help students develop metacognitive skills (White & Frederiksen, 2005).

The lack of a statistically significant distinction between groups on pre-to-posttest gains indicates that placing self-assessment prompts before or after the explanation prompts had no effect on students' knowledge integration score. This is consistent with the similarities of the groups in the amount of connections that students make among their ideas and among representations. Within the unit, even when provided with explicit prompts to connect ideas, students explaining their understanding on average made only partial connections among ideas on the knowledge integration scale.

Asking students to evaluate their understanding not only helps students make connections among ideas, but also appears to help students more critically and accurately assess their understanding. The combination of explanation and self-rating prompts helps learners become aware of gaps in explanatory knowledge about specific aspects of chemical reactions. These kinds of self-regulation skills are ultimately essential for guiding study practices.

## Conclusions

Dynamic visualizations of molecular interactions present an exciting and novel opportunity for chemistry instruction. This chapter illustrates the importance of monitoring skills to succeed in inquiry-based, visualization-enhanced chemistry units. Although dynamic visualizations are generally effective learning tools (Chang et al., in preparation), they need to be carefully embedded in instruction in order to succeed. Visualizations used without supportive surrounding instruction can result in students overestimating their understanding and spending too little time analyzing the details of the visualization. Learners may completely overlook key concepts and ideas presented in visualizations. To learn effectively from visualizations, students need to assess and regulate their understanding. Embedding visualizations within knowledge integration instructional sequences such as explanation and self-assessment helps learners to monitor their understanding and realize gaps in their repertoire of ideas. This chapter describes first steps in characterizing how generating explanations can help students monitor the understanding of ideas presented by dynamic visualizations, and how encouraging self-assessment helps students develop more accurate self-knowledge.

# Chapter 5: The Impact of Feedback on Student Learning and Regulation with Dynamic Visualizations

The results from Chapter 4 suggest that desirable difficulties can help learners overcome the deceptive clarity of visualizations. The results highlighted the importance of developing criteria and distinguishing ideas for learning with dynamic visualizations. Overall, eliciting explanations helped students realize gaps in knowledge, but this was not the case for all students. Some students simply gave up, or gave a very superficial response. Even if students knew they did not understand a concept, they may or may not have acted upon these judgments to remedy gaps in their understanding. This kind of self-regulation (Brown, 1987) is extremely important in technology-enhanced environments (i.e. Azevedo, 2007; Pintrich, 2000; White & Frederiksen, 2005; Winne, 2005; Zimmerman & Tsikalas, 2005). In this chapter I explore how desirable difficulties can contribute to self-regulation with visualizations, and how feedback can contribute to the development of self-regulatory skills.

To foreshadow the results, this study suggests that desirable difficulties promote self-regulation by encouraging students to revisit information to remedy gaps in understanding of sort out conflicting ideas. Through these activities, students distinguish existing ideas and ideas from the visualizations. Receiving external feedback on multiple-choice questions and navigational guidance did not act as a desirable difficulty. Instead, those activities appeared to promote less sophisticated criteria for understanding and were not as effective at encouraging students to distinguish ideas.

## Rationale

Learners who deliberately and intentionally monitor their understanding use internal feedback to build coherent and interconnected networks of ideas. Self-monitoring learners develop criteria for their understanding, accurately assess their understanding relative to those criteria and act upon differences by asking a teacher, seeking help from peers, or looking back at text for examples or more information (Butler & Winne, 1995). However, novices, less motivated or less aware students may not recognize conflicting ideas, may develop or change to simple criteria to reconcile differences, or even give up on the process entirely (Black & William, 1998).

These kinds of skills are especially salient for learners engaging in inquiry projects using technology-based environments, and in particular, environments using dynamic visualizations. Giving students dynamic visualizations does not ensure that students will learn the intended concepts, interact with the visualizations as the designers intended for them to interact, or that students make any connections to other ideas (Chapter 1). Visualizations can be deceptively clear, resulting in learners overestimating their understanding of the presented concepts (see Chapter 4). Even if students realize they do not understand the visualization, they may or may not use suitable strategies to remedy gaps in their knowledge. Students need to be able to monitor their understanding and appropriately act upon their judgments to learn effectively from dynamic visualizations (Zahn, Barquero, & Schwan, 2004).

External feedback can help students working with visualizations in technology-enhanced environments develop self-monitoring strategies. Immediate feedback can be a powerful learning tool in both laboratory and classroom settings, especially in cases where the learning materials are more educationally complex (Richland, Linn & Bjork, 2007). Feedback can help focus students' attention to relevant aspects of visualizations. External feedback can help learners become aware of gaps in their understanding, develop more complex and relevant criteria, and guide students to take appropriate action. Technology-enhanced environments can prompt explanations and self-assessments to help students realize if they do not understand critical ideas presented by the visualization (e.g. Chapter 4). These prompts can help students set and develop appropriate criteria for their understanding of visualizations by modeling the kinds of questions learners should be asking of themselves. Giving students feedback according to these criteria can help students more accurately assess their own understanding. Feedback can also help students act upon these judgments by giving students targeted guidance to revisit visualizations.

However, other research suggests that feedback can actually hinder monitoring skills (Moreno & Valdez, 2005). By providing rapid external evaluation to students, feedback can discourage the use of self-evaluative strategies and practices (Mathan & Koedinger, 2005). Immediate feedback in computer-based environments may encourage mindless clicking instead of mindful interaction (Baker et al., 2008). Immediate feedback during the learning process can give students an overly optimistic view of their understanding (Bjork, 1994). Desirable help students develop more robust conceptual understanding by having students struggle with difficult concepts. Students need to wrestle with why certain ideas and connections among ideas in their repertoire are not productive (Linn & Eylon, 2006) and immediate evaluative feedback can preclude these beneficial processes (Koedinger & Aleven, 2007).

This study investigates the impact of immediate feedback and self-evaluation on student learning and monitoring with dynamic visualizations embedded within a technology-enhanced curriculum unit. Few studies have investigated the impact of immediate feedback with students using dynamic visualizations. Previous studies have explored the nature of intrinsic feedback *within* the visualization (Rieber, Tzeng & Tribble, 2004), but few investigate the impact of feedback *after* students use dynamic visualizations. That is, how feedback on assessment items testing main concepts of the visualizations (i.e. multiple choice questions) given to the students immediately after using visualizations can impact student learning. This study explores how feedback can guide students to engage in beneficial monitoring practices in terms of revisiting the visualization to improve gaps in knowledge.

## Prior Research

WISE projects guide students' inquiry with the Inquiry Map, a persistent representation on the left side of the screen with steps for students to complete (see Figure 2.1). Although the curricular units are designed with activities and steps in certain sequences, students are free to choose any step at any time.

My classroom observations from previous studies revealed that students typically continue through the unit as designed. Classroom observations also revealed that students revisited steps when they were confused or did not understand something. I therefore regard these revisits as indicative of self-regulation, and analyzed the conditions that elicited this kind of behavior. Specifically, I investigated what students do when they encounter explanation prompts.

Building upon the self-assessment findings of the last chapter, I was interested in how feedback could impact students' interactions with and conceptual understanding of dynamic visualizations. I noticed that when students had difficulty using the prompts to build understanding (see Chapter 3) both the teacher and I would often refocus the students to particular aspects of the visualization. This would break the visualization down into smaller pieces that students could put together to form a more integrated understanding. For instance, during the greenhouse visualization, students would often ask for help when a prompt asked students about how carbon dioxide and infrared radiation relate to the greenhouse effect. I would then ask the students about what happened in the visualization when infrared radiation "ran into" a carbon dioxide molecule. This guided the students to notice that carbon dioxide reflects (or more scientifically, absorbs and re-emits) infrared radiation back to Earth, resulting in the atmosphere retaining heat.

Based on these observations and experiences, I was interested to see if incorporating external feedback with the visualizations could help students develop self-regulation skills by revisit relevant parts of the visualization. The *challenge question* feature in WISE asks students a multiple-choice question and gives feedback to the student. If the student responds correctly, the student receives feedback that they are correct and can move onto the next step. If the students answer incorrectly, they are told that they are incorrect and guided back to the particular step with the appropriate information. Students can then retry the multiple-choice question until they are correct. Students are not allowed to navigate to subsequent pages until they correctly answer the question. These challenge question steps had been shown to help students' reading comprehension in WISE (Fishbach, 2005). This kind of feedback could help students focus upon relevant aspects of the visualization, catch students immediately after working with visualizations and help them realize gaps in their understanding. Providing external feedback could potentially improve student understanding of the visualizations, and external guidance of interactions based on this feedback (such as being forced back to the visualizations and not being able to continue until the question is answered correctly) could help students develop self-regulatory techniques such as revisiting visualizations to improve their understanding.

Specifically, this study answers the following questions:

- How does external feedback compare to self-assessment without feedback to support learning and self-regulation with visualizations?
- What kinds of activities help students regulate their learning in terms of navigation through the unit?

# Methods

## Participants

Chemistry high school students in tenth and eleventh grades (n=249) from three teachers at one school completed *Chemical Reactions* after covering chemical reactions concepts in textbook-centered activities. All three teachers had no previous experience running the *Chemical Reactions* unit. The enrollment of students at this school consisted of over 20% of students from traditionally underrepresented populations in science, as well as 12% socioeconomically disadvantaged students.

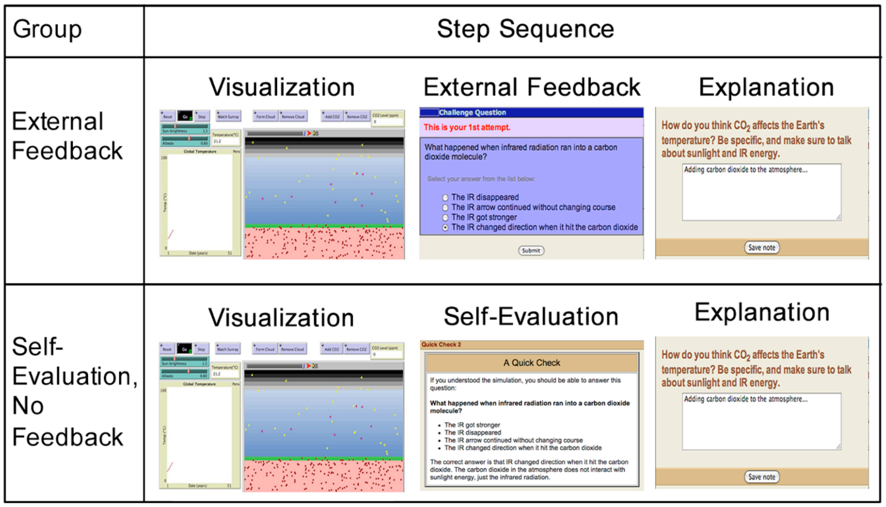
## Technology

The logging capabilities of the WISE 3.0 platform allow characterizations of how students progress through the unit. The WISE interface documents when students click on any step, including when they begin writing an explanation, note, or self-assessment. WISE records how long they stay on each step, whether they revise an answer, and the nature of their subsequent activities. WISE also records how students interact with the visualizations--when they pause, replay, or change a variable for the model. These kinds of logging capabilities have been utilized in previous studies to examine the duration and quality of learner's interactions with visualizations or the computer-based environment (Buckley et al., 2004; McElhaney & Linn, 2008; Varma, 2008).

In this study I investigated how students guided their own learning by looking at the navigational logs of students progressing through the unit. I compared where students navigate after explanation prompts to where students went after other steps within the unit, such as evidence pages (non-interactive information display), visualizations, and self-assessments. For instance, students could have decided to go back to visualizations after explanation prompts help them identify what they do not understand. Alternatively, students could continue to the next step in the project, either because they do not recognize the gap or because they think the gap will be remedied with future activities. I explore the self-regulation activities of learners by looking at logs of student actions.

## Treatment

To investigate how feedback impacts student understanding and monitoring with the visualizations, students were randomly assigned within classes to Explanatory Feedback (EF) and Self-Evaluation-No Feedback (SE-NF) conditions (Figure 5.1). Research suggests that students learn and transfer better with feedback that provides explanations for why answers are correct or incorrect as opposed to feedback that merely communicates correct or incorrect (Mayer & Moreno, 2007). In the External Feedback condition, the step after the visualization contained a multiple-choice question with feedback designed to focus the learner on a particular idea of the visualization. If the students correctly answered the question, they were told their answer was correct and were provided with a short explanation of the correct answer. If they answered incorrectly, students received feedback that their answer was incorrect and were



This is your 1st attempt.

What happened when infrared radiation ran into a carbon dioxide molecule?

Select your answer from the list below:

○ The IR disappeared
○ The IR arrow continued without changing course
○ The IR got stronger
● The IR changed direction when it hit the carbon dioxide

How do you think $CO_2$ affects the Earth's temperature? Be specific, and make sure to talk about sunlight and IR energy.

Adding carbon dioxide to the atmosphere...

If you understood the simulation, you should be able to answer this question:

**What happened when infrared radiation ran into a carbon dioxide molecule?**

- The IR got stronger
- The IR disappeared
- The IR arrow continued without changing course
- The IR changed direction when it hit the carbon dioxide

The correct answer is that IR changed direction when it hit the carbon dioxide. The carbon dioxide in the atmosphere does not interact with sunlight energy, just the infrared radiation.

How do you think $CO_2$ affects the Earth's temperature? Be specific, and make sure to talk about sunlight and IR energy.

Adding carbon dioxide to the atmosphere...

Figure 5.1 External Feedback and Self-Evaluation No-Feedback conditions for revisiting study.

guided back to the visualization with more detailed instructions about visualization. This “forced revisit” was designed to help students develop appropriate monitoring actions with visualizations. After revisiting the visualization, students could then retry the multiple-choice question with feedback. Students could not access later steps in the unit until they correctly answered the feedback question. Students who responded correctly moved to the next step where they were prompted to explain more complex phenomena in an open-ended response. For instance, a multiple-choice question with feedback asked students, “What happened when sunlight energy encountered a carbon dioxide molecule?” If the students answered correctly, they were able to go on to the next step that asks students to explain how carbon dioxide affects the Earth’s temperature. The External Feedback treatment occurred twice after two greenhouse visualization steps in Activity 2.

Students in the Self-Evaluation No-Feedback condition interacted with the same visualizations as the External Feedback condition. The step after the visualizations for the Self-Evaluation No-Feedback condition had the same question as the External Feedback condition (i.e., “What happened when a sunlight energy encountered a carbon dioxide molecule?”), but the text on the page said that to fully understand the visualization, one should be able to answer the question. The step encouraged students to revisit the visualization if they did not know the answer. This group had no feedback, the step was merely a text page, and students could access any step they wanted. The next step for the Self-Evaluation No-Feedback group contained the same explanation prompt as the External Feedback group (i.e., “How does carbon dioxide affect the Earth’s temperature?”).

