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Promote Chemistry Learning with Dynamic Visualizations: Generation, Selection, and
Critique

By

Zhihui Zhang

A dissertation submitted in partial satisfaction of the

requirements for the degree of

Doctor of Philosophy

in

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in the

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of the

University of California, Berkeley

Committee in charge:

Professor Marcia C. Linn, Chair

Professor Sophia Rabe-Hesketh

Professor Michael J. Clancy

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Abstract

Promote Chemistry Learning with Dynamic Visualizations: Generation, Selection, and

Critique

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Doctor of Philosophy in Education

University of California, Berkeley

Professor Marcia C. Linn, Chair

Dynamic visualizations can strengthen chemistry instruction by illustrating atomic level phenomena. Visualizations can help students add ideas about unseen phenomena involving atomic particles. They allow students to interact with phenomena that cannot be investigated in hands-on laboratories. Connecting dynamic, atomic representations with associated observable phenomena and symbolic representations has the potential to increase the coherence and comprehensiveness of student understanding.

Consistent with the knowledge integration framework, students enter chemistry courses with multiple non-normative ideas about chemical reactions. Following the knowledge integration framework, an inquiry project entitled *Hydrogen Fuel Cell Cars* engaged students in making predictions, exploring new ideas, distinguishing among ideas, and reflecting while connecting atomic interactions to everyday issues such as cars and fuel. To add normative ideas, a dynamic visualization that shows bond breaking and formation during hydrogen combustion was embedded in the unit. Using an iterative design process, a series of studies compared four approaches to distinguishing ideas: unguided exploration of the visualization, generating drawings of the sequence of events in the visualization, critiquing sequences of drawings attributed to a peer, and selecting among alternatives sequences. Progress was assessed using assessments that required students to articulate coherent accounts of chemical reactions.

The dissertation describes the design and development of the instruction, reports on a series of comparison studies conducted in typical middle schools that compare student performance in each of the four conditions: exploration, drawing, critique, and selection. The results reveal that visualizations can be deceptively clear so students may ignore important details when exploring a visualization. When learners generate, select, or critique drawings of atomic interactions, they recognize gaps in their knowledge, develop criteria for distinguishing among ideas, and increase in ability to select normative ideas. The dissertation demonstrates the importance of encouraging students to distinguish ideas when learning with visualizations. It suggests design principles for creating instructions featuring visualizations that can succeed in typical classrooms.

Dedication

To my family, for your love and support

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Chapter 1: Introduction

With the advance in technology, using dynamic visualizations such as simulations and models is becoming central to scientific research. It has become a routine for many scientists to employ computer visualization for data analysis, modeling, and communication (e.g., Fahrenkamp-Uppenbrink, Szuromi, Yeston, & Coontz, 2008). In science education, more and more researchers and designers have realized the power of these technologies and begun to seek ways to design curricular materials that take advantage of dynamic visualizations (Jong, 2006; Kali, 2006; Linn, Lee, Tinker, Husic, & Chiu, 2006). Students' ability to use computer technology to visualize, explain and understand science phenomena comprises an essential part of science literacy for 21st century learners (Fensham, 2008; diSessa, 2000; Osborne, & Dillon, 2008; NRC, 2010; Tytler, 2007).

My dissertation investigates ways to make computer visualizations more beneficial and powerful to support student learning. Dynamic visualizations offer a new way to understand scientific topics. They can demonstrate processes and phenomena that are too small (e.g., movement of molecules), too big (e.g., greenhouse effect), too fast (e.g., explosion), or too slow (e.g., evolution) to explore in traditional science classrooms and labs. In chemistry, such visualizations can be especially powerful because students struggle to make sense of chemical phenomena on the molecular level. Dynamic visualizations can help students add ideas about atomic interactions. When embedded in inquiry-based curricula, they can help students establish links with everyday events and use these molecular-level ideas to explain observable phenomena. However, learning with visualizations is challenging. Students may become confused and overwhelmed. They need support to integrate new ideas from the visualization with their prior knowledge.

Research Questions

My dissertation investigates how instructional activities designed using knowledge integration patterns can help students integrate ideas from dynamic visualizations and develop robust understanding of complex scientific phenomena. The study compares designs that are focused on helping students distinguish among the ideas presented in visualizations and the ideas students develop in observations of the natural world.

The research questions addressed are:

1. *How can we design technology-enhanced curricular projects that feature computer visualizations to help students link ideas and develop integrated understandings of chemical reactions?*

Students hold a repertoire of ideas about chemical reactions, most of which come from their everyday experiences. To develop coherent understanding, instructions should support students to link their prior ideas with those learned in classrooms such as reaction equations and atomic interactions. Research suggests that successful instructions often build upon student existing knowledge and employ an inquiry context so that learners can apply their knowledge to solve real-life problems. Further, research also suggests using visualizations to help students add ideas about atomic interactions as learners often have difficulties visualizing the unseen processes.

I am interested in designing instruction that takes advantage of inquiry context and dynamic visualizations to promote integrated understanding of chemistry. I designed an inquiry-based project entitled *Hydrogen Fuel Cell Cars (HFC)*. Learners learn about how hydrogen combustion takes place at the molecular level with a dynamic visualization, link with ideas of everyday life such as car safety, and apply the integrated understanding to decide whether we can use hydrogen to power cars in the future. I investigate the overall effectiveness of the project on student understanding of chemical reactions. Do they establish normative links among ideas at various levels? How does this project affect students with low, middle, and high levels of prior knowledge? What difficulties do learners have in learning this project? What are implications for instructional designers?

2. *How can we design instructional activities that support students to integrate ideas about atomic interactions from dynamic visualizations?*

Pilot testing the HFC project reveals that learners often failed to integrate ideas about chemical reaction processes such as bond breaking and formation from the visualization. Often students played the visualization too fast and did not notice these detailed changes. Sometimes they only focused on partial of the processes and integrated partial ideas. They could not develop normative links with other relevant ideas.

To solve this problem, I took advantage of knowledge integration patterns and designed three instructional activities: generating drawings, selecting pictures, and critiquing pre-made drawings. All the three activities were designed to engage students in productive knowledge integration processes of adding new ideas and distinguishing their old and new ideas. I conducted a series of comparison studies to determine the value of these activities. First, I compared the performance of students who generated drawings of reaction processes with those who spent more time interacting with the visualization. Then, using generation as a baseline activity, I designed selection and critique activities and investigated their effects with that of generation. What are the advantages of generating drawings of chemical reactions versus interaction on supporting students to integrate ideas from visualizations? What are the advantages of generation versus selection versus critique on promoting integrated understanding with visualizations? How can we design effective generation, selection, and critique activities? What are implications for designers of instructions with visualizations?

3. *How do instructional activities of generation, selection, and critique support students with diverse backgrounds to develop integrated understanding of chemical reactions?*

Instructional activities are able to guide students in focusing attention on the crucial part of the visualization and distinguishing among their old and new ideas. I seek to understand how these activities respectively help students integrate ideas about chemical reaction processes from the visualization. How do students under different conditions perform on pretest, posttest, and embedded assessment? How do the activities affect students with different prior ideas? What are students' initial interpretations of the visualization? What ideas are integrated through

generation, selection, and critique? What are the roles of drawing, selection, and critique in supporting student knowledge integration from the visualization? I am also interested in how and whether these activities change student interactions with the visualization. Do students revisit the visualization to integrate new ideas during these activities?

Rationale

The rationale of this dissertation encompasses research from three areas: challenges in learning chemistry, dynamic visualizations, and knowledge integration perspective. First, I review research on student chemistry beliefs and their difficulties in learning chemistry. Literature suggests that students often have difficulties in visualizing chemical changes at the molecular level and linking with phenomena at other levels. Second, I synthesize studies on using dynamic visualizations to help students add molecular-level ideas in chemistry. While visualizations can assist students to learn unseen processes, learners face more challenges such as deceptive clarity. The effect of using visualizations in classrooms remains inconclusive. Third, I explore how instructional design can take advantage of the knowledge integration framework and support students to effectively integrate ideas from visualizations. I discuss the knowledge integration framework, design principles, and patterns, and suggest that visualizations coupled with instruction designed with the knowledge integration patterns can help students add normative ideas, distinguish ideas, and refine connections among ideas.

Challenges in Learning Chemistry

Much research shows that students have difficulties making sense of chemical phenomena at the molecular level (Ben-Zvi, Eylon, & Silberstein, 1986, 1987; Krajcik, 1989, 1991; Stavridou & Solomonidou, 1998; Yarroch, 1985). For instance, students have trouble understanding the particulate nature of matter and assume that a single atom or molecule has the same properties as that of the aggregate. Ben-Zvi, Eylon and Silberstein (1986) asked tenth-grade 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 failed to differentiate the properties of the substance and that of the atom. They viewed particles as very small bits of the continuous substance. Such ideas persisted after explicit instruction about the nature of the atomic model.

Similar problems were found in student understanding of chemical reactions that can be traced to understanding the atomic level. Often students view a chemical equation as a composition of letters, numbers, lines and arrows, similar to that of a mathematical equation, instead of a dynamic process of atom rearrangement, bond breaking, and formation (Krajcik, 1991; Yarroch, 1985). Ben-Zvi, Eylon, & Silberstein (1987) asked 994 10th grade students to draw two electrolysis reactions: $2\text{KF}(\text{l}) \rightarrow 2\text{K}(\text{s}) + \text{F}_2(\text{g})$, and $\text{Cu}^{2+}(\text{aq}) + 2\text{e}^- \rightarrow \text{Cu}(\text{s})$. Altogether 59.7% of the students drew the reactants and products without any indication that something is happening during the processes. They drew two KF molecules on the left, two K atoms and one F₂ molecule on the right, and an arrow in the middle. Their drawings were just a one-to-one “translation” of each symbol in the equation. Only 9.5% of the students drew pictures showing movement of ions towards the electrodes. After one year of chemistry study, these students still keep their intuitive ideas and cannot develop integrated understanding about chemical bonding. In another

study, Boo (1998) interviewed 48 12th 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.