In Activities 3 and 4, both student groups interacted with dynamic molecular visualization steps then explained their understanding in the following embedded assessment steps. No feedback was given to either group. Thus, the unit only gave feedback to the External Feedback group in Activity 2.

## Data Sources

Pretests and posttests are given immediately before and after enactment of each unit to individual students. The pretests and posttests were identical to those used in the Self-Assessment and Revisiting studies of Chapter 4. All items required some sort of constructed response. During project enactment, embedded assessments captured student thinking with open response items. Pairs of students working through the project answered the embedded assessments together.

This study considered two of the embedded assessments: one immediately after the second greenhouse visualization in Activity 2 about how carbon dioxide impacts the global climate, and one at the end of Activity 3 about how excess reactants relate to balanced equations. In Activity 3, both groups received the same steps and step sequence without feedback. I used student responses and log data from Activity 3 to compare groups after the treatment.

## Knowledge Integration Analysis

The scoring of pretests, posttests, and embedded assessments followed the knowledge integration analysis framework in Chapter 2. This study includes two of the embedded assessments within the curriculum in particular: one immediately after the second greenhouse visualization in activity two about how carbon dioxide impacts the global climate, and one at the end of activity three about how excess reactants relate to balanced equations.

# Results

## Implementation

All three teachers implemented the pretest to individual students immediately before starting the unit. Most student pairs completed the unit after one week, and the teachers administered the posttest immediately following the completion of the run. Seventeen students were omitted from analysis because of missing data.

## Student Learning

Overall, paired t-tests revealed significant gains on individual pretests to posttests across groups after controlling for pretest score (Pretest: M(SD)=21.0(6.1); Posttest: M(SD)=28.1(6.3); Pooled effect size=1.1; t(248)=25.7, p<.001). Students in the External Feedback condition scored slightly less than those in the Self-Evaluation No-Feedback condition on the posttest, although this difference was not significant after controlling for pretest score (Figure 5.2; Table 5.1)

Table 5.1. Mean scores, standard deviations, and effect sizes for pretest and posttests by treatment group.

| | **Pretest** | | **Posttest** | | |
|---|---|---|---|---|---|
| | **M** | **SD** | **M** | **SD** | **Effect size** |
| Overall (n=232) | 21.3 | 6.1 | 28.4 | 6.2 | 1.2 |
| Explanatory Feedback (n=126) | 20.6 | 6.1 | 27.6 | 6.6 | 1.1 |
| Self-Evaluation, No Feedback (n=106) | 22.3 | 5.9 | 29.4 | 5.4 | 1.3 |

## Embedded Assessments

For greenhouse items (Activity 2), students in the External Feedback condition did not score as well as those in the Self-Evaluation No-Feedback condition on the embedded assessment after the greenhouse visualizations, controlling for prior knowledge as measured by the pretest (External Feedback : M(SD)= 2.65(1.22), Self-Evaluation No-Feedback: M(SD)= 3.01(.90); F(2, 231)=4.49, p=.012; beta=-.29, t=-2.04, p=.042; Figure 5.3). Posttest score was

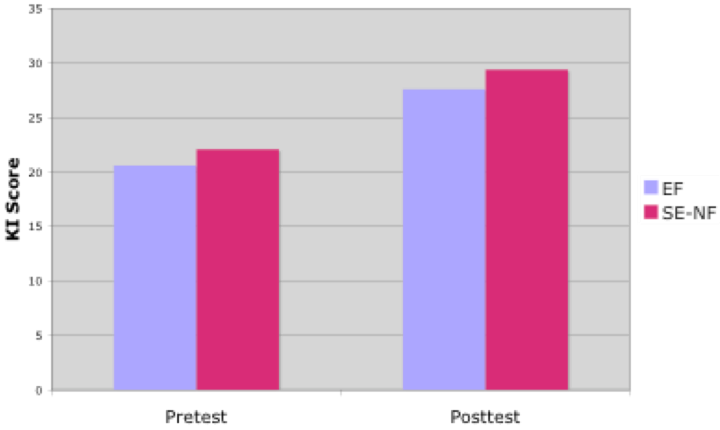


Figure 5.2. Pretest and posttest scores for Feedback and No Feedback groups.

regressed with pretest score, embedded assessment score, treatment group and whether or not the student revisited the visualization as predictors. Pretest score was the only significant predictor of posttest score. There were no differences among treatment groups. There was a small positive effect of revisiting the visualization on posttest score, however it was highly collinear with other predictors. The embedded assessment did not significantly predict posttest score. This could be due to the other learning opportunities that happen after the embedded item, such as drawing, generating more explanations, and constructing a letter.

Within the External Feedback condition, 26% of the students answered incorrectly and were forced back to the visualization. There were no significant differences among students who answered incorrectly and those who answered correctly on pretest or posttest scores.  Students who were forced back had lower scores on the embedded greenhouse item than the students who answered the multiple choice item correctly; this difference was borderline significant (Forced: M(SD)=2.26(1.54), Correct: M(SD)=2.78(.93); $t(199)=1.85$, $p = .07$).

For limiting reactant items, pretest and the embedded assessments were significant predictors of posttest score. Revisiting the molecular visualization had a positive effect on posttest score but was not significant. There were no significant differences among treatment groups.

## Student Monitoring

The designed curriculum had 57 steps in total. Counting the revisited steps, across all groups the mean of total visited steps was 64.1, with an average of 8.2 (SD=5.4) revisits per project. The average percentage of revisited steps to total steps visited in the project was 12%. Students tended to revisit more steps in Activities 2-3 than in 4-5, possibly due to limitations of class time. Within the External Feedback condition, 20% of the student pairs were forced to go back to the visualization.

Across projects, the most common revisiting pattern was from explanation steps to visualization steps. Figure 5.4 displays what steps students revisited throughout the unit. All of the steps in the unit are across the horizontal axis. Where students revisited "from," or the step where students went back from, is listed across the top graph by treatment group. Where students revisited "to," or the step where they chose to go to, is listed along the bottom graph by treatment

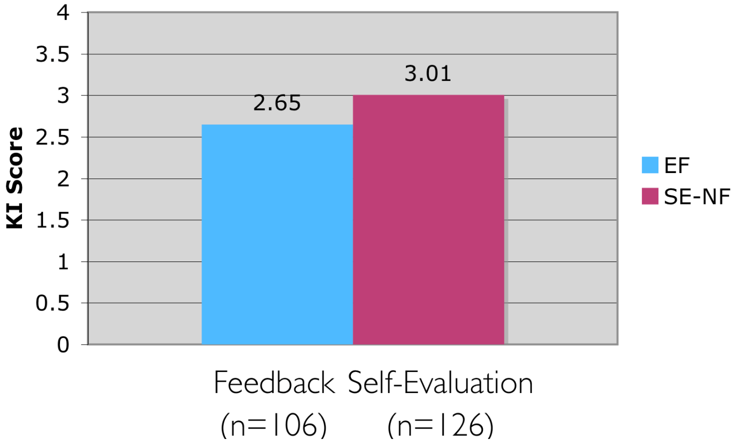


Figure 5.3. Greenhouse item explanation scores by treatment group.

group. Although most students follow the inquiry map to guide their interactions with the unit in a fairly sequential manner, the figure demonstrates the complexity of how pairs of students revisited specific steps in the curriculum. Some students revisited after explanation steps, or drawing steps, or evidence steps.

Despite this complexity, there were common patterns that emerged from the log file data. In the external feedback condition, the most popular patterns were explanation to visualization (9% of the total revisits), the forced question to a visualization step (6%) and evidence steps (webpages of information and questions, without student interaction) (5%). For the self-evaluation condition, explanation to visualization (11%), evidence to evidence (5%) and visualization to evidence (4%) were the most frequent revisiting patterns.

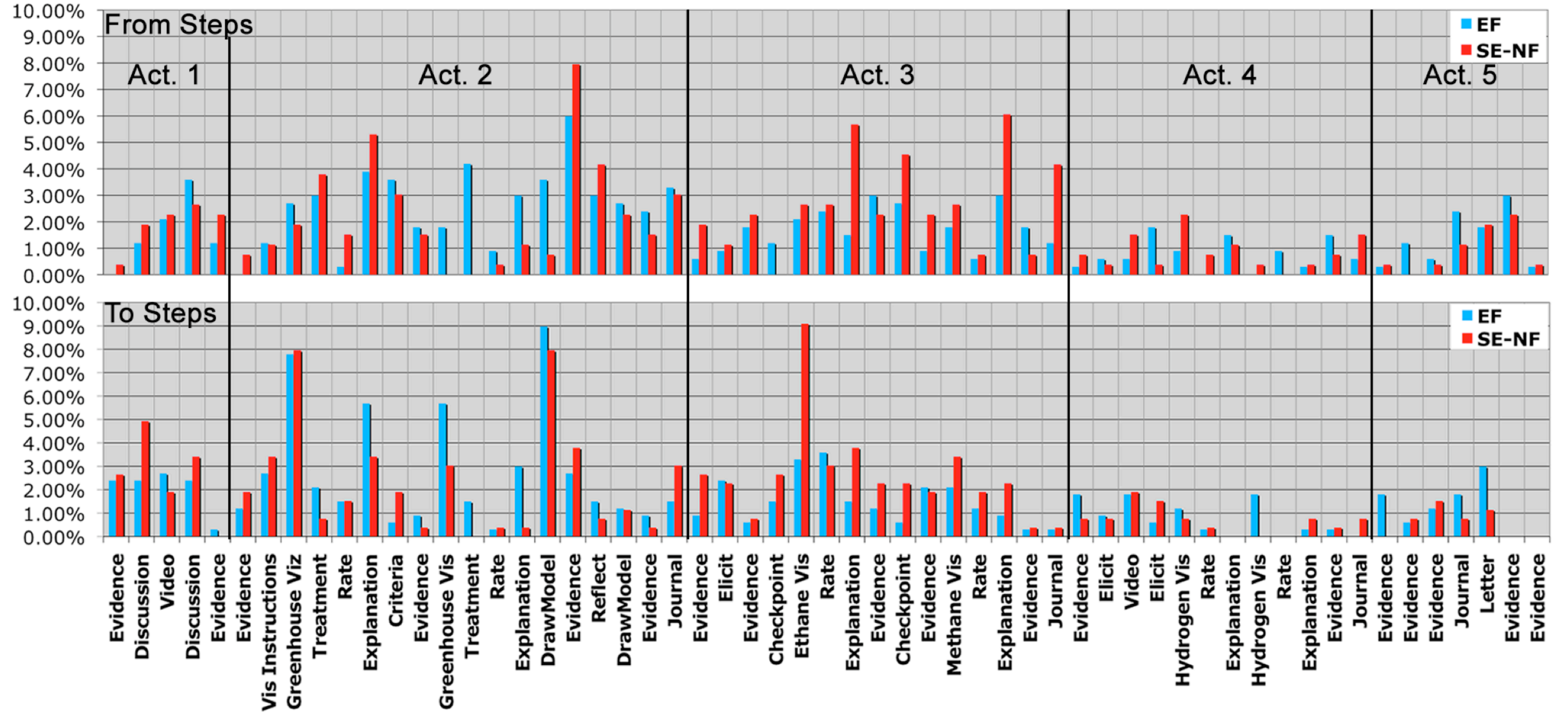


Figure 5.4. Graph of student revisits “from” and “to” each step by treatment group.

During Activity 2, the two groups had similar numbers of revisits to visualizations, even though some of the student groups were forced to revisit the greenhouse visualizations. (External Feedback: M(SD)=1.1(1.2), *n*=80; Self-Evaluation No-Feedback: M(SD)=.94(1.0), *n*=65; Figure 5.5). A logistic regression was used to predict if student groups would revisit visualizations in Activities 3 and 4 from whether the student revisited the greenhouse visualization in Activity 2. Treatment group was a significant predictor of revisiting the visualization in subsequent activities. During Activities 3 and 4, the Self-Evaluation condition led to more revisits than the External Feedback condition (External Feedback: M(SD) = .63(1.1); Self-Evaluation No-Feedback: M(SD) = .98(1.1)). Students who were in the External Feedback group were .50 as likely to revisit the visualization as those in the Self-Evaluation No-Feedback group. Revisiting the visualizations in Activity 2 was not related to revisiting the visualizations in Activities 3 and 4.

This study represents first steps towards capturing self-monitoring instances with log data. Other studies have tried more sophisticated measures with log files. Buckley et al. (2004) conceptualized the quality of learners' interactions with BioLogica as the duration that the learner spends with the activity divided by the number of learner actions within the activity. Short durations with lots of activity were regarded as lower quality, whereas long durations with less activity were regarded as higher quality. However, these measures did not reliably compare across learners. Students that may be completely off task, talking to friends or completing other assignments could have a high quality index, whereas students that click between multiple screens to build explanations could be captured as lower quality.

More complex measurements of interaction quality may therefore prove to be valuable. However, more research needs to be done within these complex environments and contexts to create such a measure. The revisit measures are a first step. They provided insight into self-regulation. They raise issues that could be addressed with more powerful documentation of student actions.

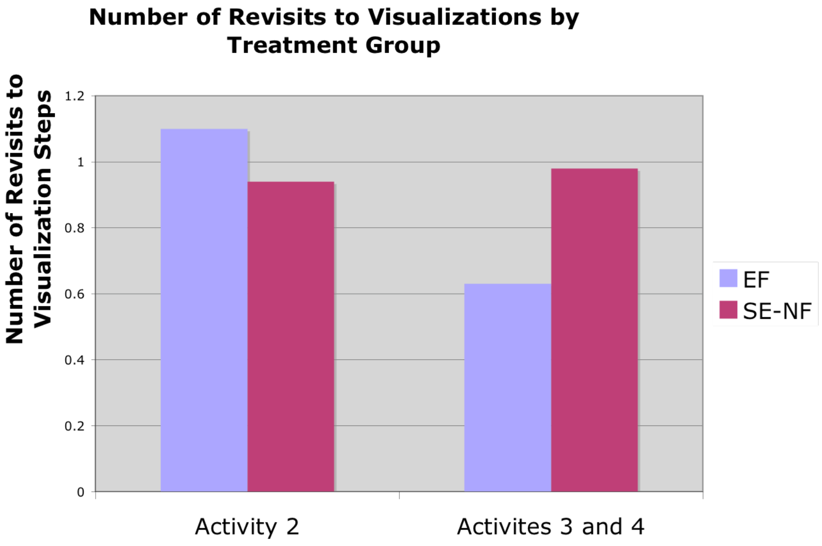


Figure 5.5. Number of revisits to visualizations in activity two and activities three and four by treatment group.