Research suggests that these difficulties may stem from different types of representations involved in chemistry learning. Learning chemistry involves understanding and linking representations at the molecular or submicroscopic (e.g., atomic interactions), symbolic (e.g., equations), and observable or macro (e.g., color change) levels (Gabel, 1998; Gilbert & Treagust, 2009; Johnstone, 1993). For instance, to form a normative understanding of hydrogen combustion ($2\text{H}_2 + \text{O}_2 \rightarrow 2\text{H}_2\text{O}$), students need to comprehend at least: (a) the structural aspects of chemical reactions, including the molecular structure of reactants and products (hydrogen gas, oxygen gas and water); (b) the symbolic representations of H_2 , O_2 , H_2O , and $2\text{H}_2 + \text{O}_2 \rightarrow 2\text{H}_2\text{O}$, including coefficients, subscripts and conservation of matter; (c) the interactive nature of a chemical reaction, such as bond breaking and formation; and (d) observable phenomena associated with the reaction such as an explosion and fire (Ben-Zvi et al., 1987). They need to understand different representations to demonstrate the reaction at the macro, submicro, and symbolic levels and the triplet relationship among the representations (Gilbert & Treagust, 2009). An expert's understanding would include more complex information, such as the chain reaction process and conditions under which explosions would occur.

While expert chemists can move easily between different representations and understand relationship among representations, novice students find it challenging to understand chemical phenomena at the molecular or submicro level and link with other representations (Kozma & Russell, 1997; Kozma, 2003). Many students end up understanding chemical reactions based on observable phenomena with no links with molecular views (Keig & Rubba, 1993; Nakhleh, Samarapungavan, & Saglam, 2005). Stavridou and Solomonidou (1998) asked 40 students (12 to 18 years old) to identify chemical reactions among 19 phenomena and interviewed their conceptions of chemical reactions. They found that younger students gave definitions of chemical reaction as phenomenology of change, and viewed reactions as 'events' with some phenomenological manifestations, e.g. color change, gas release, explosion, etc. They were unable to distinguish atomic movement involved in different types of changes, e.g. physical or chemical changes. The older students (five students aged 18) who had learned more chemistry courses were able to develop some fragmented ideas of how molecules change during chemical reactions, yet unable to connect to observable phenomena.

To develop integrated understanding, students need support to add ideas at the molecular level and connect different representations. Textbooks and formal instruction fail to do so because textbooks often emphasize symbolic representations and present confusing images of chemical concepts at the molecular level (Ben-Zvi, Eylon, & Silberstein, 1987). Formal instructions often neglect everyday examples, making chemistry overly abstract. Students taught using traditional instruction usually develop fragmented ideas and cannot establish connections between representations.

One promising solution is to use dynamic visualizations to help learners visualize chemical reactions at the molecular level. Dynamic visualizations can represent unseen processes and phenomena such as bond breaking and formation during chemical reactions. They can incorporate other representations such as reaction equations and a temperature bar showing how the temperature changes during a reaction. By dynamically linking them, dynamic visualizations can demonstrate how different representations are coordinated and support students to make conceptual links among represented ideas. The conception of viewing chemical reactions as a static process may be changed if students see a dynamic visualization that demonstrates atomic interactions together with the reaction equation. In the next section, I discuss how instruction featuring dynamic visualizations can help students learn chemistry.

Dynamic Visualizations

Dynamic visualizations offer great promises for science learning. They can demonstrate unseen processes and offer a complete model of the dynamic processes. Compared to static visuals that use indicators such as arrows to symbolize temporal changes, dynamic visualizations bring temporal ideas to life and supports understanding (Park & Hopkins, 1993).

Several studies have shown that visualizations improve the learning of abstract chemistry topics by adding ideas about molecular processes (Ardac & Akaygun, 2004; Barak & Dori, 2005; Frailich, Kesner, & Hofstein, 2009; Marbach-Ad, Rotbain, & Stavay, 2008; Wu, Krajcik, & Soloway, 2001). Williamson and Abraham (1995) designed animations that illustrated chemical processes of dissolving salt in water with combined symbolic and molecular representations. They found that students who used animations outperformed those who were only lectured without viewing any animation. Similarly, Sanger, Brecheisen, and Hynek (2001) found that college students who viewed animations of diffusion of perfume molecules and osmosis of water molecules had better understanding of random and constant movement of particles than those who did not do so. Because many students are unable to picture a dynamic process at the molecular level by reading pictures and graphs on textbooks, dynamic visualizations are necessary to enhance their understanding about molecular processes.

Dynamic visualizations can promote integrated understanding by incorporating multiple representations and supporting students to establish connections between them (Ainsworth, 1999). Multiple representations can complement learning by including pieces of information in each individual representation and show coordinated changes in the representations simultaneously. Students can create referential connections between corresponding features of different representations with their knowledge of one representation mapped onto another (Seufert, 2003).

One example is the visualization tool developed by Kozma and his colleagues (Kozma, 2003; Kozma et al., 1996; Kozma & Russell, 1997), *MultiMedia and Mental Models (4M: Chem)*. *4M: Chem* employs four coordinated representations to explain chemical phenomena- a video of a lab experiment, the corresponding chemical equation, a dynamic real-time graph, and a molecular animation. For instance, to present a chemical equilibrium process, $2\text{NO}_2(\text{g}) (\text{brown}) \rightleftharpoons \text{N}_2\text{O}_4(\text{g}) (\text{colorless})$, *4M: Chem* includes a video segment showing the change of color within an enclosed tube under different temperatures; an equation with chemical formulas and symbols; an animation showing the interaction and movement of molecules; and a graph showing how the

concentration of two gases changed over time. These four representations are shown simultaneously and linked to each other. Analysis of student conversations when working with the environment demonstrates that students used *4M: Chem* to identify when their ideas conflicted with the presented information and to refine connections among ideas about chemical equilibrium. One pair of students initially viewed equilibrium as a static state with equal quantities of substance. They thought that 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 two students used the 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, another visualization tool *eChem* (Wu, Krajcik, & Soloway, 2001) provides interactive features that allow students to construct molecular models, view them at different angles, analyze and compare their physical properties at the macroscopic level. Wu et al. (2001) showed that after using *eChem* for six weeks, a majority of high school students were able to transform 2D structures into 3D models and used molecular structures to explain properties of chemical compounds. Transcripts of students working with *eChem* suggest that students can use visualizations to realize when their ideas conflict and refine links among ideas of chemical structure and bonding. This study also suggests that dynamic visualizations affect how students interact with each other. Students who view molecular visualizations tend to discuss the molecular processes with each other as they explore the visualizations. These social interactions enable students to put complex observations into words and may contribute to improved understanding.

Besides the above-noted benefits, visualizations can also broaden participation in science. They offer new ways to represent complex problems and help connect ideas. Adding visualizations to instructions increase interest and insights in science (Boo & Watson, 2001). When asked what helps them learn science, two-thirds of sixth graders chose visualizations over explanations, reading, partners, and teachers (Corliss & Spitulnik, 2008).

Yet researchers also warn that dynamic visualizations may not be universally beneficial. Learners can be distracted by perceptually salient parts of the visualization and focus on aspects that may or may not be conceptually relevant. For instance, they may only see bouncing balls when we show them an animation intended to demonstrate phase changes. Some animations of the microscopic world include so much information that overwhelms students. They may exhibit no advantages over static diagrams (Tversky, Morrison, & Betrancourt, 2002). A meta-analysis of research over the past decade shows that the effect sizes for visualizations range from -1.5 to +2.3 in recent literature (Chang, Chiu, McElhaney, & Linn, submitted). The impact of visualization on student learning remains controversial.

Visualizations may be deceptively clear and lead learners to overestimate their understanding. Students may think that they understand visualizations while they only focus on superficial aspects. Chiu (2010) asked students to rate their understanding after learning a visualization that shows bond breaking and formation during hydrogen combustion. One group of students rated their understanding right after they had

interacted with the visualization. The other group of learners rated after they had written an explanation about their observations. The results show that students who were asked to rate right after viewing the visualization believed that they had better understanding than those who rated after the explanation. Further analysis suggests that the visualization represent dynamic information in such an apparently simple way that students believe that they understand chemical reactions. Yet, in fact, the visualization includes so much information about bond breaking and formation that students need to make many interactions to appreciate it. When they were asked to write explanations, they realized that they had gaps in their understanding. The recognition of those gaps led to a decline in their estimation of their understanding. Thus, students overestimated their initial understanding at first. But when asked to generate an explanation, learners realized that the visualization was more complex. The overestimation can prevent learners from further review of their ideas.

To maximize the potential benefits of visualizations and develop deep understanding of the underlying scientific concepts, learners need to first understand the format of each representation incorporated in the visualization, including the subtleties of the representations and conventions for interpreting them (Ainsworth, 1999; Winn, 1991). Next, they should select what they perceive to be the most relevant aspects and make careful observations. Third, they must distinguish between the newly conceived ideas and their prior knowledge, recognize when these ideas conflict, demote the naive views, promote the correct ideas, and refine connections with other ideas. Researchers explore different instructional supports that can help students learn with dynamic visualizations. Quintana et al. (2004), for example, emphasize the benefits of using scaffolds, such as embedded questions to strengthen the connections between ideas and representations. Another promising approach is to design activities following knowledge integration patterns that can engage students in productive knowledge integration processes.

Knowledge Integration Perspective

This research explores designing instructional activities that follow the knowledge integration framework (Linn & Eylon, 2006) to promote integrated understanding of scientific topics underlying dynamic visualizations. The knowledge integration perspective views learners as holding a repertoire of ideas rather than a single view of a scientific phenomenon (Davis, 2003; diSessa, 1987; diSessa & Minstrell, 1998; Linn, Clark & Slotta, 2002). For instance, in his interview with a college student named J, diSessa (diSessa, et al., 2002; diSessa & Sherin, 1998) found that students often hold contradictory ideas of the same phenomenon. J struggled to explain how Newton's second law of motion ($F=ma$) can be applied to explain pushing a book across a table at constant velocity. She was unable to reconcile her intuitive idea that the motion of the book must result from unbalanced forces with her formal knowledge that unbalanced forces must produce an acceleration. Although she successfully applied the law $F = ma$ to solving problems from her physics class, she chose her intuitive idea as the normative explanation and set $F = ma$ aside. J's explanation shows that students are able to hold conflicting ideas in their repertoire simultaneously. These ideas are isolated and learners do not recognize the conflicts. They even believe some ideas belong to the school and others belong to the out-of-school.

To help learners develop coherent understanding, instructions should support students to recognize conflicting ideas and refine their knowledge. Researchers (Linn & Eylon, 2006) advocate instructions that engage students in four knowledge integration processes: eliciting students' current ideas (e.g., existing observations about the explosion of a hydrogen balloon), adding new ideas (interacting with a dynamic visualization of chemical reactions), distinguishing among ideas (asking to represent the molecular processes involved in chemical reactions), and sorting out ideas (asking for explanations about how the molecular view relates to their observations). Through a combination of the four processes, students can be aware when their ideas conflict with each other and take an active role in connecting new ideas with prior knowledge and refining their understanding.

To give designers more concrete ideas about how to design curricular projects to promote knowledge integration, Linn and Hsi (2000) identified design principles. Based on the experience in designing effective projects with new technologies such as computer visualizations and online discussion forums for the Computer as Learning Partner (CLP) project, they proposed four principles: *make science accessible*, *make thinking visible*, *help students learn from others*, *promote autonomy*.

- First, *making science accessible* means allowing students to build on previous knowledge and connect new ideas to their prior knowledge. Research (Linn et al., 2004) shows that instruction is effective when teachers elicit students' repertoire of ideas as a starting point and guide students to add new ideas, sort out, and refine their repertoire of ideas. The instruction should help students recall what they already know and rethink their existing ideas. This is often accomplished by finding personally relevant problems and contexts that allow students to link their ideas in science classrooms with everyday issues. This approach pays attention to the diverse background and ideas learners bring to class, capture their interest, and motivate integration of new ideas. For instance, the heat and temperature project in the CLP made science accessible by introducing the instruction in personally relevant contexts. Students are asked to investigate everyday phenomena like the difference between touching metal chairs and Styrofoam cups. Contrary to traditional textbooks and instruction that teach science distant from students' previous experience, this project shows students how science can be applied to everyday life.
- *Making thinking visible* involves modeling and demonstrating how ideas are connected and organized in new knowledge networks. Instruction can take advantage of technologies and employ tools such as SensorMaker and prompts that allow students to articulate and inspect their own ideas. By making their own knowledge visible, students can monitor their learning and engage in linking, distinguishing, and reconciling ideas. They can use the tools to share their thinking with peers and teachers, receive feedback, and refine their understanding. Further, instruction can incorporate dynamic visualizations that illustrate how experts view the scientific phenomena. For instance, the heat and temperature project made thinking visible by employing powerful visualizations that enable learners to visualize abstract concepts. It uses dynamic visualizations that show molecular interactions when conductors, insulators, and semiconductors are heated up and how the interactions are linked with observable phenomena.

- *Helping students learn from others* refers to providing students with opportunities to exchange ideas with their peers. Instruction can incorporate various learning activities such as debates, discussions, creating arguments, and comparing views. These activities introduce learners with new ideas and beliefs from other students. Learners need to debate and negotiate with each other to reach shared understanding. These tools help students reflect, consider more ideas from peers, and develop criteria to distinguish among ideas. The heat and temperature project asked learners to participate in online discussion. Students shared their ideas with peers, negotiated using evidence from the project, and resolved differences between the views.
- *Promoting autonomy and lifelong learning* encourages students to monitor and reflect on the quality of their own learning. To encourage lifelong learning, learners need to constantly monitor their own progress, recognize new ideas, and connect them with their prior knowledge. Instruction can help by providing students opportunities to work on complex inquiry projects so that learners can link personally relevant issues with what they learned in science classrooms. Reflective prompts can highlight inquiry processes students engage in and encourage them to apply the processes in future learning. The heat and temperature project promoted autonomy by engaging students in reflection ideas about thermodynamics and using these ideas to critique a news article from a fictitious newspaper.

Besides principles, Linn and Eylon (2006) synthesized the research on the design of science instruction into design patterns. Patterns are instructional activities that engage learners in the four knowledge integration processes. Each pattern focuses strongly on one or two processes. Instructional designers can combine multiple patterns in effective sequences to promote knowledge integration. The patterns can help designers create effective science instruction by taking advantage of design knowledge from the broader educational research and design communities. Patterns give designers a framework that ensures instruction provides students with opportunities to build on prior knowledge, distinguish between new and old ideas, intentionally refine their knowledge, and generalize their ideas to broader contexts.

In my research, I am especially interested in designing instructions that follow knowledge integration patterns such as generation and critique to promote integrated learning with dynamic visualizations. These patterns focus on engaging students in process of distinguishing ideas and can be especially powerful to chemistry students. Chemistry students often come to class with rich, diverse ideas about chemical phenomena. Some ideas are scientifically normative while others are not. To develop integrated understanding of chemical phenomena, learners need to add ideas about atomic interactions and link with ideas at symbolic and observable levels. Dynamic visualizations can help add the molecular-level ideas. Instruction based on the knowledge integration patterns can encourage students to recognize when the new ideas and their existing knowledge bump against each other, solve conflicts, establish links among ideas, reflect and refine their understanding. A combination of the instruction and visualizations can help students understand chemical phenomena at the molecular level and promote normative connections among various levels.

To sum up, this section describes the benefits of embedding dynamic visualizations within instruction that follows knowledge integration patterns. Visualizations can help students add normative ideas and the instruction can engage students in the knowledge integration processes of distinguishing ideas and establishing normative connections among ideas.

Dissertation Overview

This dissertation focuses on investigating three activities to promote integrated understanding of chemical reactions with a dynamic visualization: generating drawings of chemical reaction processes, selecting pictures to represent the processes, and critiquing drawings made by fictitious peers. The visualization shows bond breaking and formation during hydrogen combustion. It is embedded within an inquiry-based curricular project entitled *Hydrogen Fuel Cell Cars* (HFC). Students investigate how hydrogen combustion takes place at the molecular level and decide whether hydrogen can be used to power cars in the future. Informed by the knowledge integration framework, the HFC project was designed to support students to link atomic-level ideas with everyday events such as car safety. To support students to integrate ideas from the visualization, I designed the three activities, which aimed at prompting students to distinguish their intuitive ideas with normative ideas from the visualization and to refine their understanding. My study contributes to educational research by providing ways to make new technologies such as visualizations effective in classrooms and offering ways to design instructional activities that help students distinguish and refine ideas in technology-enhanced settings.

My dissertation includes eight chapters. Chapter 1 discusses the benefits of combining dynamic visualizations and knowledge integration activities in promoting integrated understanding of chemistry. Chapter 2 discusses the design and refinement of the HFC project and hydrogen combustion visualization.

Chapter 3 explores the overall impact of the HFC project on student understanding. The findings show that although students significantly improved their understanding after the project, many of them failed to integrate ideas at the molecular level (e.g., bond breaking and formation) from the visualization. The visualization may be deceptively clear to students.

Chapter 4 investigates how to improve student learning with the visualization, in particular, how instruction can be designed to draw student attention to important details conveyed in the visualization and help them integrate atomic-level ideas. Does it help if asking students to spend more time interacting with the visualization? Will they notice the nuanced information and integrate the molecular-level ideas? This study designed a generation activity that required students to create drawings about the molecular processes during hydrogen combustion. It compared the learning of students who generated with those who spent more time interacting with the visualization. Results show compared to interaction, the generation activity supported students to integrate more ideas about chemical reaction processes into their repertoire. Student responses to embedded assessments show that the generation succeeded because it prompted students to realize gaps in their prior interpretations of the visualization, select key ideas from the visualization, distinguish them from their naïve ideas, and refine understanding.

These findings help clarify the effectiveness of generative activities such as drawing in helping students distinguish ideas. However, one question remains from the study in Chapter 4: which one plays a more important role in facilitating student

knowledge integration from visualizations, constructing models or distinguishing ideas? Studies on modeling and constructionism suggest that asking students to generate models or artifacts can support them to develop deeper understanding of the underlying concepts (Lehr & Schauble, 2004; Papert, 1991). In this study, it is difficult to tease out the effect of generation and distinguishing ideas.

To help clarify the importance of distinguishing ideas, in Chapter 5 and 6, I designed the other two activities: selecting pictures to represent chemical reaction processes, and critiquing pre-made drawings by fictitious peers. I compared their impact with that of generating drawings. Neither selection nor critique involves students in generating representations and therefore these studies eliminate the possible effect of generation. Students need to select (or critique) by distinguishing among the non-normative ideas in the choices (or the pre-made drawings to be critiqued) from normative views in the visualization.

Chapter 5 discusses the iterative design of the selection activity: simple selection and complex selection. Complex selection was designed to incorporate common alternative ideas students hold and had similar effect on promoting integrated learning as generating drawings. Simple selection, however, was not successful because the choices did not represent student alternative ideas and thus did not engage students in distinguishing normative from non-normative ideas.

Chapter 6 investigates the impact of critique on student learning with visualizations. The drawings to be critiqued were designed to represent student common non-normative ideas. Results show that students under the critique and generation conditions achieved similar performance. They all developed integrated understanding of chemical reaction processes from the visualization. Further, computer log files demonstrate that students under both conditions have similar interaction patterns with the visualization. Learners frequently revisited the visualization during the activities, which suggests that they recognize gaps in their prior knowledge and return to integrate new ideas. Taken together, the results from Chapter 5 and 6 confirm the necessity of supporting students to distinguish ideas when learning with dynamic visualizations.

The main purposes of Chapter 7 are to replicate findings from previous chapters by comparing the effectiveness of the three activities, and to explore the nature of the criteria students used to distinguish ideas. I designed an embedded question that asked students to report the criteria they developed and categorized them. The result shows that generation, selection, and critique activities successfully helped students integrate ideas from the visualization, which is consistent with the previous studies. Analyzing the criteria shows that all three activities helped students develop valid criteria to distinguish normative and non-normative ideas about chemical reaction processes.

Chapter 8 summarizes results of the empirical studies with respect to distinguishing ideas and desirable difficulties, and provides directions for designing instruction with visualizations as well as design patterns. Table 1.1 summarizes the research questions, key methods, and findings of all empirical study chapters.

Table 1.1. Research questions, methods, and findings of all empirical study chapters.