# Discussion

This chapter sought to clarify the role of feedback, generative activities and self-regulation for learning with dynamic visualizations. The results suggest that generative activities promote self-monitoring through the development of criteria and by encouraging students to revisit information to sort out conflicting information or remedy gaps in understanding. Activities such as answering multiple-choice questions and receiving feedback appeared to be undesirable and too easy, promoting less sophisticated criteria for understanding and not supporting students to distinguish ideas.

## Feedback and Dynamic Visualizations

Both groups benefitted from writing explanations. The external feedback used in this study did not add value to the instruction. Only a few students were impacted since only 26% of the students answered incorrectly in the external feedback condition.

The feedback treatment did not help students' immediate learning as measured by the embedded assessments. The students who were encouraged to evaluate their learning may have developed more encompassing criteria for their understanding, whereas the feedback condition may have encouraged those students to develop simpler criteria for their understanding. Since only a fourth of the students answered incorrectly in the external feedback condition, this assessment may have been too easy for the students. A more challenging assessment may have helped students develop more rigorous criteria for their understanding.

Students in the feedback condition were less likely to revisit the visualizations in activities after the treatment. This could be due to the treatment design. If students got the question correct, they received feedback telling them their answer was correct accompanied by an explanation. It did not encourage them to revisit the visualization. If students answered the question incorrectly, they were forced to return to the visualization until they answered correctly. This may have encouraged students to simply click and follow the curriculum, instead of actively engaging with the project. Students without the "forced" revisit who self-evaluated their understanding developed and maintained similar levels of revisiting the visualizations throughout the project. These students may have developed ways to act upon gaps in their knowledge.

Although immediate feedback may be beneficial in certain settings, these results may not translate to educational settings (Richland, Linn & Bjork, 2007) or benefit learners using dynamic visualizations. These findings point to other instructional approaches such explaining your understanding to impact students' learning and monitoring with dynamic visualizations within technology-based environments.

## Revisiting and Generative Activities

Results demonstrate the most common revisiting pattern to be from explanation steps to dynamic molecular visualizations. These results suggest eliciting explanations that connect visualizations to other ideas may help students identify what they do not understand and encourage students to revisit visualizations to remedy gaps in their knowledge.

Across both groups, steps that engaged students in generative activities encouraged students to revisit information. This clarifies the role of generative activities on self-monitoring and self-regulation. Generative activities not only support students to develop criteria and assess their understanding (Chapter 4) but also help students to act upon those assessments and revisit information. In this way, generative activities help students monitor and regulate their understanding.

These findings elaborate the sequence of learning activities undertaken within the same curriculum for each pair of students. Some peers revisit visualizations after explanation steps; other peers revisit visualizations after drawing steps. Students switch between evidence steps and their notes, or from visualizations back to text descriptions of concepts and phenomena. The majority of students use the inquiry map to guide their interactions with the unit, but the intricacies of each pair of students' interactions highlight how the curriculum, learners, and surrounding environment can impact the way students monitor their understanding.

Future research can clarify the nature of students' monitoring skills within these complex learning environments. For instance, this study reveals when students revisit their explanations, but does not reveal how the revisiting decision is made. Although self-rating prompts give insight into the monitoring value of prompting explanations, more information is needed about how students interact with each other while responding to explanation and self-rating prompts.

## Conclusion

This chapter explored how feedback can impact student monitoring and learning with visualizations. Analysis of the log data indicated that explanation prompts and other generative activities encouraged students to regulate their learning by going back to refine their understanding. The results from the feedback comparison revealed that explanatory feedback with navigational guidance can actually hinder learning and self-monitoring as compared to self-assessment without navigational guidance. This chapter suggests that pairing visualizations with explanations and self-assessments helps students learn effectively with visualizations by encouraging monitoring and regulation of understanding.

# Chapter 6: Explanation Prompt Specificity and Learning with Dynamic Visualizations

The previous chapters suggest that students can use dynamic visualizations to form connected and durable knowledge, that explanations help students recognize what they may not understand and encourage them to go back and revisit the visualizations, and prompting self-assessment helps students become more accurate judges of their understanding. However, immediate external feedback did not "catch" students to revisit or refocus upon the visualization. In fact, the feedback condition was less beneficial than a self-assessment step and may have encouraged students to develop less sophisticated criteria for their understanding.

Building upon these results, this study investigates how different kinds of explanation prompts can encourage learners to make and retain connections among ideas with dynamic visualizations. Since explanation prompts had such a strong impact on learning from previous classroom runs, I wanted to explore the nature of the explanation prompts. This study examines how explanation prompt specificity can impact the types of ideas that students distinguish and how students monitor their understanding. This chapter explores how different kinds of prompts can guide students to monitor different kinds of ideas and how this, in turn, can influence learning from dynamic visualizations. Specifically, I ask the following questions:

- How do general- and specific-link explanation prompts affect the number of connections and kind of ideas that students distinguish and connect with *Chemical Reactions*?
- How do general- and specific-link explanation prompts influence how students evaluate their understanding and act upon these judgments in *Chemical Reactions*?

## Rationale

The combination of visualizations and explanation prompts appear to have a synergistic impact on learning. This chapter seeks to understand how this combination can most effectively benefit learners. The benefit of learning through explaining to oneself or others can extend to dynamic visualizations (Buckley et al., 2004; Rieber, Tzeng, & Tribble, 2004). Prompting for explanations can focus the learner's attention to specific aspects of visualizations, which is particularly important for dynamically presented information (Lowe, 2004). For example, Pallant and Tinker (2004) used specific prompts in Pedagogica software ("Describe how the two molecules move--pay specific attention to the distance between molecules") to help students effectively use the open-ended environment of Molecular Workbench. Students using the Pedagogica curriculum acquired robust mental models of atomic interactions and transferred their understanding to new contexts. In *Chemical Reactions*, the hydrocarbon visualization steps have students manipulate methane and ethane molecules with different ratios to oxygen to form carbon dioxide and water. In the next step of the project, the explanation prompt asks students, "Explain how the left over atoms in the visualization relate to the balanced equation, $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$." This encourages students to relate unreacted molecules within the visualization to the ratios of the balanced equation, and relate atoms and bonds between atoms to the symbolic level of the balanced equation (for example, "They relate because the equations tells [sic] us that we need twice as many oxygen molecules as methane molecules. We were given two methanes and 5 oxygens, when we only need 4 oxygens, therefore we can predict that we will have one oxygen molecule left over"). Without the prompts, students may construct the right numbers of carbon dioxide and water molecules and think they fully understand the visualization, but not make any connections to the balanced equation (see Chapter 3).

Many studies call for content-specific supports to help the learner explain critical concepts (i.e. Ardac & Akaygun, 2004; Buckley et al., 2004; Chang & Quintana, 2006; Frederiksen, White & Gutwill, 1999; McNeill & Krajcik, 2006; Sandoval & Reiser, 2004; Slotta & Chi 2006). Specific explanation prompts can problematize key aspects of the dynamic visualizations. According to Reiser (2004), instructional support that problematizes concepts "shape students' performance and understanding of the task in terms of key disciplinary content and strategies" (p. 273). Supporting this kind of problematizing of the dynamic visualizations can help students realize gaps in their understanding (see Chapter 4).

However, prompt specificity can impact the types of connections students make among ideas with visualizations. Focusing students upon certain concepts may result in shallow, narrow connections (i.e. "We had one oxygen molecule left") or inaccurate connections to visualizations (i.e. "We had 2 oxygen atoms left over. This relates to the balanced equation because the equation was not properly balanced"; or "We had 2 oxygen left over, this relates to the balanced equation because it added extra molecules"). Students may only monitor and refine their understanding of the particular prompted idea within the visualization. Specific prompts may limit students to consider only that specific set of ideas instead of connecting with a wider range of ideas, thus narrowing reflection (Aleven et al., 2006).

General prompts that encourage students to reflect upon their own ideas, identify weaknesses, or generate useful connections could be more effective than content-specific prompts (Davis, 2003; White & Frederiksen, 1998). For example, Davis (2003) compared generic reflection prompts (e.g. "right now, we're thinking…") to directed prompts (e.g. "To do a good job on this project, we need to…") within the WISE environment. Davis found that students with generic prompts were able to reflect more productively, eliciting more ideas more coherently than students in the directed prompt condition. White and Frederiksen (1998) found that asking students to reflect and assess their understanding in a content-general but guided way helped students improve on conceptual and inquiry measures. Chi et al. (1994) prompted students to explain what they understood after each sentence of a text passage, and those prompted explainers learned more than the control group that merely reread the sentence.

Supporting students to explain dynamic visualizations with general prompts may help students reflect upon whatever they are currently thinking, and strengthen connections among current ideas and visualizations. General prompts may encourage students to consider and connect a wider range of ideas as compared to prompts that focus the students to certain ideas. Thus, this study explored the relative impact of general- and specific-link explanation prompts on student learning and monitoring with dynamic visualizations embedded within a technology-enhanced curriculum unit. This study compared general-link prompts that encourage students to explain the visualization without any particular focus to specific-link prompts that encourage students to explain a particular relationship between two concepts or ideas related to the visualization. Although both general and specific-link prompts promote the generative activity of explaining surrounding interactions with visualizations (i.e. Chi, 2009), this study explored how the specificity of explanation prompts can influence what ideas students distinguish and how students rate their understanding.

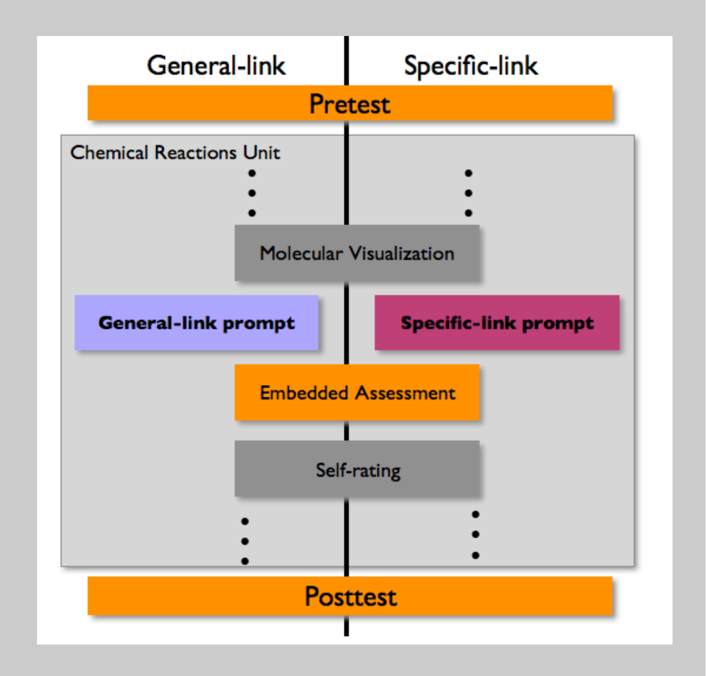


Figure 6.1. Specific-link and General-link treatment conditions.

# Methods

## Participants

This study includes two high school chemistry teachers and seven classes of high school students. Teacher 1 participated in the design and refinement of the *Chemical Reactions* unit and had previous experience running *Chemical Reactions* in past years. Teacher 1 ran the project with five classes, two of which were honors classes. Teacher 2 had not previously run the *Chemical Reactions* unit, but had run other TELS projects in other subjects in past years. Teacher 2 ran the project with two regular chemistry classes. Students with missing pretest, posttest, or project data were excluded from this analysis. There were approximately 140 students with complete data from the seven classes. Students went through the unit in pairs, with the same pairs throughout the week. Teacher 1 provided some guidance as to the grouping of students (working together with predetermined lab partners or assigning people together who did not have a partner) whereas Teacher 2 let students fully choose their partners. All students received minimal textbook-based instruction of chemical reactions concepts prior to the project implementation.

## Treatment

I made two versions of the *Chemical Reactions* module, one with general-link prompts and one with specific-link prompts immediately following visualization steps (Figure 6.1). Both projects were identical except for the wording of the prompts: the general-link treatment consistently asked the students to “Explain the visualization,” whereas the specific-link treatment asked students to connect key concepts to the visualizations (e.g. “Explain how the balanced equation relates to the hydrogen combustion visualization”). The specific-link treatment prompted for different concepts for each explanation. Both treatments had identical embedded assessments following these prompts. Students were asked to evaluate their answer to the first embedded assessment, to rate their understanding of limiting reactants surrounding the second embedded assessment, and asked to rate their understanding of the visualization surrounding the third treatment prompt. Student pairs were randomly divided within classes between the two treatments.

I scored pretests, posttests, embedded assessments and self-ratings as described in Chapter 2.

# Results

## Explanations and Embedded Assessments

Figure 6.2 and Table 6.1 display average scores for explanation items by treatment. To understand the relationship among treatment and score, a two-level ordinal logistic regression was used with the explanation question as the first level within student pairs and treatment as the second level between student pairs. Explanation score was used as the dependent variable and treatment, question, honors status and the interaction between treatment and question were explanatory variables. There was no overall significant difference of scores between the two treatments, but there was a significant interaction between question and treatment ($\beta = 0.23$, $z = 2.17$, $p = 0.03$), indicating that students in the general-link group were more likely to score higher in later questions controlling for honors status. Honors students were significantly more likely to score higher than non-honors students ($\beta = 1.64$, $z = 4.66$, $p < 0.00$).