Chapter	Research questions	Key methods	Key findings
3. Examining the Effect of the HFC Project	<p>What are the challenges in forming an integrated understanding of the energy diagram?</p> <p>How do scaffolded visualizations improve student understanding of energy change during chemical reactions by building connections between ideas at observable, molecular, and symbolic levels?</p>	<p>Compared pre and posttest of students who learned the HFC project. Examined learning gains of students who started with low, middle, and high prior knowledge.</p> <p>Analyzed student responses to embedded prompts to understand how students made connections among representations.</p> <p>Categorized student non-normative ideas before the project and tracked their performance on the posttest to understand student learning difficulties.</p>	<p>Students made significant gains in connecting ideas about chemical reactions after the project.</p> <p>Students with all levels of prior knowledge benefited from the project. Learners with low prior knowledge achieved the most learning gains.</p> <p>Some students had difficulties integrating ideas about bond breaking and formation from the visualization.</p>
4. Can Generating Drawings Enhance Learning with Dynamic Visualizations?	<p>What are the advantages of generating drawings versus interaction on supporting students to integrate molecular-level ideas from the hydrogen combustion visualization?</p> <p>What is the impact of generating drawings on students with different prior knowledge?</p> <p>How does</p>	<p>Compared pre and posttest performance of students who generated drawings with those who interacted to understand the advantage of generation.</p> <p>Categorized students' prior ideas and tracked their performance on the posttest to understand the impact on students with various ideas.</p> <p>Analyzed student explanations and drawings created during the project to understand how generation helped students</p>	<p>Generation supported students to integrate more ideas about chemical reactions than interaction.</p> <p>Generation motivated students to interpret the visualization more carefully and led to more productive explanations about ideas represented in the dynamic visualization.</p> <p>Students in the interaction group were less successful in linking the visualization to</p>

	generating drawings contribute to integrated understanding?	learn.	underlying concepts and wrote less detailed explanations.
5. Generation and Selection	How do selection tasks contribute to integrated understanding of chemical reactions? What are the advantages of selection versus generation of drawings of chemical reactions for all learners and for learners with non-normative, mixed, and partially normative ideas? What are the implications for designers of instruction with visualizations?	Two studies: Study 1: compared generation with simple selection; Study 2: compared generation with complex selection Compared pre and posttest of students who generated with those who selected. Categorized student prior ideas and compared the posttest performance of students who started with similar ideas under two conditions. Analyzed student drawings and selections to understand how selection supports learning. Examined student audio recordings to investigate why simple selection was less successful than generation.	Complex selection had similar impact as generation on promoting student learning. Simple selection was less beneficial than generation. Complex selection enabled learners to recognize gaps in their knowledge and distinguish ideas. Simple selection failed to encourage students to discriminate ideas. Students selected based on their memorization of the visualization instead of their understanding. Effective selection tasks should incorporate student common alternative ideas to encourage distinguishing ideas.
6. Generation and Critique	What are the advantages of critique versus generating drawings of chemical reactions for all learners and for learners with non-normative, mixed, and partially normative ideas?	Compared pre and posttest of students who generated with those who critiqued. Categorized student prior ideas and compared the posttest performance of students who started with similar ideas. Analyzed student drawings and critiques to	Critique had similar impact on supporting students to integrate ideas from the visualization as generation. Generation and critique helped students distinguish ideas and revise their interpretations of the

	How does critique contribute to integrated understanding of chemical reactions?	understand how critique supports integrated understanding. Examined computer log files to investigate student interaction patterns under two conditions.	visualization. Both activities prompted similar interaction patterns with the visualization: students revisited the visualization frequently to integrate new ideas.
7. What Criteria do Students Use to Distinguish Ideas?	How do generation, selection, and critique impact learners? Do student prior ideas make a difference in their performance? What criteria do students develop to distinguish ideas in selection, critique, and generation?	Compared pre and posttest of students under the three treatments. Categorized student prior ideas and compared the posttest performance of students who started with similar ideas under two conditions. Analyzed student reported criteria to understand the nature of criteria they used to distinguish ideas.	The three activities had similar impact on supporting students to integrate ideas with visualizations. These activities all supported students to develop valid criteria to distinguish ideas. Learners in the generation group on average developed more complicated criteria than those in the selection and critique groups. Some students in the generation group established criteria about how to represent the molecules instead of the aggregate.

Chapter 2: Hydrogen Fuel Cell Cars Project

This chapter describes the design of the *Hydrogen Fuel Cell Cars* (HFC) project and the dynamic visualization investigated in this dissertation. The HFC project is a six-day unit that aims at helping students develop integrated understanding of chemical reactions by linking ideas at molecular, observable, and symbolic levels. It features a dynamic visualization that demonstrates bond breaking and formation during hydrogen combustion. This chapter discusses the curricular activities of HFC designed to promote knowledge integration, and the design and refinement of the visualization. In addition, it also introduces the design of assessment and knowledge integration scoring rubrics used in this dissertation.

Instructional Standards and Learning Goals

The particulate nature of chemical reactions is a focus of middle school physical science curricula. According to the California Science Education Framework (2003), students should understand that “*Chemical reactions are processes in which atoms are rearranged into different combinations of molecules.*” Students should “*know reactant atoms and molecules interact to form products with different chemical properties.*” In addition, students are also required to understand the particulate nature of the reactants and products and relate to observable phenomena associated with chemical reactions. Previous research suggests that students often find it challenging to coordinate and connect these ideas, which leads to various misconceptions and learning difficulties (Eylon & Linn, 1988; Harrison & Treagust, 2000).

The main purpose of the HFC project is to help students develop integrated understanding of chemical reactions by establishing normative links among ideas at various levels. In particular, the learning goals are:

1. To link ideas about molecular processes such as bond breaking and formation with molecular representations and reaction equations.
2. To link ideas about bond breaking and formation with observable phenomena such as temperature change and explosion.
3. To link ideas about bond breaking and formation with other relevant chemistry concepts such as activation energy and the conservation of matter law.

Hydrogen Fuel Cell Cars Project

This inquiry-based project is situated within the context of hydrogen fuel cell cars, with a purpose to connect molecular processes with observable phenomena associated with chemical reactions. By researching and comparing chemical reactions in gasoline-powered cars and hydrogen fuel cell cars, students gather information and build their own ideas on which type of cars are better and why. The inquiry process strengthens the establishment of conceptual connections between everyday issues and underlying principles of chemical reaction processes. The dynamic visualization embedded in the project provides students with vivid illustrations of how the molecular processes take place during chemical reactions and how the temperature changes with the processes.

TELS Project Design and Technology

The HFC project was designed by a partnership following the Technology-Enhanced Learning in Science (TELS) design process (Holmes & Linn, 2005). The

partnership model (Shear, Bell & Linn, 2004), informed by the knowledge integration framework, brings together teachers and researchers to develop a curriculum that can be used in a practical setting while investigating key theoretical issues. The teachers involved in the HFC project started working closely with me during the TELS summer retreat in 2005. We discussed student difficulties in learning chemical reactions, initial ideas of the project, what inquiry context was appropriate, curricular activities, and assessments. In the following semester, I designed the project and pilot tested with chemists, other researchers in the TELS group, teachers, and small groups of students. Based on their feedback, I revised the projects several times. Then in the spring of 2006, I implemented this project in a public high school in California. Ever since then, this project has been run and tested in more than 40 classrooms across the country. I made immediate refinements to the project after each implementation based on suggestions from teachers and students. In the summer retreat, the teachers who used the HFC project and I examined student responses to the assessments embedded in the project and discussed further revisions to the project. These teachers are affiliated with the TELS center and have been working closely with me in the design of the HFC project.

The HFC project employs two technology platforms to teach chemical reactions: the Web-base Inquiry Science Environment (WISE) from the University of California, Berkeley, and Molecular Workbench from the Concord Consortium. The WISE draws from over twenty years of computer-based science learning and provides an environment to help students develop deep understandings of science (Linn, Davis & Bell, 2004). The WISE interface gives designers diverse pedagogical tools to put knowledge integration principles into practice (Slotta, 2004). Students can read scientific facts, conduct experiments and collect data, and participate in online discussion forum where they can argue against each other using evidence. It also features embedded questions and prompts which encourage students to reflect and explain their understandings. Figure 2.1 shows a screenshot of the WISE HFC project. The left side shows inquiry steps incorporated in the project. The background shows a page illustrating the driving question. The foreground shows a WISE note that calls for students' explanations.

The partnership with the Concord Consortium adds to the WISE technology by contributing dynamic molecular visualizations (Pallant & Tinker, 2004). Specifically, this tool helps visualize the collective motions of atoms and molecules based on estimations of classical dynamics and applicable forces (Xie & Tinker, 2006). These two technologies have been integrated into the larger TELS technology, providing curriculum designers and users a coherent platform to effectively design and deliver successful instructional materials.

Figure 2.1. Screenshot of the Hydrogen Fuel Cell Cars project. The left side shows inquiry steps incorporated in the project. The background shows a page illustrating the driving question. The foreground shows a WISE note that calls for students' explanations.

Design to Promote Knowledge Integration

The design of the HFC project is informed by the knowledge integration framework (Linn, Davis & Eylon, 2004). Students hold a repertoire of ideas about many topics in chemistry (Ben-Zvi, Eylon & Silberstein, 1987), e.g., they have ideas about combustion reactions from their everyday experiences such as igniting candles and setting up campfires. This repertoire of ideas encompasses the diverse, alternative concepts that students hold in their minds. Students bring these ideas to the chemistry classes, and some of them may not be scientifically normative and internally consistent. For coherent science learning, students need to integrate and distinguish these ideas with those learned in science classrooms. The knowledge integration framework provides guidance and principles for designing instruction to help students reconcile and integrate their prior knowledge with new ideas.

Specifically, this project is designed following the four meta-principles of the knowledge integration framework:

- First, to *make science accessible*, this project is built upon students' prior knowledge of cars, chemical reactions, and energy. It starts by eliciting students' existing ideas about gasoline powered cars. Learners integrate new ideas about chemical reactions by exploring molecular processes involved in hydrogen combustion and connecting with personally relevant issues such as car safety. Different from traditional chemistry instruction which features textbooks and lab work, this unit shows students how chemistry can be applied to everyday life. In particular, the context of cars and fuels captures high school students' excitement and interests and makes the unit more accessible to students.
- Second, to *make thinking visible*, this project employs multiple visualizations to illustrate chemical reactions at different levels, including a video of the burning of


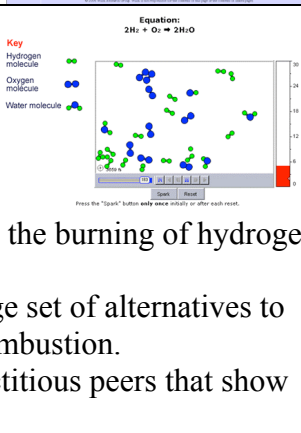
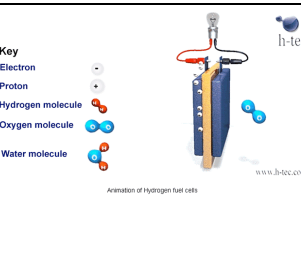
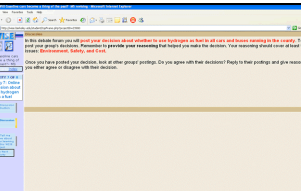
a hydrogen balloon, an interactive dynamic visualization that shows molecular processes during hydrogen combustion with synchronous temperature change, and a flash movie of the reaction between hydrogen and oxygen inside hydrogen fuel cells. These visualizations demonstrate different ideas such as bond breaking, formation, and energy, and highlight how different aspects of chemical reactions correlate with each other.

- Third, to *help students learn from others*, this curriculum employs an online discussion forum where students present their own ideas and critique others' postings. At the end of the project, students participate in an online discussion about the pros and cons of gasoline powered and hydrogen fuel cell cars. They need to use scientific evidence to construct arguments and decide whether hydrogen fuel cell cars can replace gasoline cars in the future. This discussion offers students a chance to share their own ideas with others, understand peers' views, and resolve conflicting ideas. In addition, students work in pairs in the HFC project, which promotes collaborations and peer discussions about the project.
- Fourth, to *promote autonomy and lifelong learning*, the HFC project adopts the *reflection* design pattern and incorporates embedded prompts that ask students to explain their understanding. For instance, after interacting with the visualization, students are asked to explain their observations from the visualization. These prompts help students become aware of new ideas added and connect with their prior knowledge. In addition, the online discussion provides students opportunities to reflect. They need to reflect on their integrated ideas, construct arguments, and apply the ideas to solve personally relevant issues.

Curricular Activities

The HFC project encourages student integration of ideas about chemical reactions with an inquiry context of hydrogen fuel cell cars. The guiding inquiry question is “*Will gasoline powered cars become a thing of the past?*” The activity sequence of the module with screenshots is laid out in Table 2.1.

Table 2.1. Activity sequence of the Hydrogen Fuel Cell Cars module with screenshots.

<p>Activity 1 Gasoline powered cars</p>	<p>General introduction to gasoline powered cars, air pollution and energy. Focus on the inputs and outputs of cars.</p>	
<p>Activity 2 Hydrogen combustion</p>	<p>Observe a video showing the burning of a hydrogen balloon. Explore a dynamic visualization showing how the burning of hydrogen happens at the molecular level.</p> <p><i>Generating drawings:</i> draw and explain how the burning of hydrogen gas happens at the molecular level.</p> <p><i>Selecting pictures:</i> select pictures from a large set of alternatives to represent interim phases during hydrogen combustion.</p> <p><i>Critique:</i> critique two sets of drawings by fictitious peers that show interim phases during hydrogen combustion.</p>	
<p>Activity 3 Why using fuel cell in hydrogen fuel cell cars?</p>	<p>Predict what will happen if hydrogen burns in internal combustion engines as gasoline. Explore visualizations showing how hydrogen and oxygen react inside hydrogen fuel cells. Explain why hydrogen fuel cells improve car safety.</p>	
<p>Activity 4 More about hydrogen fuel cell cars & discussion</p>	<p>Participate in an online discussion by searching for information, applying content knowledge, and constructing arguments of the advantages of one car over another.</p>	

Activity 1 Gasoline cars or Hydrogen fuel cell cars?

The main purpose of Activity 1 is to elicit student existing ideas and introduce the inquiry question. Students brainstorm their existing ideas about gasoline powered cars, energy, and the chemical reaction involved in cars. They also review relevant ideas about gasoline combustion and greenhouse effects. Figure 2.2 presents a WISE page that shows the inquiry question of this project.

Hydrogen fuel cell or Gasoline powered cars?

Consider the following situation:

You are planning to buy a new car and are told that hydrogen fuel cell cars will be on the market soon. Compared to gasoline cars, hydrogen fuel cell cars use the newest technology and use liquid hydrogen as fuel. Which one will you buy?

To help you decide which car to buy, in this project, we will explore what chemical reactions make gasoline and hydrogen power gasoline cars and hydrogen fuel cell cars.

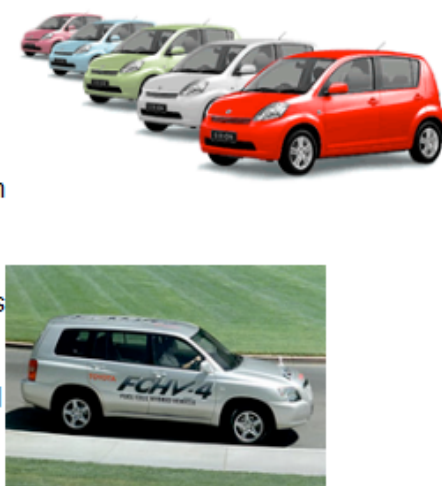


Figure 2.2. Screenshot of Activity 1 Step 1 of the HFC project. Students are presented with the inquiry question.

Activity 2 Hydrogen combustion

The purpose of activity 2 is to help students develop integrated understandings of hydrogen combustion. Students first review the basics about hydrogen, oxygen, and chemical reaction equations. Then they observe a video that shows the explosion of a hydrogen balloon to learn observable phenomena associated with hydrogen combustion. Afterwards, they interact with the dynamic visualization that demonstrates bond breaking, formation, and energy change during hydrogen combustion. The visualization helps students understand what molecular processes take place during the reaction (see Figure 2.3 for screenshots of visualizations used in Activity 2). Embedded prompts were designed to help students construct links among these various ideas. For instance, one embedded prompt asks “*How is this reaction related to the conservation of matter?*” It encourages students to consider the link between chemical reactions with the conservation of matter.

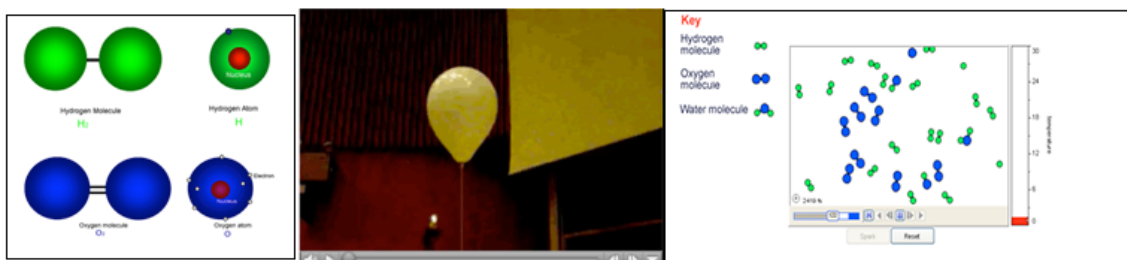


Figure 2.3. Screenshots of visualizations used in Activity 2. *Left*: molecular representations of hydrogen and oxygen atoms/molecules. *Middle*: a video that shows the burning of a hydrogen balloon. *Right*: a dynamic visualization that shows bond breaking and formation during hydrogen combustion.

In addition, the instructional activities (generation, selection, and critique) developed and investigated in this dissertation were designed to occur after the visualization step. These activities ask students to create, select, or critique drawings about molecular processes involved in hydrogen combustion. They enhance student learning with the visualization by integrating ideas about bond breaking and formation and developing normative links with relevant concepts such as activation energy and conservation of matter. I will discuss the design of each activity in the analytical chapters.

Activity 3 Why using fuel cell in hydrogen fuel cell cars?

In activity 3, students focus on investigating hydrogen fuel cell cars. They start by predicting the safety of using hydrogen as fuel and answering “*Is it safe to burn hydrogen inside the internal combustion engine as gasoline? Explain why.*” This question requires students to connect their understanding of hydrogen combustion with everyday experience about car safety. Then they explore dynamic visualizations that illustrate how hydrogen and oxygen react inside hydrogen fuel cell cars and how the energy is transformed to power cars. Students compare with burning hydrogen in the air and explain why hydrogen fuel cells improve car safety. This activity also takes advantage of embedded prompts to promote conceptual connections among chemistry concepts and everyday events. Figure 2.4 shows screenshots of the two visualizations adopted in Activity 3.

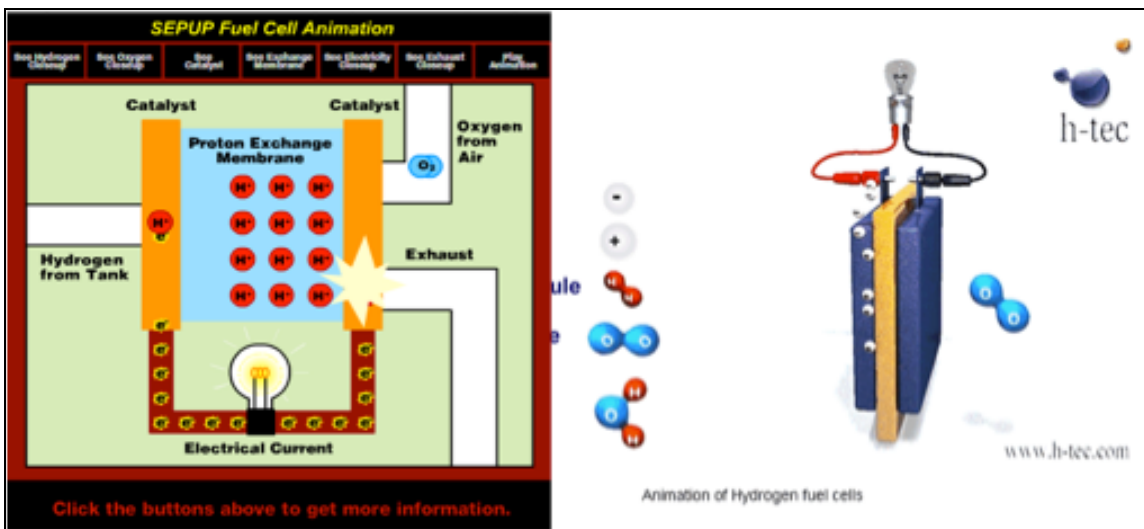


Figure 2.4. Screenshots of two visualizations used in Activity 3. Both visualizations illustrate how hydrogen and oxygen react inside hydrogen fuel cells and how the energy is transformed into electrical energy.

Activity 4 Can Hydrogen Fuel Cell Cars replace gasoline cars?

Students participate in an online discussion to solve a real-life issue: “*The Office of Transportation has been informed that a new type of fuel, hydrogen, is available. Officials are proposing to use hydrogen as fuel in all buses running in the county. Do you agree or disagree with this idea of replacing our current buses with hydrogen fuel cell buses? Explain your reasoning. Please make sure your reasoning should address at least*

three issues: molecular, safety & environment, and economic.” They need to apply what they learn about combustion reaction, and gasoline and hydrogen fuel cell cars to construct argument about the advantages of one car over another. In particular, the instruction of the discussion question requires them to consider concerns at the molecular and macroscopic levels, which promotes links among these ideas. This activity provides learners a chance to reflect and refine their understanding.