Although the number of connections was similar across groups, the kinds of ideas that were elicited varied. The responses to general-link prompts included a more diverse range of ideas, with many responses recounting the students’ actions with the visualization. The specific-link responses largely consisted of the targeted ideas and related ideas within the visualization. For

Table 6.1. Explanation scores by treatment and class.

| Treatment | *N* *(pairs)* | Exp. 1 M (SD) | Exp. 2 M (SD) | Exp. 3 M (SD) | Exp. 4 M (SD) | Exp. 5 M (SD) | Exp. 6 M (SD) |
|---|---|---|---|---|---|---|---|
| Specific-link | 36 | 2.73 (0.65) | 2.78 (1.12) | 2.58 (0.73) | 2.08 (0.77) | 2.91 (1.06) | 2.37 (0.73) |
| Regular | 24 | 2.52 (0.51) | 2.33 (1.05) | 2.42 (0.72) | 1.79 (0.59) | 2.68 (1.13) | 2.09 (0.60) |
| Honors | 12 | 3.17 (0.72) | 3.67 (0.65) | 2.92 (0.67) | 2.67 (0.78) | 3.33 (0.78) | 2.92 (0.67) |
| General-link | 39 | 2.55 (0.86) | 2.72 (1.10) | 2.49 (0.76) | 2.54 (1.10) | 3.13 (0.96) | 2.51 (0.73) |
| Regular | 29 | 2.38 (0.82) | 2.72 (1.03) | 2.31 (0.66) | 2.45 (1.15) | 3.00 (1.05) | 2.41 (0.69) |
| Honors | 10 | 3.11 (0.78) | 2.70 (1.34) | 3.00 (0.82) | 2.80 (0.92) | 3.50 (0.53) | 2.80 (0.79) |

example, the first explanation either asked students to explain the visualization or to explain how the balanced equation related to the visualization. Students in the specific group answered, "The numbers of molecules I produced relates to the balanced equation because they both have the same total number of atoms" whereas students in the general condition answered, "In the visualization we created our reactant into the product of the reactant. There were 6 H2O [sic] molecules and 4 CO2 molecules." In the explanation steps students in the general-link condition expressed more molecular and ideas about chemical reactions than students in the specific-link condition, whereas students in the specific-link condition expressed more of the specific, targeted ideas from the prompt, such as limiting reactants and connections symbolic levels.

## Self-Ratings and Evaluations

Across both the explanation evaluation (Rate Question 1) and the self-ratings (Rate Questions 2-5), the general group rated themselves as more knowledgeable than the specific group (Figure 6.3, Table 6.2). To investigate this relationship, a two-level ordinal logistic regression with rating question as the first level and treatment group as the second level with self-rating as the dependent variable and treatment, honors and the interaction between question and treatment as explanatory variables. Overall, there was a marginally significant effect of students in the general-link group to be more likely to rate themselves as more knowledgeable than students in the specific-link group ($\beta$=1.08, z=1.83, p=0.067). Honors students were significantly more likely to rate themselves as more knowledgeable ($\beta$=1.10, z=4.66, p<0.00).

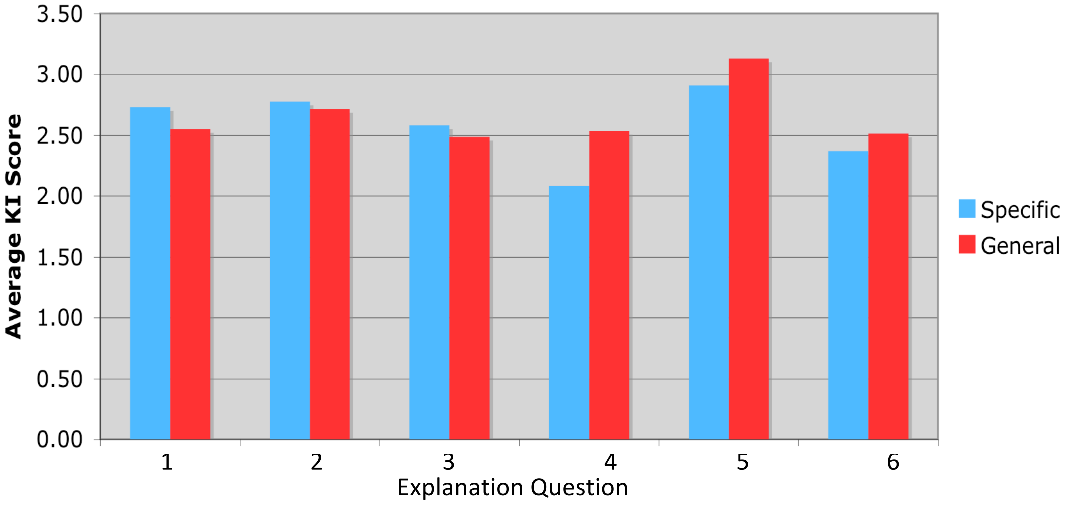


Figure 6.2. Embedded explanation scores by treatment group.

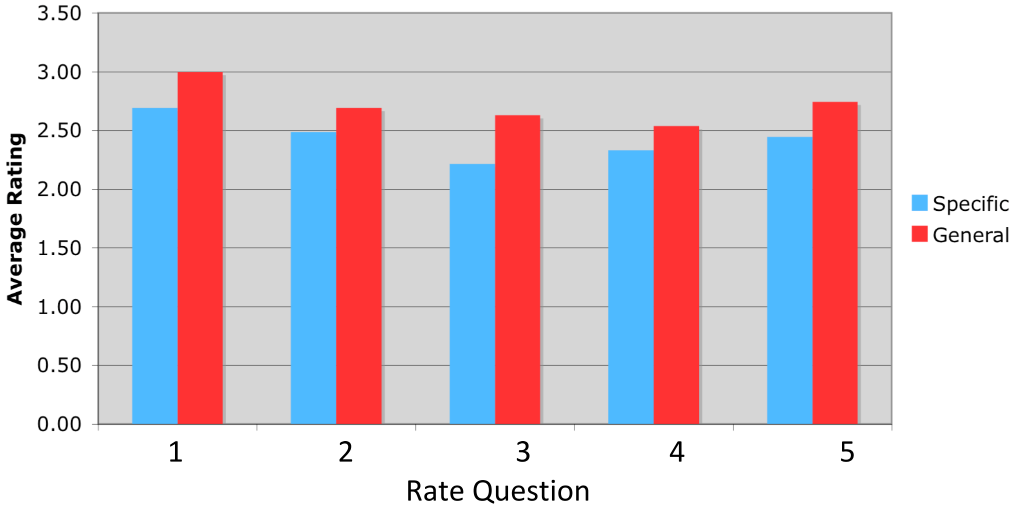


Figure 6.3. Average self-ratings by treatment group and question.

When the students were asked to evaluate their own explanations on a knowledge integration scale similar to the one used to code their explanations, (Rate Question 1), students with general prompts gave higher evaluations, even though their scores were on average lower than the specific group. Additionally, when students rated their understanding of limiting reactants before and after their second explanation (Rate Questions 2 and 3), the specific group ratings decreased. This replicates the *illusion of explanatory depth* found in many studies (Rozenblit & Keil, 2002), and prior work with self-ratings in *Chemical Reactions*, suggesting that the specific prompts help students recognize what they may not understand. However, the general group ratings did not decrease. The general prompts may not have been as effective at highlighting gaps in students' understanding. Instead, the self-assessments suggest that the

Table 6.2. Self-rating scores by treatment and class

| Treatment | *N (pairs)* | Rate 1 | Rate 2 | Rate 3 | Rate 4 | Rate 5 |
|---|---|---|---|---|---|---|
| Specific-link | 36 | 2.69<br>(0.79) | 2.49<br>(0.77) | 2.22<br>(0.67) | 2.33<br>(0.93) | 2.44<br>(0.77) |
| Regular | 24 | 2.63<br>(0.88) | 2.24<br>(0.72) | 2.04<br>(0.61) | 2.13<br>(0.99) | 2.25<br>(0.79) |
| Honors | 12 | 2.83<br>(0.58) | 3.00<br>(0.60) | 2.58<br>(0.67) | 2.75<br>(0.62) | 2.83<br>(0.58) |
| General-link | 39 | 3.00<br>(0.66) | 2.69<br>(0.89) | 2.63<br>(0.79) | 2.54<br>(0.94) | 2.74<br>(0.79) |
| Regular | 29 | 2.97<br>(0.68) | 2.69<br>(0.81) | 2.59<br>(0.82) | 2.48<br>(1.02) | 2.72<br>(0.84) |
| Honors | 10 | 3.11<br>(0.60) | 2.70<br>(1.16) | 2.78<br>(0.67) | 2.70<br>(0.67) | 2.80<br>(0.63) |

general prompts could have helped students connect the visualizations to their current thinking, interpret the visualization using their own words, and reflect upon their interactions with the visualization.

When students rated their understanding of the visualization before and after explaining (Rate Questions 4 and 5), self-ratings increased for both groups. This suggests that explaining could make both groups feel like they better understand the visualization.

## Pretest and Posttest Assessments

Overall, students' knowledge integration scores significantly increased from pretest to posttest, similar to other studies with *Chemical Reactions* (Figure 6.4, Table 6.3). There was a large effect from pretest to posttest, with an effect size *g* = 0.92 (Hedges & Olkin, 1985). Regression analysis was performed with posttest score as a dependent variable and pretest score, honors status, teacher and project as covariates (R2 = 0.66, F(4, 129)=2.92, p=0.00). Pretest score and honors status significantly predicted posttest score (pretest: β=0.81, t=12.18, p=0.000; honors: β=1.60, t=2.00, p=0.047). Although there were large differences on the pretest between teachers, controlling for pretest score there was not a significant effect of teacher on posttest score. There were no significant differences between treatments on posttest score.

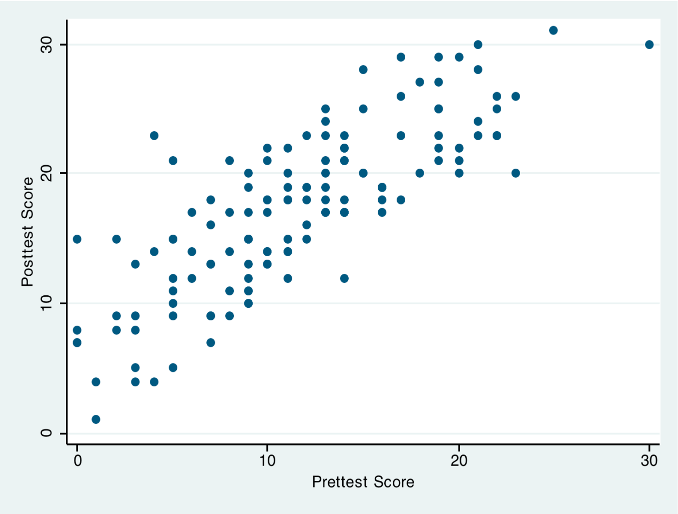


Figure 6.4. Pretest and posttest knowledge integration scores for General- and Specific-link groups.

Table 6.3. Average pretest and posttest scores by treatment, teacher, and class

| | | Specific-link | | | General-link | | |
|---|---|---|---|---|---|---|---|
| | | N | Pretest M *(SD)* | Posttest M *(SD)* | N | Pretest M *(SD)* | Posttest M *(SD)* |
| Overall | | 70 | 11.60 | 17.00 | 69 | 11.52 | 17.46 |
| | | | *(5.93)* | *(6.24)* | | *(6.29)* | *(6.52)* |
| Teacher 1 | Honors | 23 | 15.00 | 20.74 | 17 | 15.12 | 21.41 |
| | | | *(5.86)* | *(5.55)* | | *(6.00)* | *(5.34)* |
| | Regular | 26 | 12.96 | 16.42 | 33 | 12.91 | 18.12 |
| | | | *(4.81)* | *(5.88)* | | *(5.13)* | *(5.99)* |
| Teacher 2 | Regular | 21 | 6.19 | 12.24 | 19 | 5.89 | 12.79 |
| | | | *(3.89)* | *(5.58)* | | *(4.62)* | *(5.72)* |

## Duration and Navigation Logs

Duration and navigation patterns were calculated using the log files of students' interactions with the project (Table 6.4). Across both groups, those in the top quartile of gain scores spent more time with the unit, revisited more, spent more time with the visualizations, revisited from explanations more and tended to go from explanations back to the visualization back to the visualizations. There were no significant differences among treatment groups for duration, duration of the visualization, number of revisits (when students chose to visit a step out of sequence), or number of revisits from the specific treatment explanation steps to other steps. To investigate the effect of students' interactions within the unit on overall learning, the gain score was regressed with total time, time spent with visualizations, treatment, pretest score, and honors status as covariates ($R^2$=0.15, F(5, 128)=4.46, p<0.001). Neither total time spent on the project nor treatment significantly predicted gain from pretest to posttest. After controlling for

Table 6.4. Average pretest score, gain, duration, duration with visualizations, revisits, and revisits from explanations for treatment groups and honors classes

| Project | *n* | Pretest Score (SD) | Gain (SD) | Duration (SD) | Visualization Duration (SD) | Revisit Total (SD) | Revisit from Explanations (SD) |
|---|---|---|---|---|---|---|---|
| Specific-link | 65 | 11.67 | 5.6 | 3:04:28 | 0:40:30 | 18.5 | 3.63 |
| | | (6.03) | (3.9) | (36:13) | (0:13:48) | (11.1) | (2.25) |
| Regular | 44 | 10.0 | 5.4 | 2:59:15 | 0:38:52 | 17.6 | 3.64 |
| | | (5.43) | (3.9) | (38:14) | (0:13:17) | (11.0) | (2.40) |
| Honors | 21 | 15.19 | 5.9 | 3:15:26 | 0:43:56 | 20.6 | 3.62 |
| | | (5.81) | (4.0) | (29:30) | (0:14:02) | (11.2) | (1.94) |
| General-link | 69 | 11.52 | 5.9 | 2:59:43 | 0:40:09 | 19.6 | 3.13 |
| | | (6.29) | (3.9) | (39:35) | (0:16:15) | (13.4) | (2.05) |
| Regular | 52 | 10.35 | 5.8 | 3:06:53 | 0:42:03 | 21.4 | 3.2 |
| | | (5.97) | (4.0) | (40:11) | (0:17:43) | (14.6) | (2.23) |
| Honors | 17 | 15.12 | 6.3 | 2:37:46 | 0:34:21 | 14.2 | 2.89 |
| | | (6.00) | (3.7) | (0:28:50) | (0:08:41) | (6.1) | (1.40) |

total time spent on the project, total time spent with the visualizations was a significant predictor of pre- to posttest gain at the 0.05 level (t=2.11, p=0.04). Controlling for time within the project, students in honors classes gained significantly more (β=1.72, t=2.66, p=0.03). However, pretest score was a significant predictor but with a negative coefficient (β=-0.232, t=-4.12, p=0.000). This suggests that after controlling for time within the project and honors status, students who scored lower on the pretest gained more from pretest to posttest than students that started with high pretest scores.

## Discussion

Looking across explanations, self-assessments and log files, these findings suggest that specific-link prompts tend to help students problematize and distinguish certain ideas. Students rated themselves as less knowledgeable in the specific-link condition, and students' self-ratings decreased immediately after explaining the visualization. This replicates the findings in Chapter 4 investigating how explanations can help students monitor their learning and distinguish ideas with dynamic visualizations. Although the number of connections was similar between specific and general groups for assessments, the ideas that students connected in the specific-link treatment were focused around the targeted connections. Students tended to revisit information after explanation steps in the specific-link condition more often than students in the general-link condition. This suggests that specific-link prompts can encourage students to identify weaknesses or gaps in their knowledge, and act upon those gaps by revisiting information after explaining.