Hydrogen combustion Visualization

This dissertation focuses on helping students learn from the hydrogen combustion visualization embedded in Activity 2. The visualization shows how molecules and chemical bonds change during hydrogen combustion. It possesses potentials to: (a) distinguish the dynamics of chemical reactions from static ideas (Ben-Zvi et al., 1987; Krajcik, 1991); (b) link molecular and symbolic representations of bond breaking and formation; and (c) foster links with observable phenomena by connecting to a video of hydrogen combustion in a balloon that students see earlier in the project. Figure 2.5 shows a screenshot of the visualization.

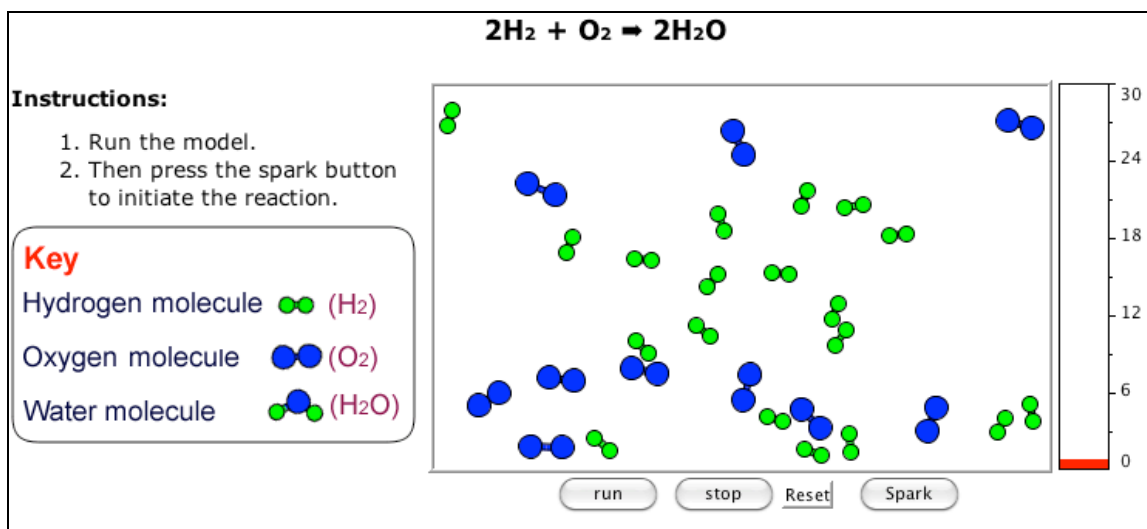


Figure 2.5. Screenshot of the hydrogen combustion visualization. Students explore how molecules and atoms react and how temperature changes during the reaction.

In particular, the hydrogen combustion visualization:

- demonstrates how chemical bonds break and form new bonds during hydrogen combustion. It is developed using the Molecular Workbench software (Xie & Tinker, 2006). Each run of the software calculates Newtonian approximations of inter-atomic forces to decide how and where atoms will move and bond.
- incorporates a temperature bar that demonstrates how temperature changes during the reaction;
- features a “spark” button to control the amount of energy provided to ignite the reaction. When clicking the spark button, students can observe bond breaking and formation during the reaction. Without clicking the spark button and providing

activation energy, students observe random movement of the molecules, but not bond breaking or formation.

- incorporates control buttons. Students can start, pause, and stop the visualization at any time and interact with it at their own pace.

By manipulating this highly descriptive visualization of hydrogen combustion, students have the opportunity to develop a deeper understanding of chemical reactions by linking ideas at molecular, symbolic, and observable levels.

Revisions of the Hydrogen Combustion Visualization

Original version of the hydrogen combustion visualization.

The hydrogen combustion visualization went through several times of refinements. Originally it was designed to promote student coherent understanding about chemical reactions by linking molecular reaction processes with energy diagram. Students had great challenges learning the energy diagram because it is abstract and confusing. Textbooks usually present the diagram at a symbolic level and do not emphasize how it is related to chemical reactions and observable phenomena. To help students improve their understanding by linking energy change with molecular movement, the original version of the hydrogen combustion visualization incorporates several parts and demonstrates synchronous changes in molecular movement, temperature, chemical potential energy and the energy diagram involved in hydrogen combustion (see Figure 2.6 for a screenshot).

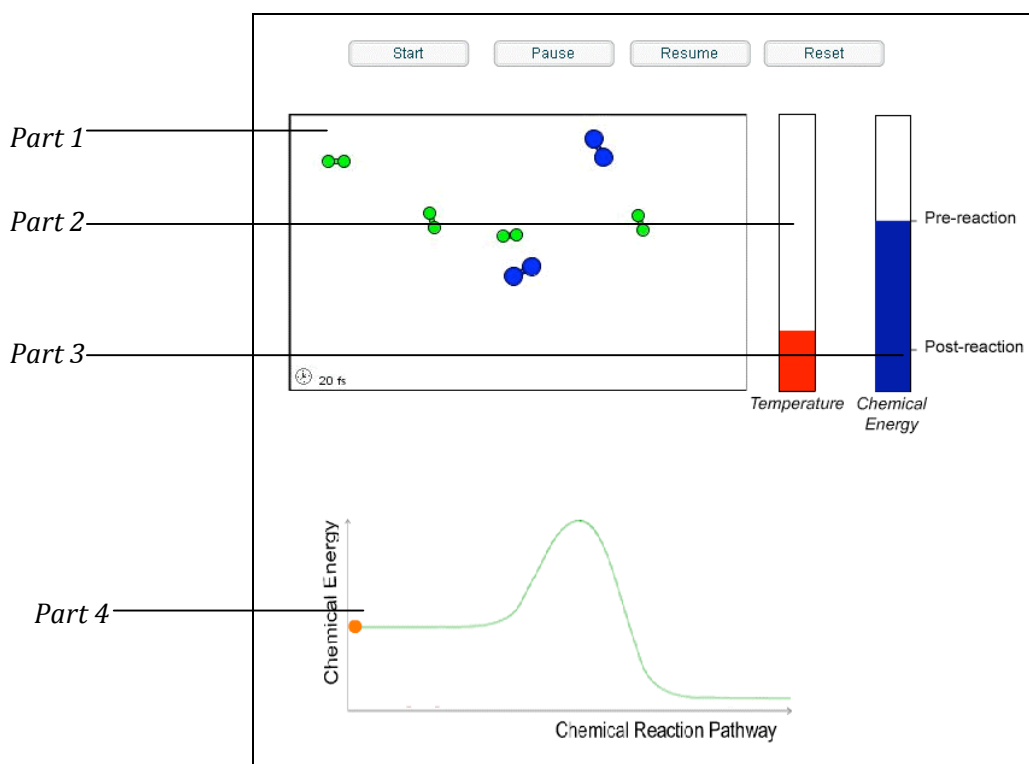


Figure 2.6. Screenshot of the original version of the hydrogen combustion visualization. It shows synchronous changes in molecular movement, temperature, chemical potential energy and the energy diagram involved in hydrogen combustion.

The original version was introduced in the HFC project in three phases with a series of visually linked simulations. Each phase was designed to help students add new ideas based on their previous views.

Phase 1: only the molecular movement (Part 1) and the dynamic temperature bar (Part 2) are represented. It shows how chemical bonds and temperature change during hydrogen combustion.

Phase 2: the chemical energy bar (Part 3) is added, illustrating changes in energy along the chemical reaction. Part 1, 2, and 3 are presented.

Phase 3: an energy diagram that features a dynamic orange dot (Part 4) is added. The orange dot moves along the diagram as the reaction takes place. It helps visually link molecular reaction processes with changes in energy levels as demonstrated in the diagram.

By adding new information at each phase, this visualization aims at helping students build normative connections between ideas about molecular movement and energy diagram.

Revision of the hydrogen combustion visualization.

The original version of the visualization was implemented in the spring semester of 2006. The result shows that while students made progress in understanding the energy diagram, they still found it challenging to link molecular-level ideas with energy change (Zhang, 2006, 2007). In particular, they often failed to integrate ideas about changes at the molecular level from the visualization. For instance, they did not notice bond breaking and formation and concluded that the visualization showed “*the molecules are moving and bouncing with each other.*” Some other students did not distinguish among new ideas and their prior knowledge and developed incorrect ideas. They explained that “*hydrogen molecules are the small green ones and oxygens are the big blue ones.*” The visualization (especially Part 1) seems to be “deceptively clear” to them. Without normative views about molecular reaction processes, students naturally experience difficulties linking it with the energy diagram. Therefore, how to better support students to integrate ideas about molecular reaction processes is a more urgent issue. Chapter 3 discusses the findings of implementing the original form of the visualization.

Based on student difficulties, I revised the visualization. To reduce the complexity of the visualization and focus student attention on molecular reaction processes, I eliminated the potential energy bar and the energy diagram. The revised version only includes Part 1 (showing bond breaking and formation during hydrogen combustion), the spark button (indicating activation energy), and the dynamic temperature bar (indicating released energy). By reducing these distracting features, I hope to draw students’ attention to molecular changes and support them to integrate these ideas with their repertoire. Another reason for removing the energy diagram is that many middle school teachers expressed interest in the HFC project and the energy diagram is not suitable for middle school students. Understanding how chemical bonds change during chemical reactions is a more appropriate learning goal for them.

Knowledge Integration Assessment and Scoring Rubrics

The design of assessments and scoring rubrics used in this dissertation were informed by the knowledge integration framework (Linn, Lee, Tinker, Husic, & Chiu, 2006). The assessments employed in this dissertation include pre and posttests, embedded questions, and instructional tasks such as drawing, critiques, and selections. All the assessments focused on examining whether students developed integrated understanding of chemical reactions by linking ideas at various levels. The pre and posttest include nine items (see Appendix B for the questions and scoring rubrics):

- two recognition items that ask students to select molecular representations for interim phases during hydrogen combustion;
- three critique items that require learners to critique pre-made drawings about how methane combustion takes place at the molecular level;
- two drawing and explanation questions that ask to draw and explain molecular processes during the reaction between nitrogen and hydrogen gas;
- two selection items that require students to select representations for interim phases during the reaction between hydrogen and chlorine gas.

Students need to explain their reasons in all questions. The recognition items aim to examine student understanding of hydrogen combustion. The other seven questions test knowledge transfer and measure whether students can apply their knowledge to new contexts and explain other chemical reactions. All items in the assessments went through several rounds of revisions after review from assessment experts, scientists and science educators. These questions are used in studies discussed in Chapter 4, 5, 6, and 7. The assessment adopted in Chapter 3 is discussed in that chapter respectively.

Assessments were scored based on the knowledge integration framework. The knowledge integration scores range from 0 to 4. These scores reward students for making complex links between ideas students demonstrate in their explanations. Higher knowledge integration scores indicate more complex connections between ideas. Previous research shows that the knowledge Integration scoring rubric, compared to coding schemes used in TIMSS (correct vs. incorrect or correct vs. partial vs. incorrect), provides a more precise and sensitive measure for the development of students' ideas in science (Linn et al., 2006). Table 2.2 shows one pre/post test item, the knowledge integration scoring rubric designed for this item, and student sample answers. The question asks students to identify the correct molecular representation of chemicals before hydrogen combustion begins. To score high, students need to correctly connect the symbolic and molecular representations.

In addition, student response to the embedded questions, their drawings, selections, and critiques generated during the HFC project were also coded using the knowledge integration framework. The design and scoring rubrics were discussed in each chapter respectively.

Table 2.2 Knowledge integration scoring rubric for one recognition item. The question asks students to select and explain pictures of molecules before hydrogen combustion starts.

Knowledge Integration Score	Description	Sample answers
4 Complex	Elaborate two or more scientifically valid links among hydrogen combustion reaction process, changes to chemical bonds, and energy.	<i>“Before heat is added the hydrogen atoms are connected, moving slowly. However, when the hydrogen gas begins to burn, the temperature increases causing the hydrogen atoms to break apart and move faster. Yet, we are not at that stage yet, so for now they are still connected.”</i>
3 Basic	Elaborate a scientifically valid link between hydrogen combustion reaction process and changes to chemical bonds.	<i>“the reaction hasn’t started, so the bonds between H₂ and O₂ are not broken yet. they are still hydrogen and oxygen molecules.”</i>
2 Partial	Have correct ideas about hydrogen combustion reaction process or changes to chemical bonds or energy change, but do not elaborate links between them.	<i>“no extra energy is added.”</i> <i>“both hydrogen and oxygen are found uncombined in nature, as are other elements.”</i>
1 Incorrect idea/link.	Have incorrect ideas about chemical reaction processes or changes to chemical bonds, or fails to make correct links between the two ideas.	<i>“they started with separated atoms.”</i>
0 No Answer or Off-task answer.	No answer at all. Or write some text, but it does not answer the question being answered.	<i>“I don’t know.”</i> <i>“I guessed.”</i>

Chapter 3: Examining the Effect of the Hydrogen Fuel Cell Cars Project

This chapter discusses the overall impact of Hydrogen Fuel Cell Cars project on promoting student coherent understanding of chemical reactions. High school students often fail to integrate their intuitive ideas about energy with underlying chemical principles of chemical bonding. To help them develop integrated understanding about chemical reactions, I designed the HFC project, which helps students connect ideas about atomic interactions to energy by exploring these ideas in the context of hydrogen fuel cell cars. This project features the original version of the hydrogen combustion with embedded prompts. The visualization demonstrates synchronous changes in molecular reaction processes and energy diagram, and the prompts were designed to encourage links among ideas.

This study focuses on investigating how a technology-enhanced inquiry project that embeds dynamic visualizations within knowledge integration patterns can enhance student learning of chemistry. The research questions addressed are:

1. What are the challenges in forming an integrated understanding of the energy diagram?
2. How do scaffolded visualizations improve student understanding of energy change during chemical reactions by building connections between ideas at observable, molecular, and symbolic levels?

This study compares student performance on the assessments before and after the project and their responses to embedded prompts. To foreshadow the results, the research found that students made significant gains in connecting ideas about chemical reactions after learning the HFC project. Students with all levels of prior knowledge benefited from the project. In particular, learners with lower prior knowledge achieved more learning gains than those who started with other levels of knowledge. Overall, this study illustrates the power of embedding dynamic visualizations in inquiry projects using proven knowledge integration principles.

Rationale

Energy Diagram and Student Learning Difficulties

Understanding energy change in chemical reactions is critical for chemistry learning. As required by the California Science Education Framework (2003), students should understand that *“The net heat released to or absorbed from the surroundings comes from the making and breaking chemical bonds during a reaction. Students understand and relate heat to the internal motion of the atoms and molecules.”* This standard requires learners to understand energy change by linking it with ideas at the molecular level (e.g., making and breaking chemical bonds) and observable level (e.g., net heat released to or absorbed from the surroundings). Students often find it challenging to relate with ideas at various levels and cannot form such an integrated understanding.

In high school textbooks, the topic of energy change in chemical reactions is usually taught with the energy diagram, which is used to determine and explain why some reactions can occur while other cannot (Wilbraham et al., 2000). The following shows two energy diagrams adopted by high school textbooks and curricular materials (Figure 3.1). The y-axis represents potential energy of the reaction system. It is typically

plotted for different reaction stages: reactants, transition states, and products. The x-axis represents the progression of the underlying chemical reaction. Energy diagrams are often used to determine whether a reaction releases or absorbs energy (by comparing the energy levels of reactants and products) and which reaction can take place more easily (by comparing the activation energy required by the reactions).

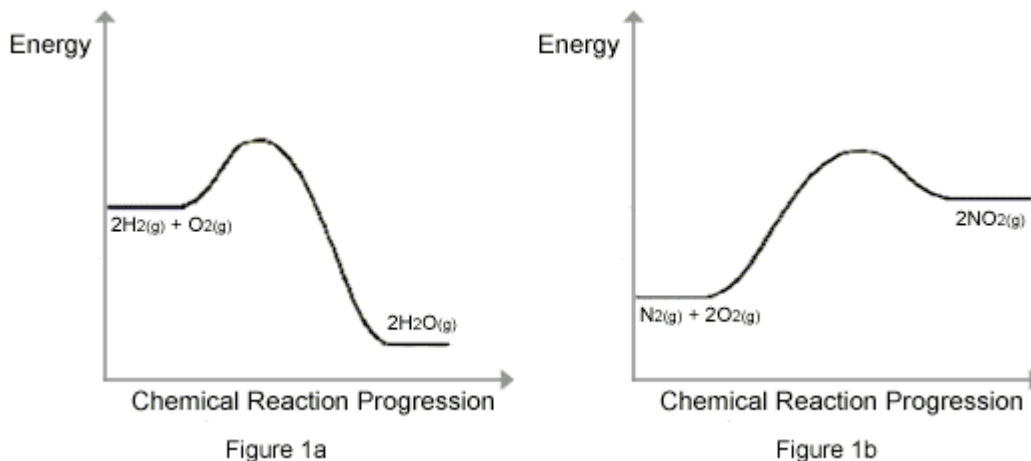


Figure 3.1. Two examples of typical energy diagrams used in high school chemistry textbook. Left: an energy diagram for the reaction of hydrogen gas and oxygen gas to produce water vapor. Right: an energy diagram for the reaction of nitrogen gas and oxygen gas to produce nitrogen dioxide gas.

Chemists argue that this model should be intuitive and obvious. For instance, they think that “hilly” nature of the diagram is supposed to be analogous to rolling a ball up a hill and allowing it to roll down. More specifically, this diagram is supposed to convey this idea: just like that it takes energy to roll a ball up a hill, it takes energy to reach the activated complex (the top of the hill). Once the reactants have reached the top of the hill, they will form the products because the products are at a lower energy, just as a ball will roll down a hill because the bottom of the hill is at a lower potential energy level.

Yet the topic of energy itself is abstract and complicated. Understanding energy change through the energy diagram makes students even more confused. Often they fail to integrate ideas about energy diagram to their repertoire or establish connections among ideas. Many factors contribute to this challenge:

First, the energy diagram is typically taught as a mathematics problem. It is difficult for students to realize the need to link it with relevant ideas about chemical reactions. Formal instructions often direct students to calculate the difference between energy levels of reactants and products (ΔH) to decide whether the reaction is endothermic or exothermic. Learners end up memorizing how to calculate ΔH . They do not feel the need to understand the diagram or connect with molecular-level of ideas about chemical reactions.

Second, this energy diagram captures different levels of chemistry knowledge, including the observable, molecular, and symbolic levels. To form a coherent understanding, one must understand how to interpret the representations incorporated in the diagram (symbolic) such as potential energy levels of reactants and products, activation energy, and underlying chemical reaction equations, how energy changes with

chemical bonds (molecular), and how the potential energy change relates to the surroundings (observable). An expert's understanding of the diagram also includes deeper macroscopic and microscopic knowledge, e.g., how bonding changes in the activated complex. While expert chemists can easily understand the interconnections among these levels, novices and students do not realize the complexity and fail to make correct connections between and within these levels (Kozma, 2000).

Third, most classroom instruction fails to take into account of the complexity of knowledge needed to understand the energy diagram. Chemistry textbooks present the energy diagram statically at a symbolic level and instructions do not emphasize other levels of chemistry knowledge. Teaching energy diagrams often ignores the fact that they are based on the corresponding chemical reactions and macroscopic phenomena. This approach neglects opportunities for students to integrate the diagram with previous chemistry knowledge. Thus it is very challenging for students to form a coherent understanding of the diagram.

Technology-enhanced curriculum materials can provide promising ways to solve this problem. For example, animations with coordinated changes at molecular and symbolic levels could support and strengthen connections between representations at the two levels. This could lead to better understanding and help students form conceptual connections.

Embedding Dynamic Visualization within the Knowledge Integration Framework

Scientists often rely on computationally rendered visualizations to make sense of unseen phenomena. Visualizations can help integrate ideas from the unseen processes and develop accurate explanations of observable phenomena. In recent years visualizations have begun to appear in educational contexts as a novel way to augment student learning (Barab, Hay, Barnett, & Keating, 2000; Pallant & Tinker, 2004). These visualizations can foster integrated thinking of chemistry by presenting coordinated changes at different levels (molecular, observable, and symbolic) (Ardac & Akaygun, 2004; Greenbowe, 1994; Xie & Tinker, 2006). For instance, a representation with synchronous changes in numbers of particles and molecular movement can better support students to understand balancing equations than static graphs (Chiu, 2005).

Despite the benefits, researchers warn that dynamic visualizations need to be carefully designed to ensure that they can help students make sense of the phenomena and link new ideas with prior knowledge (Boo & Watson, 2001). Otherwise, students may become overwhelmed trying to process visualizations and form superficial connections among ideas.

Instructions should provide guidance to encourage learners to develop links among ideas. For instance, Ardac and Akaygun (2004) found that for 8th graders, the effectiveness of a multimedia-based environment could be improved if instruction included additional prompting that required students to attend to the correspondence between different representations of the same phenomena. The study by Wu, Krajcik, and Soloway (2001) showed that 11th grade students demonstrated their preferences of certain types of representations and did not use all types of three-dimensional models interchangeably when using a computer software called *eChem*. Guidance was needed to support student learning of the models and linking underlying chemical concepts.