In comparison, students in the general-link prompt tended to connect ideas about the molecular level and chemical reactions, reflecting upon their interactions with the visualizations. Students in the general-link condition tended to rate themselves as more knowledgeable than students in the specific-link condition, and their self-assessments remained the same before and after explaining. This suggests that general prompts encourage connections and distinguishing among current ideas, similar to other research on prompted explanations with general prompts (Chi et al., 1994; Davis, 2003). The general prompts did not seem to trigger the same kind of awareness of gaps in understanding as the specific prompts, suggesting that general prompts may not problematize a certain aspect of the visualization, but instead help students reflect upon or verbalize their interactions with the visualization.

Prior research suggests that expertise plays a role with prompt specificity (Aleven et al., 2006; Davis, 2003). Research points to specific guidance benefitting students with lower prior knowledge and more general guidance benefitting students with more prior knowledge (Kalyuga et al., 2003). However, students with very low prior knowledge were able to use the general prompts to reflect upon the visualization, albeit superficially (i.e. "the red balls were the hydrogen and the gray balls were the oxygen") whereas students with very low prior knowledge in the specific condition had trouble making the specific connections (i.e. "I don't know" or "I don't understand"). This suggests that the difficulty of the task and the targeted concepts may also contribute to the effectiveness of specific and general support for learning with visualizations. In some cases, general prompts can be more beneficial for students with very low levels of prior knowledge. If specific guidance is too difficult, students may give up and students with high levels of prior knowledge can even become too self-critical. In this case, general prompts can encourage students at any level to reflect and make connections among ideas.

These results build upon prior research with general and directed reflective prompts (e.g. Davis, 2003) and content-specific and general explanation prompts in inquiry science instruction (McNeill & Krajcik, 2006). Davis (2003) found that directed prompts benefitted students who engaged in content-focused reflection. Because the students studying *Chemical Reactions* were asked to explain their interactions with the visualizations immediately after interacting with the visualizations, this encouraged students to engage in content-focused reflection, with specific prompts showing benefit for knowledge integration. However, Davis (2003) found that students with low autonomy, or students that did not believe in taking control of their own learning, did not benefit from generic reflection prompts. This study did not measure the level of autonomy of the student, however, students with very low prior knowledge were able to use the general prompts to reflect. Again, the use of dynamic visualizations may account for these differences. Students with very low prior knowledge still interacted with the visualizations and were able to explain what they did, even if it was scientifically non-normative. This may have enabled an entry point for students to reflect upon their understanding differently than the students in the Davis (2003) study.

McNeill & Krajcik (2006) found that content-specific prompts were more beneficial than generic explanation scaffolding. In the specific condition, students answered very specific questions without the overall claim, evidence and reasoning focus. In their generic condition, students were reminded to use claims, evidence and reasoning in their explanation. However, the generic condition in the McNeill and Krajcik study was still somewhat structured. This condition was more similar to the directed reflection prompts of the Davis (2003) study. Providing this structure, albeit generalized over the curriculum, may have narrowed reflection. In contrast, the generic prompts used in this study were so vague that students could interpret the prompts as they wished. This may have enabled them to engage in explanation.

The lack of difference among treatments on pretest to posttest gains suggests the overall importance of generating an explanation, whether it is specifically prompted or generally prompted, as a valuable learning tool with visualizations. Generation encourages students to infer new knowledge, connect new information with prior knowledge, organize, restructure, and repair understanding (Chi, 2009). Whether prompted in a specific or general fashion, this kind of struggle and slowing down of learning can result in durable and coherent knowledge (i.e. Bjork 1994, 1999; Bjork & Linn, 2006). Asking students to generate an explanation can “wake up” the student, slow down learning and help engage students in reflection, reorganization or the realization of gaps in understanding. This aligns with research on dual-processing approaches to reasoning and judgment (i.e. Evans, 2003) that suggests that people tend to initially engage in quick, intuitive, associative and relatively effortless reasoning, and that these visualizations are initially deceptively clear (Chapter 4). Desirable difficulties or periods of disfluency encourage people to reason more carefully and analytically, and reconsider initial ideas (Alter et al., 2007).

These findings underline the benefit of dynamic visualizations embedded within knowledge integration patterns on learning complex science. Controlling for total time in the project, more time spent with visualizations resulted in larger gains from pretest to posttest. Students interacting with typically unseen or invisible levels can gain a deeper understanding of molecular or large-scale phenomena, such as the chemical reactions and global climate visualizations used in this study. Supporting knowledge integration activities, such as generating explanations, encourage students to use dynamic visualizations most effectively.

# Conclusions

This study sheds light on the kinds of instructional support surrounding dynamic molecular visualizations that can help learners add, evaluate and refine scientific ideas. It also suggests ways to help students develop self-monitoring skills in technology-based learning environments. These results suggest that general explanation prompts may help students reflect upon visualizations and distinguish current ideas and concepts, whereas specific-link prompts problematize certain ideas and help students recognize gaps in their understanding. The overall learning gains of both approaches point to the benefit of using generation activities to support knowledge integration in technology-enhanced learning environments with dynamic visualization.

# Chapter 7: Looking Across the Studies, What Contributes to Learning with Dynamic Visualizations?

## Summary of Findings

*Overarching question: How can visualizations and knowledge integration contribute to improve chemistry learning?*

This dissertation investigated how dynamic visualizations in curriculum designed following the knowledge integration framework contribute to improve chemistry learning. Students hold a repertoire of ideas about scientific concepts (Linn & Eylon, 2006). In particular, students have various ideas about the particulate nature of matter and have trouble making connections from atomic-level interactions to observable phenomena and associated symbolic representations (Johnstone, 1993). Dynamic visualizations give students the ability to interact with and test their ideas about atomic-level phenomena. The knowledge integration perspective leverages students existing ideas and supports students to distinguish and make connections among their ideas. This dissertation explored how this combination of visualizations and knowledge integration patterns benefits chemistry students.

*Study 1: Designing and refining instruction about chemical reactions*

The first study reported on the design and refinement of an instructional unit on the topic of chemical reactions. The goals for the unit were to have students connect ideas about chemical reactions such as energy, conservation of mass, and limiting reagents on molecular, observable and symbolic levels. I designed and refined the unit using the scaffolded knowledge integration metaprinciples of *make science accessible, make thinking visible, help students learn from others,* and *promote autonomous lifelong learning* (Linn, Davis & Eylon, 2004).

Testing of the unit involved a pilot test of honors students in the fall semester that were currently studying chemical reactions. The pilot group encountered technical difficulties with the visualizations. Non-honors students tested the unit in the spring after receiving basic chemical reactions instruction, and slightly reconfigured content to adjust for the loading times of the visualizations. Pretest and posttest assessments were given to comparison students with traditional textbook instruction at the same time as the test students.

Increases from pretest to posttests for both the pilot and test groups revealed that students added normative ideas about chemical reactions and made connections among these ideas on symbolic and molecular levels. Regression analysis found no difference among pilot and test groups, controlling for pretest score. Students both before and after learning about chemical reactions with different levels of prior knowledge made similar gains in ideas and connections. Both the pilot and test groups significantly differed from the comparison group, suggesting that students studying the unit outperformed students revising material and retaking the same tests.

These results replicated across contexts. Students studying the same project at another school had similar learning gains. We gave these students year-end delayed posttests in addition to the pretests and posttests surrounding the unit. Students' scores not only increased from pretests to posttests, but also increased from posttests to delayed posttests months after the implementation of the unit. These findings suggest that the combination of dynamic visualizations and scaffolded knowledge integration principles improved students' integration of ideas about chemical reactions.

Case studies of students and classroom observations revealed the strengths and limits of the instruction. Based on the first version results, the curriculum was refined. Refinement involved increasing accessibility to the content through a slightly reformulated driving question. Instead of focusing on investigating increasing levels of atmospheric carbon dioxide, the project redesign focused on how chemical reactions relate to climate change. In order to help *make thinking visible*, refinements to the molecular visualization decreased complexity and increased relevance to the overall project.

Case studies and classroom observations also revealed that some students had difficulty making connections from the visualizations to other topics, such as limiting reactants and symbolic equations. Students passed through visualization steps on a superficial level and when embedded assessments asked them to generate an explanation, they would then stop and ask for help.

### *Study 2. Deceptive clarity of visualizations*

The results from the efficacy study demonstrated the varied experiences that students have with the dynamic visualizations. Some students see bouncing gray balls in a rectangle, other students see atoms forming and breaking bonds and reacting in certain ratios. Students begin the project with varied ideas about chemical reactions, and end with more connected and normative ideas about chemical reactions. From these results, I was interested in how students develop understanding and distinguish new ideas from the visualizations within the unit. Typically, science instruction adds ideas into students' repertoires without giving time for students to develop criteria, distinguish, and reflect upon their ideas. Analysis of studies featuring dynamic visualizations revealed that this is also the case for visualizations – students can add ideas but without proper guidance to distinguish or reflect, isolated ideas remain in students' repertoires (e.g. Lowe, 2004). Additionally, research demonstrates the importance of self-monitoring with interactive technology-enhanced environments (Zahn, Barquero & Schwan, 2004). In order to distinguish ideas, learners need to be aware of their understanding, have criteria for their understanding that enables them to be aware of conflicting ideas, and act upon conflicting ideas. This study explored the interplay between self-monitoring and distinguishing of ideas.

I designed the steps surrounding the visualizations to engage students in the knowledge integration pattern of eliciting ideas, adding ideas, distinguishing ideas, and reflecting upon ideas (Linn & Eylon, 2006). For instance, to elicit ideas about the connections among symbolic and molecular levels, the unit asks students to describe what the coefficient and subscript represent in $7O_2$. Students then interact with a molecular visualization and form molecules of carbon dioxide and water from methane and oxygen molecules. By creating different numbers of different molecules, the visualization helps them connect ideas about the symbolic and molecular levels. The next step asks students to relate their actions in the visualization to the balanced equation. This helps students distinguish among their ideas from the visualization and their ideas about symbolic representations of chemical reactions (e.g. the balanced equation). The next step guides students to reflect and evaluate their explanation. Each sequence of steps surrounding visualizations followed this knowledge integration pattern.

Because of the importance of distinguishing ideas with visualizations, I was particularly interested to explore how students distinguished their ideas in the unit and how the knowledge integration pattern contributed to self-monitoring. I used judgments of learning to determine how students assessed their learning of the visualization. I prompted explanations after the visualizations to capture if students distinguished their ideas and to determine what students learned.

The judgments of learning revealed that students overestimated their understanding after visualization steps. Robert Tinker (2009) coined the term *deceptive clarity* to describe these findings -- that students think they understand visualizations better than they actually understand the visualizations. The combination of visualizations and explanations reduced the deceptive clarity of the visualizations. After explaining, students rated themselves as less knowledgeable. Classroom observations and analysis of the written explanations suggested that explaining reduces deceptive clarity because it helps students develop criteria and distinguish among their ideas from the knowledge integration perspective. Students working with dynamic visualizations finish the step or the task and are relatively less critical of their understanding. This could be because students follow the visualization instructions, observe changes in the visualization after manipulating variables, and then they figure they understand and proceed to the next step. The visualization instructions contain similar questions to the explanation prompts, but students are not asked to generate an explanation. Once prompted to generate an explanation, the students realize that they don’t understand how the visualizations relate to other concepts in the unit. Students refine the criteria for their understanding that now encompasses understanding what they did in the visualization, the overall concept, and how the visualization relates to the overall concept. These results suggest that the act of generating an explanation forced students to articulate and distinguish their elicited ideas before the visualization, their interactions with the visualization, and new ideas that they may have added with the visualization.

These results clarified evidence from research that suggests learning from visualizations is difficult because the visual complexity overwhelms novices (Mayer, 2001; Paas, Renkl & Sweller, 2003). Students have no trouble interacting and learning complex scientific practices through massively complicated visual environments such as videogames (Steinkuehler, Duncan, 2008). The problem may not be so much that visualizations are cognitively overwhelming, but that students’ criteria for their understanding are different for visualizations. These findings suggest that students need to have opportunities to develop criteria for and distinguish among their ideas, as well as opportunities to develop self-monitoring skills for learning with visualizations. These results suggest that combining generation activities such as explaining with visualizations encourages students to develop more sophisticated criteria and promotes distinguishing of ideas.

### *Study 3. Desirable difficulties: Feedback and self-regulation of learning.*

The results from Study 2 suggest that desirable difficulties can complement learning from visualizations by helping students overcome deceptive clarity. Bjork (1994, 1999) coined “desirable difficulties” to describe conditions of instruction that appear to create immediate impediments for the learner, reduce the rate of *apparent* learning, but often lead to long-term retention and transfer. Desirable difficulties such as generating explanations, providing feedback to revisit information, using tests as learning events, spacing and interleaving instruction have been found in laboratory settings to benefit learning. In this study I investigated how these desirable difficulties could translate to learning and self-monitoring with visualizations.

The knowledge integration framework emphasizes autonomous learning (Linn, Davis & Eylon, 2004). Autonomous learners develop criteria for their understanding, accurately assess their understanding relative to those criteria and act upon differences by asking a teacher, seeking help from peers, or looking back at text for examples or more information (Butler & Winne, 1995). Learners who monitor their understanding use this kind of internal feedback to build coherent and interconnected networks of ideas. To help learners develop these monitoring skills, the scaffolded knowledge integration framework suggests designing and providing feedback that encourages revisiting of new ideas and activities. For instance, within the WISE environment students guide their own learning with help from the inquiry map. Students can navigate to any step within the environment, but a persistent representation of sequential steps along the left side of the screen helps students develop inquiry strategies. Instruction through the WISE environment can scaffold the development of internal feedback and model expert practices of revisiting information. From the knowledge integration and inquiry learning perspective, feedback should promote self-monitoring. However, the best ways to design feedback and support this kind of learning is not clear.

The literature on the benefits of feedback yields mixed results (Richand, Linn & Bjork, 2007). Research suggests that immediate feedback can be beneficial for complex learning materials (Kulik & Kulik, 1988). External, immediate feedback can also be particularly beneficial for correcting high-confidence errors (Butterfield & Metcalfe, 2001). The research with cognitive tutors offers a long history of success with immediate external feedback (Anderson et al., 1995). Particular to visualizations, external feedback can help learners become aware of gaps in their understanding, develop more complex and relevant criteria, and guide students to take appropriate action. In this way, external feedback and guidance can scaffold self-monitoring practices for students learning with visualizations. Especially for authentic classrooms with many students, external feedback can improve the ability for teachers to give individualized, tailored instruction to their students.

In contrast, other research suggests that this kind of immediate feedback can actually hinder monitoring skills (Moreno & Valdez, 2005). Immediate feedback can encourage mindless clicking instead of thoughtful revisits to information (Baker et al., 2008). Instead of acting as a desirable difficulty, instruction featuring immediate feedback can give students an overly optimistic view of their understanding (Bjork, 1994), and testing without feedback can be a powerful learning event (Roediger & Karpicke, 2005). Even within the cognitive tutoring research, recent studies suggest that immediate guidance is not as beneficial as withholding feedback (McLaren, Lim & Koedinger, 2008; Mathan & Koedinger, 2005).

Given the contested nature of feedback and the potential to promote learning with visualizations, I explored if feedback could promote self-monitoring with visualizations. I compared students with immediate, external feedback to students with no feedback in the step immediately following the visualizations. Students in the external feedback condition answered a multiple-choice question testing the main concepts of the visualization. If students answered incorrectly, they were forced back to the visualization step until they answered correctly. Students in the no feedback condition were given the same question at the same point as the feedback group, but without any answer choices, feedback, or restrictions on navigation. These conditions were used in Activity 2, with subsequent instruction exactly the same. The WISE environment logged students' actions with the unit to reveal navigational practices.

Students in the feedback condition scored significantly lower on the prompted explanations immediately after the treatment steps, even though only about a fourth of the students within the explanation group answered incorrectly and were forced back to the visualization. Additionally, students in the feedback condition decreased revisiting the visualizations after the treatment, whereas students without feedback maintained similar levels of revisiting the visualizations. This suggests that the feedback condition may have hindered self-monitoring. Specifically, the feedback condition may have been too easy for students and reinforced less sophisticated criteria. The positive feedback for students answering correctly may have contributed to an inflated sense of understanding, which carried over to the explanation immediately following. In later activities without the feedback condition, there were no differences on the embedded explanations. Overall, there were no differences among treatments pretest and posttest assessments, which is not surprising given the relatively small treatment within a large instructional unit that features many learning activities.

Looking at the navigational practices of both groups revealed that generative activities encouraged students to revisit information. Students went back from explanation steps, journal steps, and other generative steps. Students tended to go back to visualization or drawing steps where students created models of their understanding. The most common pattern across both groups was going from an explanation step back to a visualization step.

This study clarified the role of generative activities, self-monitoring and knowledge integration patterns. Generative activities promoted self-monitoring through the development of criteria and by encouraging students to revisit information to sort out conflicting information or remedy gaps in understanding. Through these activities, students distinguished existing ideas and ideas from the visualizations. Activities such as answering multiple-choice questions and receiving feedback did not act as a desirable difficulty. Instead, those activities appeared to be undesirable and too easy, promoting less sophisticated criteria for understanding and not supporting students to distinguish ideas. These findings resonate with other studies that illustrate how generation activities help students distinguish ideas (Zhang & Linn, 2008; Linn et al., in press).

Implicit to this argument is the relationship between students' criteria for their understanding and their willingness to continue to distinguish among ideas. Finding the right instructional support to help students develop the appropriate level of criteria is difficult. If students get too critical, then they may get frustrated and give up. If students see themselves as too knowledgeable, they may miss learning opportunities.

### *Study 4. Scope of explanation and distinguishing ideas*

The fourth study explored how generative activities can influence how students develop criteria and distinguish ideas. I explored how the specificity of explanation prompts can influence what ideas students distinguish and how students rate their understanding.
From Study 2, it appeared that explanations helped learners notice gaps in their understanding. Study 3 suggested that explanations helped students act upon these judgments as well as develop criteria for their understanding. However, I used specific explanation prompts that asked students to distinguish particular ideas. Research demonstrates that content-specific supports can help learners understand critical concepts (e.g. Ardac & Akaygun, 2004; Buckley et al., 2004; Chang & Quintana, 2006; Frederiksen, White & Gutwill, 1999; McNeill & Krajcik, 2006; Sandoval & Reiser, 2004; Slotta & Chi 2006). Especially for learning with dynamic visualizations, specific explanation prompts can focus learners to distinguish key ideas.

However, other research suggests that specific prompts can narrow reflection (Aleven et al., 2006). Study 3 suggested that focusing students by specific factual recall hinders students' learning with visualizations. Specific prompts may prevent or distract students from considering and distinguishing a wider range of ideas. More expert students may just focus on those limited concepts instead of integrating other ideas. For students who have very little understanding of the particular prompted concepts, students may give up entirely instead of struggling to understand (see Study 1).

General, non-specific prompts may be more advantageous for students learning with visualizations. Research suggests general prompts can help students reflect upon their current thinking, and identify any gaps in their understanding (Chi et al., 1994; Davis, 2003). Prompting general explanations may help students working with visualizations distinguish whatever current, conflicting ideas they may have. General prompts may help more expert students distinguish a range of ideas, and help engage more novice students in distinguishing their ideas instead of turning them off entirely.

To test these conditions, I created two versions of the project. The general-link treatment had general-link explanation prompts (e.g. "Explain the visualization") that followed visualization steps. The specific-link treatment had prompts that asked students to explain specific concepts and connections (e.g. "How did the visualization relate to the balanced equation"). Students assessed their understanding before and after these explanation prompts, and I used data logs to determine navigational practices of the students.

Results found no differences among treatments for the embedded explanations, assessments or pretest and posttest scores. However, results suggest that the students used explanations to learn from the visualizations in different ways. Students in the specific-link group replicated the findings from Studies 2 and 3. Students rated themselves as less knowledgeable, revisited information after explaining, and used the explanations to distinguish the specific ideas prompted.

Conversely, students in the general-link condition rated themselves as relatively more knowledgeable, their ratings did not decline after explaining, and they did not revisit information as often. This is similar to findings that the illusion of explanatory depth is not found for narratives, facts, or procedures (Rozenblit & Keil, 2002). The content of the general explanations mainly consisted of molecular ideas about chemical reactions. These findings suggest that the students may have used general explanations to make sense of their actions within the visualizations (e.g. Keil, 2006). These reflective, narrative explanations were just as beneficial as the specific explanations.

These results suggest that general-link prompts may encourage all learners to distinguish their ideas from the visualizations, without limiting reflection for more expert students or discouraging more novice students. These results suggest that more emphasis needs to be placed on developing students' self-monitoring skills.

Overall, these findings reinforce the impact of encouraging knowledge integration processes with instruction featuring dynamic visualizations, especially developing criteria and sorting out ideas. It appears that specific-link prompts may help students develop criteria for and distinguish their ideas. General-link prompts may help students reflect and reinforce their understanding of visualizations, as well as distinguish and sort out their ideas at all levels of sophistication.

# Dynamic Visualization Design Principles

This dissertation demonstrates that instruction featuring dynamic visualizations based on knowledge integration principles and patterns can lead to promising improvements in chemistry learning. Students can use dynamic visualizations to construct robust knowledge about the atomic level, and supporting instruction can help students make connections to other ideas.

This dissertation also highlights the complexities that dynamic visualizations introduce into instruction. It suggests directions for design of instruction including refinements of design principles based on classroom trials. I offer the following refinements to design principles with visualizations (Kali & Linn, 2008; Plass, Homer & Hayward, 2009) and put forth design principles for instruction surrounding dynamic visualizations (Chang et al., in preparation; Moreno & Mayer, 2007).

## Design visualizations that enable interaction with unobservable or abstract phenomena

A central goal of science education is for students to increase their understanding of the natural world by adding new, normative ideas. Dynamic visualizations add benefit to classroom instruction by enabling direct interaction with phenomena that are very large or small in scale. Through interactions with these visualizations, students can construct understanding of these traditionally unavailable or unseen phenomena. This extends *student-controlled pacing* (Moreno & Mayer, 2007), *task appropriateness* (Schnotz & Rasch, 2005), and *manipulation of content* (Plass, Homer & Hayward, 2009). For maximum benefit in classrooms, interactions within visualizations should be student-controlled, aligned with learning goals, allow changes in content (manipulate heat, concentration, etc.), and focus on phenomena that are unobservable or abstract.

Designers need to leverage the technological capabilities of visualizations by encouraging interactions with unobservable and abstract phenomena. As part of the curriculum design and refinement of the *Chemical Reactions* module, the development team and I focused on the types of ideas and interactions that dynamic visualizations afforded students that are typically impossible through traditional instruction. For instance, in *Chemical Reactions* students are able to add heat to molecular models of chemical reactions and see the resulting change in molecular motion or molecular composition. These interactions with the molecular level would be nearly unfeasible using textbooks and lectures. Similarly, students use visualizations of the greenhouse effect that make sunlight, infrared, and heat energy visible for students. Students can change levels of carbon dioxide, cloud cover and albedo and see the results of their experiments through changes in infrared and heat energy as well as temperature graphs. The greenhouse visualization allows students to inspect and connect very small (sunrays, infrared, carbon dioxide) and very large (Earth's atmosphere) levels.

Classroom testing reinforced this design principle. The *Chemical Reactions* module originally had a visualization where students interactively balanced an equation with corrective feedback. Although students found the visualization engaging and the teachers initially thought it was a great visualization, upon further inspection with student assessment data we all agreed that the balancing equation visualization was not as important or as effective as the molecular models of chemical reactions. We then revised the curriculum to focus more on balanced equations and chemical reactions on a molecular level.

This highlights the importance of the design of visualizations on complex learning. Using dynamic visualizations to add ideas about simple, observable processes does not take full advantage of dynamic visualizations for learning. Studies that give learners short, isolated and less relevant visualizations do not show benefits to learning in part because the visualizations are designed to distinguish very specific aspects of visualization and cognition, and less focused upon sequence and content of instruction. For example, Mayer et al. (2005) explored cognitive advantages of static sequences of frames compared to animations in terms of cognitive load. Participants in these experiments had either two sheets of paper with static frames of various phenomena (car brakes, waves, lightning, toilets) or animations of the same physical systems. Participants came into the experiment, answered a questionnaire, viewed either an animation or studied the paper version for 140 seconds, answered a retention question for four minutes, and answered four transfer questions with a maximum time of 2.5 minutes each. From these kinds of experiments the researchers suggest that animations have no more benefit than static pictures.

This dissertation suggests that designing visualizations that allow interactions with unseen or abstract processes enables students to construct meaningful knowledge from visualizations. Constructivist approaches to learning and instruction based on the work of Piaget (1970) and Vygotsky (1978) value how students' own experiences with the world around them influences and contributes to the generation of knowledge (Bereiter & Scardamalia, 1989; Bransford, Brown & Cocking, 1999; Brown & Campione, 1994; Collins, Brown & Holum, 1988; Greeno et al., 1996; Hmelo-Silver, Duncan & Chinn, 2006; Linn & Eylon, 2006). The kinds of interactive activities with visualizations described above allow students to construct understanding in similar fashion to building machines and computer programs (e.g. Papert, 1980; Resnick, 1996; Wilensky & Reisman, 2006). Technology-enhanced instruction featuring dynamic visualizations can transform classrooms by allowing students to construct their own understanding of these unseen levels of phenomena. Traditionally, students receive instruction through lectures and textbooks about how atoms and molecules interact and form the world around us. This dissertation demonstrates that students interacting with atomic visualizations can construct coherent, robust and connected understanding of phenomena on multiple levels, and this experience is especially powerful for both teachers and students. Teachers refer back to the visualizations in subsequent instruction. Students remember visualizations months after implementation. Science instruction should incorporate constructive approaches to learning about unseen and abstract phenomena to help students develop integrated and complex knowledge.

## Design instruction featuring visualizations to build on students' ideas

This dissertation highlights the importance of eliciting and building on students' ideas for learning and instruction with dynamic visualizations. First, the design process of *Chemical Reactions* began by looking at benchmark assessments that elicited students' ideas about molecular representations of chemical phenomena. As curriculum developers, we were able to see the diversity of students' ideas and the difficulties students faced learning chemistry. We used this information as well as prior research in chemistry education to decide where dynamic visualizations could best contribute to learning. Without careful consideration of existing student ideas, instruction that uses dynamic visualizations may not be as effective. For example, students can typically learn to balance equations mathematically without much trouble. Using a dynamic visualization to help students learn how to balance a equation may be motivating and/or possibly decrease the amount of time needed to learn the material, but most likely would not show as much lasting difference on student learning as the molecular visualizations of chemical reactions. Conversely, students have trouble visualizing chemical reactions on a molecular level. Understanding chemical reactions serves as a foundation for basically the second half of a typical high school chemistry class, with stoichiometry, solutions, kinetics, equilibrium, acid-base reactions, oxidation/reduction reactions and organic chemistry following from chemical reactions. By looking at students' existing ideas and difficulties, we were able to pinpoint a particularly powerful place to embed visualizations within the curriculum.

Within the *Chemical Reactions* curriculum, eliciting students' existing knowledge about chemical reactions foregrounded students' prior knowledge and enabled students to form lasting connections from the visualizations to their prior knowledge. For example, before students manipulated methane and ethane molecules to make carbon dioxide and water, the unit asks students about the meaning of subscripts and coefficients of the balanced equation on a molecular level (e.g. "The chemical equation in the previous step shows $7O_2$. What do the seven and two represent in terms of atoms and molecules?"). This made the students aware of their existing understanding. For example, one pair responded, "The 7 stands for 7 times of the original amount of oxygen. The 2 stands for the amount of the oxygen." After working with the visualizations, embedded prompts ask students to relate the visualization to the coefficients and subscripts, (e.g. "How did the numbers of atoms and molecules in the visualization relate to the balanced equation?"). By eliciting students' ideas, students see where their initial ideas may bump up against new ideas added with the visualization. After working with the visualization, the students revised their initial answer to reflect a more normative understanding, "The 7 stands for how many molecules are there. The 2 stands for how many atoms in the molecule [sic]." Eliciting students' existing ideas about the connections among molecular and symbolic representations of coefficients and subscripts made students' current thinking available for them to inspect, add to with the visualizations, and subsequently revisit and refine with future instruction.

Eliciting existing ideas not only makes students' thinking visible to curriculum design and the students themselves, but also to their teachers. Every new teacher to run the unit was shocked to see the drawings of chemical reactions produced by their students (e.g. Figure 3.4). Making students' thinking explicit helps teachers tailor instruction for specific learners as well as more accurately gauge the overall class level. The WISE environment enables teachers to look at class cross-sections of student data at one time. Teachers can quickly glance at student work or student work within visualizations and see particular pairs that may need more help. This enables teachers to help students build upon their existing ideas.

## Help students overcome deceptive clarity of visualizations

Visualizations can be deceptively clear to students, and instruction should help students develop criteria for their understanding and realize what they don't understand. Desirable difficulties seem to help students overcome deceptive clarity, help students refine criteria for their understanding, and encourage students to revisit information. This enables students to distinguish their ideas and construct understanding through cycles of misunderstanding and understanding (Miyake, 1986).

This dissertation demonstrates that all levels of students learn from visualizations when given the opportunity to develop criteria and distinguish their ideas. Instead of focusing on reducing cognitive load and making the environment less complex for the learner, future research on dynamic visualizations should focus on introducing desirable difficulties, helping students be more aware of their understanding and helping students develop criteria and distinguish their ideas.

### Engage students in generative activities to help students distinguish ideas

Generative activities may have particular benefit with dynamic visualizations because they encourage students to distinguish their ideas. Students may have existing ideas or connections among ideas on various levels. Instruction should not only support students to make connections from the visualizations to prior knowledge, but also help students distinguish among the ideas and connections so that students promote more productive ideas and connections. Certain generative activities such as general explanations have the potential to help students at any level of prior knowledge distinguish their ideas and learn from visualizations. These findings suggest that in addition to research that aims to tailor instruction to each individual student, future research on technology-enhanced instruction can investigate these kinds of general approaches that benefit all ranges of students.

Pivotal cases can serve as these kinds of generative activities to help students distinguish their ideas and learn from visualizations. Pivotal cases are well-chosen, complex examples that encourage students to reorganize new ideas with existing ideas in a normative and cohesive manner (Linn, 2005). For instance, Tate (2009) compared instruction with a pivotal case surrounding a visualization to instruction using a predict-observe-evaluate-explain pattern in a curriculum about asthma and the immune system. The pivotal case instruction led to more integrated explanations of the immune response as compared to the predict-observe-explain condition. Tate found the pivotal case instruction helped students develop criteria and sort out their understanding of the immune system.

## Implications

Overall, this dissertation demonstrates that dynamic visualizations embedded within instruction focused on knowledge integration have the potential to transform learning in chemistry classrooms. Implications from my research involve looking at visualization skills across contexts, deceptive clarity and self-monitoring skills in online learning environments, highlight the role of design-based educational research in authentic classrooms, and offer insight into educational policy.

First, dynamic visualizations will only become more pervasive in science, math, and engineering instruction. The proliferation of visualizations available for teachers and students requires researchers, teachers and students to be able to critique visualizations, choose the best visualization for the particular learning goal and provide proper supporting instruction to maximize learning with the visualizations. Future research needs to provide guidance related to these meta-visualization skills. Not only do educational researchers need to find ways to best critique, choose, and support visualizations, but also find ways to help teachers and students develop these cross-visualizations skills.

As more and more instruction moves to online and technology-based environments, research on deceptive clarity and the development of self-monitoring skills will be increasingly important. Currently, universities and colleges post lectures, powerpoint presentations, and demonstrations for students to use either as a compliment or replace face-to-face instruction. Students using these kinds of technology-based environments can also suffer from the same kind of deceptive clarity. Watching an online lecture enables learners to replay, pause, or even skip parts of the video. In a similar fashion to dynamic visualizations, developing appropriate ways to help students develop self-monitoring skills and recognize what they don't understand can maximize learning in these settings.

This dissertation highlights the importance of design-based research in authentic classroom settings. Findings in laboratory settings may not transfer to typical classroom environments, such as the role of cognitive load with novices and visualizations. The design experiments in this dissertation led to the findings of deceptive clarity, and helped clarify the role of generation activities in classrooms. Additionally, using dynamic visualizations in authentic learning contexts underscored the transformative power of these visualizations in classrooms.

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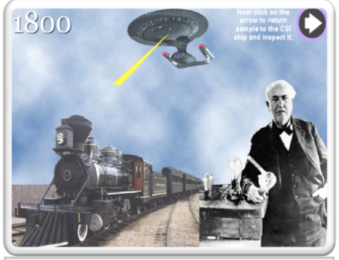
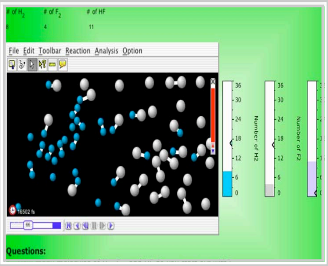
# Appendix A: Outline of the original CSI unit

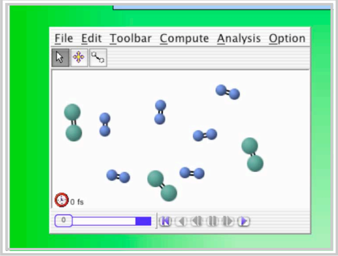
**Activity 1** This activity introduces students to the WISE interface and to the context of the project. The activity begins by explaining the greenhouse effect with animations, then by “traveling back in time” to collect sample data of carbon dioxide from different years. Students use WISE to graph their collected data, make comparisons to scientific data, and make predictions based upon their data.

**Activity 2** Students manipulate a Molecular Workbench simulation of a combustion reaction, adding and removing heat. Embedded prompts ask students to describe their observations. The students revisit the same simulation of the same combustion reaction with numerical and graphical outputs of molecular concentration. Students investigate the relationships between the chemical reaction and the ratios of molecules involved. Embedded prompts then ask students to explain how the graphs and simulations relate to the balanced equation for the reaction, and also ask students to identify what aspects of a chemical reaction the balanced equation does *not* represent.





**Activity 3** Students learn about water vapor and methane as greenhouse gases and then manually form these chemicals by breaking and creating bonds and molecules with Molecular Workbench. The activity ends with a similar exercise of atom manipulation to introduce the concept of limiting reactants. Embedded prompts ask students to make connections between their actions in these simulations and chemical reactions, balanced equations, and limiting reactants.

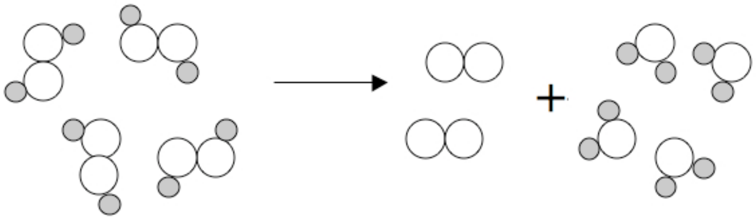


**Activity 4** The fourth mission elicits students’ strategies used while numerically balancing equations, and then asks students to reflect on these strategies after going through an interactive hydrocarbon equation exercise. Students also read about carbon dioxide as a greenhouse gas, and compare these three greenhouse gases they have learned. At the end of the unit, students have to decide how to allot research funding for these three greenhouse gases, based on the information they have learned and the chemistry concepts they have seen throughout the curriculum. Students put their arguments up on an online discussion board for other groups to critique and compare ideas.

# Appendix B: Pretest and Posttest Assessments

1. If a white circle represents oxygen and a gray circle represents hydrogen, write the balanced equation that the following picture represents.

Balanced equation: ______________________________________________



Key:
Oxygen = ○
Hydrogen = ●

2. Draw 2CO and $CO_2$ in the two boxes below using the key shown.

2CO

$CO_2$

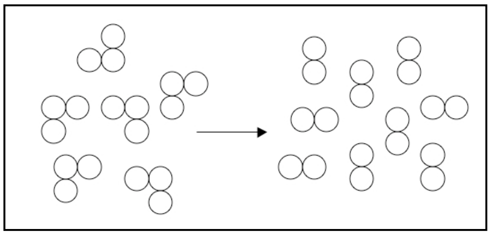
Key:
Oxygen (O) = ○
Carbon (C) = ●

3. The following equation represents ozone decomposing into oxygen gas when exposed to ultraviolet light:

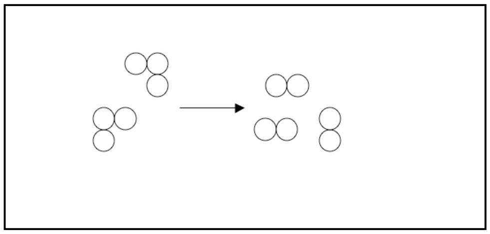
$$\mathbf{2O_3 \rightarrow 3O_2}$$

The two boxes below show molecular representations of this reaction. If you were teaching a friend, which one would you pick to explain how balanced equations relate to actual chemical reactions? (Circle one)

A.



B.



Explain your choice:

4. Draw a molecular picture of the following balanced equation below using the key shown:

**$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$**

Key:
Carbon = ●
Hydrogen = ◦
Oxygen = ○

5. Rate your understanding of how chemical equations represent ratios of molecules:

(circle one) Poor Fair Very good Excellent

6a. Suppose that a car engine uses propane, $C_3H_8$, for fuel. The balanced chemical equation for the combustion of propane with oxygen is:

**$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O$**

What are the products of this reaction?

**b.** If 3 molecules of $C_3H_8$ and 15 molecules of $O_2$ react according to the above equation, what molecules would there be at the end of the reaction?

**c**. Do you think that the products of this reaction could change the global climate?

Yes ____ No ____

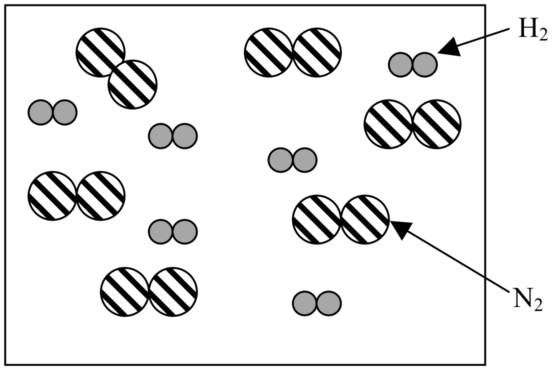
Explain how these products would or would not contribute to climate change.

**7.** Six $N_2$ molecules and six $H_2$ molecules in a **closed** container react according to the equation:

$$N_2 + 3H_2 \rightarrow 2NH_3,$$

Draw the container **after** the reaction in the space to the right.

**Before Reaction** **After Reaction**



8. Rate your understanding of limiting reactants in chemical reactions:
(circle one) Poor Fair Very good Excellent

9. Refer to the closed container and the reaction in the previous question. If you add heat to the system what happens to the reaction rate? (circle one)
Speed of the reaction increases
Speed of the reaction decreases
Speed of the reaction does not change
Explain what happens to the molecules when you add heat.

9b. Rate your understanding of how heat relates to the speed of molecules
(circle one) Poor Fair Very good Excellent
10. Rate your understanding of the greenhouse effect:
(circle one) Poor Fair Very good Excellent

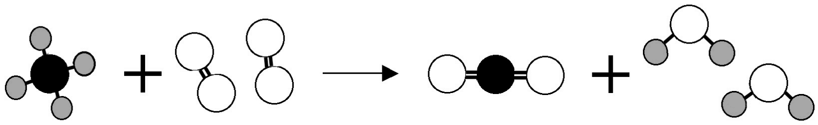
11a. How does the greenhouse effect warm the Earth? Use the space below and the key shown to draw a diagram of how sunlight, IR, and greenhouse gases warm the Earth. Feel free to write on your diagram.

11b. Explain the role of sunlight, infrared radiation (IR) and greenhouse gases in the greenhouse effect.

12a. Is there a difference between the greenhouse effect and global warming?
Yes No (Circle one)
Explain your choice.

12b. Do you think humans are contributing to global climate change?
Yes No (Circle one)
Explain your choice.

13. Consider the four choices below:

1. 
2. $\mathbf{CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O}$
3. Watching my teacher combust methane in class.
4. Greenhouse gases (like carbon dioxide) result from the combustion of hydrocarbons (like gasoline).

a. To understand the reactions that form greenhouse gases like carbon dioxide, which type of information helps you the most?
(Circle one) 1 2 3 4
Please explain your answer:

b. What type of information helps you the least?
(Circle one) 1 2 3 4
Please explain your answer:

c. What type of information is easiest to understand?
(Circle one) 1 2 3 4
Please explain your answer:

Your Gender: (circle one) Female Male

# Appendix C: Sample Assessment Rubrics

Concepts and ideas assessed:

1. Students connect molecular and symbolic representations of chemical equations
    a. Students are able to create balanced molecular representations of chemical reactions
    b. Students are able to create balanced chemical equations from molecular representations
    c. Students know coefficients are ratios of molecules interacting
    d. Students know subscripts represent bonded atoms

2. Conservation of Mass
    a. Student demonstrates understanding that the total number of atoms in the reactants have to equal the total number of atoms in the products in a chemical reaction.

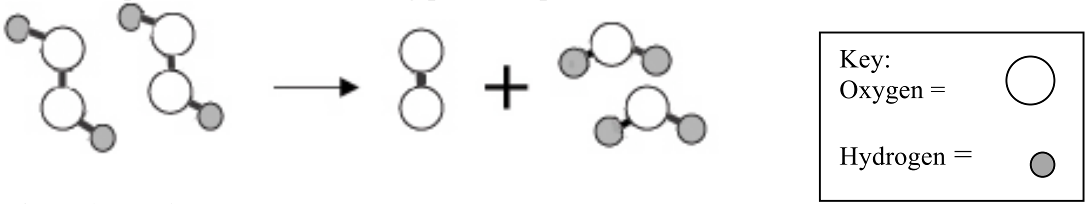
3. Students understand basics of chemical reactions
    a. Understand the *interactive* aspect of a chemical reaction
        i. Student demonstrates understanding that a chemical reaction is a process of bond breaking and bond formation.
    b. Understand the *dynamic* aspect of a chemical reaction
        i. Student demonstrates understanding that a chemical reaction is time-dependent process where molecules are in motion
        ii. Learn connection between heat and reaction rate
        iii. Learn connection between temperature and molecular speed
    c. Understand the *quantitative* aspects of a chemical reaction
        i. Student demonstrates a preliminary understanding of the ratios of chemicals in a reaction
        ii. Understand limiting reagents on a molecular scale (e.g. how it limits the amounts of products formed)
4. Energy
    a. Student demonstrates a preliminary understanding of heat as the motion of particles.

5. Students understand importance and concept of scientific modeling
    a. How models help understanding of surroundings
    b. Students learn to recognize advantages/disadvantages of certain molecular representations

6. Students understand greenhouse effect
    a. Students understand how greenhouse gases absorb/reradiate IR towards Earth
    b. Students understand difference between global warming and greenhouse effect

Item 1

**1.** If a white circle represents oxygen and a gray circle represents hydrogen, write the balanced equation that the following picture represents.



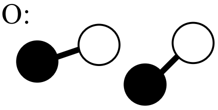
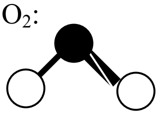
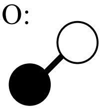
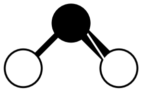
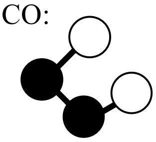
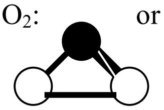
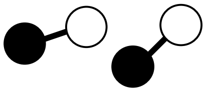
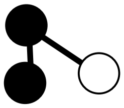
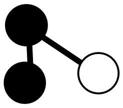
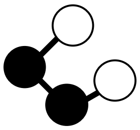
Balanced equation: ________________________________________

| *Scoring Guide* | *Description* | *Student example* |
|---|---|---|
| 4<br>Complex link | Connects coefficients to the number of molecules and connects subscripts to the number of atoms within a molecule with no alternative notation or ideas (order of H and O can be switched) | $2H_2O_2 \rightarrow O_2 + 2H_2O$<br>$2O_2H_2 \rightarrow O_2 + 2OH_2$<br>$2H_2O_2 \rightarrow 2H_2O + O_2$ |
| 3<br>Simple link | Connects coefficients to the number of molecules OR connects subscripts to the number of atoms within a molecule (consistent throughout entire answer) | $2HO \rightarrow O_2 + 2H_2O$;<br>$2H_4O_4 \rightarrow O + 2O_2H$<br>(Correct coefficients)<br>$H_2O_2 \rightarrow O_2 + H_2O$;<br>$H_2O_2 \rightarrow O_2 + 2H_2O$<br>(Correct subscripts) |
| 2<br>Partial Link | Partial connection of either coefficients or subscripts to the molecular level; uses a subscript or coefficient correctly in part of the response, but not consistently | $2HO \rightarrow O + H_2O$<br>$4HO \rightarrow O_2 + 4HO$<br>$4HO \rightarrow 2O + H_2O$ |
| 1<br>Irrelevant link | At least 1 alternative idea stated; does not use a subscript or coefficient correctly in any part of the answer. | $4HO \rightarrow 2O + 4H + 2O$ |
| 0 | No answer | |

**Item 3**

**3. What is the difference between 2CO and $CO_2$? Draw them in the two boxes below using the key shown.**

Scientific ideas to integrate:
Subscripts represent numbers of atoms within molecules
Coefficients represent numbers of molecules
Total number of atoms (mathematic understanding of number of atoms)

| *Scoring Guide* | *Description* | *Student example* | | |
|---|---|---|---|---|
| 4<br>Complex link | All three types of ideas are connected | 2CO:  | $CO_2$:  | or:  |
| 3<br>Simple link | Two of the three types of ideas are connected meaningfully | 2CO:  | $CO_2$:  |  |
| | | 2CO:  | $CO_2$:  | or  |
| 2<br>Partial Link | Mentions only one of the three types of ideas | 2CO:  | $CO_2$:  | |
| 1<br>No link | At least 1 alternative idea stated; |  |  | |
| 0<br>Irrelevant/blank | No answer/Not a scientific answer | | | |

**Item 6**

**a. Suppose that a car engine uses propane, $C_3H_8$, for fuel. The balanced chemical equation for the combustion of propane with oxygen is:**

$$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O$$

**What are the products of this reaction?**

| *Scoring Guide* | *Description* | *Student example* |
|---|---|---|
| 1<br>correct | States carbon dioxide and water in words or symbolic form | "three carbon dioxide molecules and four water molecules"<br>"$3CO_2$ and $4H_2O$", "carbon dioxide and water" |
| 0<br>incorrect | Any other alternate ideas, such as counting number of atoms | "3 carbon, 10 oxygen, 8 hydrogen"<br>"3 carbon, 6 oxygen, 8 hydrogen and 4 oxygen" |
| 0 - No answer | | |

**6b. If you had 3 molecules of $C_3H_8$ and 15 molecules of $O_2$ that completely react, how many molecules of each product would you have?**

| *Scoring Guide* | *Description* | *Student example* |
|---|---|---|
| 1 correct | Student understands that the number of molecules interacting will be triple the coefficients of the balanced equation. | “nine carbon dioxide molecules and twelve water molecules”<br>“$9CO_2$ and $12H_2O$”<br>“carbon dioxide and water” |
| 0 incorrect | Any other alternate ideas, such as counting number of atoms | “9 carbon, 30 oxygen, 24 hydrogen”<br>“9 carbon, 18 oxygen, 24 hydrogen and 12 oxygen”<br>“you would have a total of 18 molecules (3 $C_3H_8$ +15 $O_2$)” |
| 0 -No answer | | |

**6c**. Do you think that the products of this reaction could change the global climate?
Yes ____ No ____

Explain how these products would or would not contribute to climate change.

---

Scientific ideas to integrate:

6c1. Carbon dioxide and water as greenhouse gases:
- Carbon dioxide and/or waterare greenhouse gases

6c2. Greenhouse gases functionality in the atmosphere
- Greenhouse gases trap heat i the atmosphere
- Greenhouse gases reflect or re-emit infrared radiation back towards the Earth

6c3. Potential climate change outcomes
- Increased temperature of the atmosphere
- Cause global warming

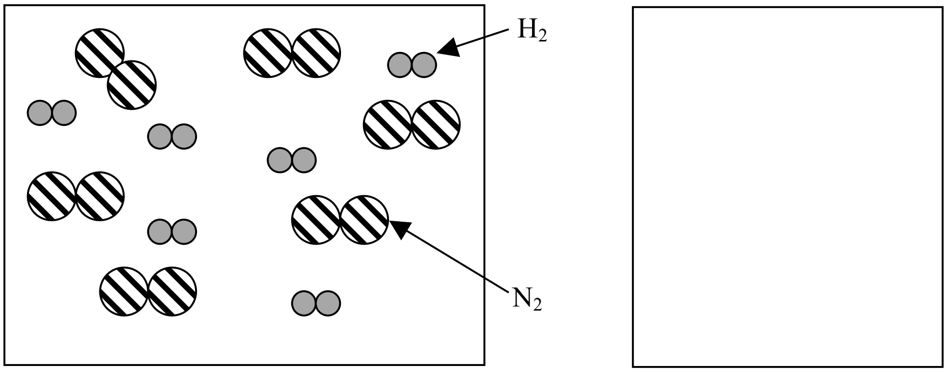
6c4. Products increase or plays an important role in climate change (from question)

| *Scoring Guide* | *Description* | *Student example* |
|---|---|---|
| 4<br>Complex link | All three types of ideas are connected. | "When $CO_2$ builds up in the atmosphere, infrared rays have more of a chance to reflect back into earth. The more this happens, the higher the global climate rises."(6c4 + 6c2+6c3) |
| 3<br>Simple link | Two of the three types of ideas are connected meaningfully | "When more fuel is burned, the products (greenhouse gases) increase accordingly, more greenhouse gases add to global warming" (6c1+ 6c3)<br>"The $CO_2$ makes IR reflect back into the Earth and traps heat" (6c4 + 6c2) |
| 2<br>Partial Link | Mentions only one of the three types of ideas | "$CO_2$ is the main factor of climate change. Too much of it used can affect the environment. This combustion will cause an increase of heat" (has 6c4 idea)<br>"After piled up from other reactions, the carbon dioxide would contribute to climate change by rivaling with the ozone layer. I'm not sure if it delpeats the ozone, but it does rival with it because carbon dioxide causes the greenhouse effect" (has 6c4 idea) |
| 1<br>No-link | At least 1 alternative idea stated | "They're much higher than normal"<br>"Because of the concern with combustion and the ozone layer" |
| 0<br>Irrelevant | Students do not treat this problem as science problem | "I don't know"<br>Something is written but does not address science e.g. "I do not like science" |

**Item 7**

Six $N_2$ molecules and six $H_2$ molecules in a **closed** container react according to the equation $N_2 + 3H_2 \rightarrow 2NH_3$,

Draw the container **after** the reaction in the space to the right.



Scientific ideas to integrate:

7.1 Coefficients of balanced equation represent ratios of interacting molecules

7.2 Subscripts represent numbers of atoms within a molecule

7.3 Conservation of mass – atoms will not be created or destroyed in a reaction

7.4 Limiting reactants - hydrogen will limit the number of $NH_3$ formed, there will be excess nitrogen left

| *Scoring Guide* | *Description* | *Student example* |
|---|---|---|
| 4<br>Complex link | All three types of ideas are connected. | There are four $NH_2$ molecules with four molecules of nitrogen. |
| 3<br>Simple link | Two of the three types of ideas are connected meaningfully | --Students draw 4 ammonia molecules (7.2, 7.4)<br>--Students draw 6$NH_2$ molecules and 3 $N_2$ molecules |
| 2<br>Partial Link | Displays only one of the three types of ideas | Students draw 2 ammonia molecules - 7.2, or an accurate molecular representation of the balanced equation<br>Students draw 12 N atoms and 12 H atoms connected in various ways (NH, $N_2H_2$, etc) – 7.3 |
| 1<br>No link | At least 1 alternative idea stated | Students draw 2 nitrogen atoms and 3 hydrogen atoms |
| 0<br>Irrelevant/blank | No answer/Not a scientific answer | |

**11b. Explain the role of sunlight, infrared radiation (IR) and greenhouse gases in the greenhouse effect.**

Scientific ideas to integrate:
11a: Sunlight from the sun is either absorbed/reflected by Earth's surface
11b: Absorbed sunlight heats up the Earth
11c Heat from the Earth escapes as infrared radiation
11d: Carbon dioxide absorbs and reradiates the infrared radiation back towards Earth
11e: Reflected infrared radiation absorbed by Earth as heat, or reflected IR heats up Earth

| *Scoring Guide* | *Description* | *Student example* |
|---|---|---|
| 4 Complex link | 2 or more scientific connections (from above) with no alternative ideas included, including heat, IR, and greenhouse gases | (164764) "First, sunlight enters the earth and makes heat energy. After the earth is hot enough, it produces IR. Some of the IR is blocked by the carbon dioxide in the atmosphere and re-enters the earth, making it even more hotter." |
| 3 Simple link | 2 or more scientific connections among ideas with or without alternative ideas included, without mentioning one of the following: heat, IR, or greenhouse gases. | (164718) "First, sunlight comes down into the atmosphere. some of it is reflected and some of it is absorbed by the Earth. when the earth gets warm enough, it releases IR and the greenhouse gases(such as CO2) reflect the IR back down to Earth. " |
| 2 Partial Link | At least 1 scientific connection with alternative ideas, without mentioning one of the following: heat, IR, or greenhouse gases. | (164752) "First, sunlight is submitted down and reflects and bounces back up. But some of it is absorbed by the earth and becomes IR. |
| 1 Irrelevant link | At least 1 alternative idea stated | (165178) "First, sunlight comes down to heat up the earth." |

12a. Is there a difference between the greenhouse effect and global climate change? Explain your choice.

Scientific ideas to integrate:
5.2a The greenhouse effect is the mechanism that keeps the Earth’s atmosphere temperate.
5.2b Global climate change refers to anthropogenic increases in greenhouse gases that cause further increases in the Earth’s temperature.

| *Scoring Guide* | *Description* | *Student example* |
|---|---|---|
| 4 Complex link | 2 or more scientific ideas identified and connected (from above) with no alternative ideas included | “The greenhouse effect is way that the global temperature stays at a temperature that can sustain life. Climate change is the fear that we are putting too much greenhouse gases into the air and not letting enough energy in the form of infrared radiation escape the Earth’s atmostphere” |
| 3 Simple link | 1 or more scientific connections among ideas with or without alternative ideas included. | (164718) “The difference between global climate change and the greenhouse effect is we need the greenhouse effect to keep the Earth warm but the global climate change is too much of the greenhouse effect, which raises the Earth's overall temperature.” |
| 2 Partial Link | At least 1 scientific idea stated from above with or without alternative ideas. | (164752) “The difference between global climate change and the greenhouse effect is... The greenhouse effect absorbs and re-emits some of thr IR towards earth. Climate change reflects the IR molecules and they go back to earth or to the sun.” |
| 1 Irrelevant link | At least 1 alternative idea stated | (164756) “Global climate change is caused by humans and ocean evaporation. When greenhouse effect is caused by.......” |
| 0 | No answer | |

# Appendix D: Embedded Answers for Case Studies

| Group | Prompt 1 | Prompt 2 | Prompt 3 | Prompt 4 |
|---|---|---|---|---|
| Pair 1: TM and KT | “When the reaction first started, the H atom apeared in the methane and in the water molecule. The molecule began to duble.” | “The graphs and the simulation relate to the balanced equation by demonstrating the equality and stability of chemicals and diagrams.” | “What I did in molecular workbench compares to the balanced quation 2H2+O2->2H2O because it shows the balancing of greenhouse gases and their contributions in the green house effect.” | “The balanced equation limits the number of product molecules that you are able to produce with the given reactant molecules.” |
| Pair 2: BC and KK | “1. When the reaction first started, the H atom...repeatedly connected then disconnected with the fluorine atom.” | “The graphs and simulation relate to the balanced equation because they all show they [sic] different ways the chemicals react and balance out.” | No answer | “The balanced equation limits the number of product molecules.” |
| Pair 3: BW and AS | “1. When the reaction first started, the H atom was attached to another H atom. Then it collided with the O atoms and other H atoms, causing it to break off of the H atom it was attached to and bond itself to other atoms.” | “They are balanced because no molecules are lost in the simulation, so there will be correct numbers of elements represented.” | “They are related because in order to have no atoms left over in the workbench, we had to get a certain amount of oxygen atoms and hydrogen atoms. This number is the same as the ratios in the balanced equation (2 H2, 1 O2, and you end up with 2H2O molecules).” | “The balanced equation tells you how many product molecules you have based on the given # of reactant molecules. |
| Pair 4: DC and JM | “1. When the reaction first started, the H atom burned aqnd [sic] mixed together with O form H2O” | “It shows the products and the reactants after the reaction, and show what needs to gto [sic] where in order for the equation to be balanced.” | No answer | “You start off with 2purple molecules, and two blue, bonded molecules. You end up with One purple, and two blu, all bonded.” |
| Pair 5: JG and RB | “1. When the reaction first started, the H atom first combined with the oxygen. After a few seconds, the highlighted hydrogen combined with another hydrogen.” | No answer | “In the workbench, we could form the balanced equation. We formed multiple bonds (represented by lines).” | “The balanced equation effected the product molecules by allowing a certain amount of molecules to bond with each other. When some molecules bond with others, some molecules are left alone.” |