Design patterns based on the knowledge integration framework (Linn & Eylon, 2006) provide a promising way to guide student learning with visualizations. The

reflection pattern, for example, refers to embedding visualizations with prompts asking students about the roles of visualizations and connections between different levels of information represented. Situated within curricula, these prompts ask students explicit questions at specific times to help students integrate and refine their ideas. In the Web-based Inquiry Science Environment (WISE) project, Davis and Linn (2000) found that careful use of the *reflection* pattern increased students' integration of middle school science concepts. This synergistic combination of dynamic visualizations with scaffolding of embedded prompts can help students effectively use visualizations and assist students' development of robust understandings of chemistry.

This study investigates how an online science inquiry project that embeds dynamic visualizations within knowledge integration patterns and prompts impacts student understanding of the energy diagram and energy change during chemical reactions. A series of dynamic visualizations were employed to illustrate how energy changes during chemical reactions. The prompts were designed to encourage students to link ideas about molecular processes, observable phenomena, and energy diagram.

Hydrogen Fuel Cell Cars project

This inquiry-based project is situated within the context of hydrogen fuel cell cars, with a purpose to connect molecular processes with observable phenomena of energy change. By researching and comparing chemical reactions in gasoline-powered and hydrogen fuel cell cars, students gather information and build their own ideas on which type of cars are better and why. The inquiry process strengthens the establishment of conceptual connections with the energy diagram by linking everyday issues and underlying principles of chemical bonding. Detailed curricular activity sequence and design are described in Chapter 2.

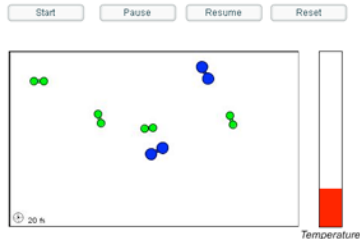
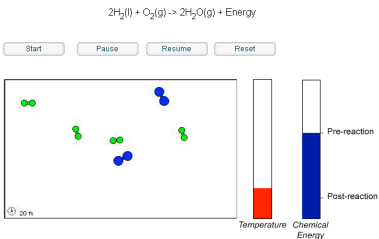
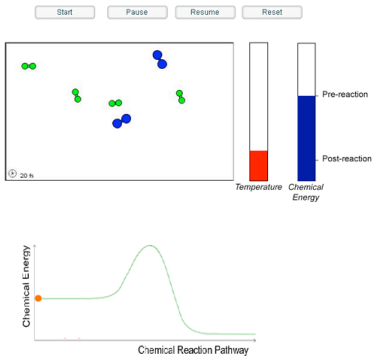
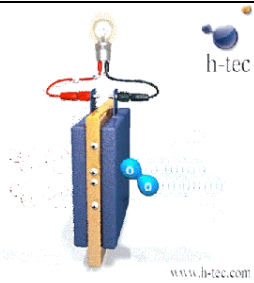
Embedding Hydrogen Combustion Visualizations

The visualization adopted in this study is the original version of the hydrogen combustion visualization. It is introduced in three phases with a series of visually linked simulations to help students build their understanding about energy and chemical reactions. In phase one, the visualization shows bond breaking, formation, and temperature change during hydrogen combustion. In phase two, the visualization adds a dynamic potential energy bar to demonstrate how potential energy changes during the reaction. In phase three, besides the molecular reaction processes, temperature bar, and potential energy bar, the visualization includes an energy diagram with an orange dot. The dot moves along the energy diagram with the molecular reaction processes to indicate how energy changes when bond breaking and formation take place.

Design patterns (Linn & Eylon, 2006) were adopted to scaffold student interaction with the visualization and to promote knowledge integration processes. Specifically, the *predict, observe and explain* and the *reflection* design patterns were employed before and after students encounter each phase of the simulations. Students need to predict outcomes of phenomena (articulating their existing ideas), observe and distinguish predictions from these new observations (adding new information to their repertoire, and forming criteria to compare and distinguish new and prior ideas), and formulate and explain connections between predicted and actual outcomes of the phenomena (refining and sorting out ideas). For instance, before students interact with phase three of the visualization, they need to predict what the energy diagram looks like and how energy changes when

molecules break bonds and form new bonds during hydrogen combustion. Students work with a worksheet to create their own representation of the energy diagram. After interacting with the visualization (phase three), they need to explain their observations by answering a prompt “*How does chemical energy change with chemical bond-breaking and formation?*” Such prompts can encourage students to scrutinize the visualization and integrate ideas about energy diagram by linking them with their prior knowledge about reaction processes. As another example, the *reflection* pattern was adopted after students explore the visualization showing how hydrogen and oxygen reacts inside hydrogen fuel cells. The prompt asks “*How does fuel cell make hydrogen combustion safe?*” To answer this question, learners need to reflect on their ideas about hydrogen combustion, compare and contrast with what they observe from the fuel cell visualization, and link this with personally relevant issues of car safety. This question prompts students to establish connections among ideas at molecular and observable levels. Table 3.1 shows screenshots of the visualizations used in this study and selected embedded prompts examined in this study.

Table 3.1 Screenshots of visualizations and selected embedded prompts to foster links among ideas.

Hydrogen combustion visualization			
Phases	Visualization content	Purpose of the visualization	Screenshot
1	Bond breaking and formation, temperature change during hydrogen combustion.	Recall students' prior knowledge about chemical bonding and molecular reaction processes involved in hydrogen combustion.	
Embedded Prompt 1: Describe how chemical bonds change during hydrogen combustion.			
2	Bond breaking and formation, temperature <i>and energy change</i> during hydrogen combustion. The energy change is shown in the dynamic energy bar.	Draw students' attention to the energy change during hydrogen combustion. Add the idea of energy change.	
Embedded Prompt 2: How does potential energy change during the reaction?			
3	Bond breaking and formation, temperature <i>and energy change</i> during hydrogen combustion. The energy change is demonstrated using two representations-energy bar and energy diagram.	Sort out ideas and establish links between energy diagram and molecular reaction processes.	
Embedded Prompt 3: How does chemical energy change with chemical bond breaking and formation?			
Hydrogen fuel cell visualization			
	Bond breaking and formation during the reaction between hydrogen and oxygen inside hydrogen fuel cells	Compare and contrast with bond breaking and formation demonstrated in the hydrogen combustion visualization. Foster links with everyday events.	
Embedded Prompt 4: How does fuel cell make hydrogen combustion safe?			

Methods

Participants

Two teachers from two public schools implemented the HFC project with 110 11th graders (seven regular chemistry classes). It was taught after students learned about bond breaking and formation and before any classroom instruction on the energy diagram.

One teacher (Ms. M) had more than twenty years of experience teaching high school chemistry and the other (Mr. W) had three years of experience. Ms. M had a lot of experience and expertise in teaching TELS lessons and other inquiry-based courses. Mr. W was a first-time user of TELS projects and he had never taught any inquiry-based classes before.

The TELS targeted professional development program supported both teachers (Varma, Husic, & Linn, 2008). An experienced TELS teacher mentor stayed the first day of the implementation in his class and supported the classroom management and student registration to the WISE website. The teachers selected pairs of students within each class to work through the entire project together, as typical in WISE projects.

Assessments and Scoring

Both teachers administered an online pretest to individual students two days before the unit began, and an online posttest the day immediately following the project. A comparison of pretest and posttest scores was used to assess overall gains due to student interaction with the curriculum unit. In addition, student responses to embedded prompts were examined in case studies to illustrate how students developed their understanding through the visualizations and prompts.

The pre and post-test consisted of the same seven items, each composed of choice and explanation parts (see Appendix A for all the questions). The explanation part required constructed response. These items were designed to test connections among ideas related to chemical reactions. Four questions asked students to connect the energy diagram with ideas of chemical reactions at the molecular and observable levels, and the rest three questions examined whether students can link to relevant concepts such as balancing equations and personally relevant issues such as fuel.

The assessment items were scored using the knowledge integration scoring rubrics (Linn et al., 2006). Higher knowledge integration scores indicated more complex connections among ideas and a more robust understanding of scientific concepts. I designed and discussed scoring rubrics with student sample answers with a large research group of over 10 researchers. These researchers scored the sample answers using the tentative rubrics and revised the rubrics until they all agreed. I coded all data to ensure the reliability.

Results and Discussions

Classroom Implementation

Both teachers successfully implemented the HFC project. They effectively supported student learning as they progressed through the unit. Both teachers frequently interacted with student pairs to clarify concepts introduced in the unit and to help students connect to their previous chemistry instruction. Students were very engaged in the unit

and discussed with each other about the content, the representations and their answers to embedded questions.

I also noticed that the embedded prompts helped most students explore and learn the visualizations and some learners still had difficulty sorting out information presented. They asked teachers what they were supposed to do with the visualizations and what purposes the visualizations served. Some students ran the hydrogen combustion visualization so fast that they did not notice any changes in chemical bonds. Some other students struggled to understand the hydrogen fuel cell car visualization because of the lack of physics knowledge. For instance, many students did not know the flow of electrons is electricity, and thus had difficulty understanding how energy is transformed to power hydrogen fuel cell cars. Further revisions of the project need to address these issues by adding supporting instructional activities and materials.

Overall Impact of the HFC Project

I compared student performance on the pre and post-test to determine the effect of the HFC project. Overall students made significant gains on all seven items [$t(109) = 13.03, p < .0001$]. This project was effective in promoting integrated understandings about energy change in chemical reactions. The mean posttest score was 21.17 with a maximum score of 32. Students on average established at least one normative link among ideas after the project. Some of them still struggled to develop connections between the energy diagram and relevant concepts and ideas.

Further analysis was carried out to understand the impact of prior knowledge on student learning. According to the mean and the standard deviation of pretest scores, students were divided into three groups with low, medium and high levels of prior knowledge (see Figure 3.2 for the distribution of students). Altogether 12 students had low level of prior knowledge before the project. Their pretest score ranged from 0 to 8, which indicates that most of them had irrelevant ideas about chemical reactions. Most students started the HFC project with medium level of knowledge ($n=81, 74\%$). Their pretest score ranged from 9 to 19. Often they had one normative idea about chemical reaction processes or energy change. Yet the idea was isolated and they did not link it with ideas at other levels. There were 17 students who held high prior knowledge on the pretest. They had correct ideas before the project. Some of them were even able to establish one link among them.

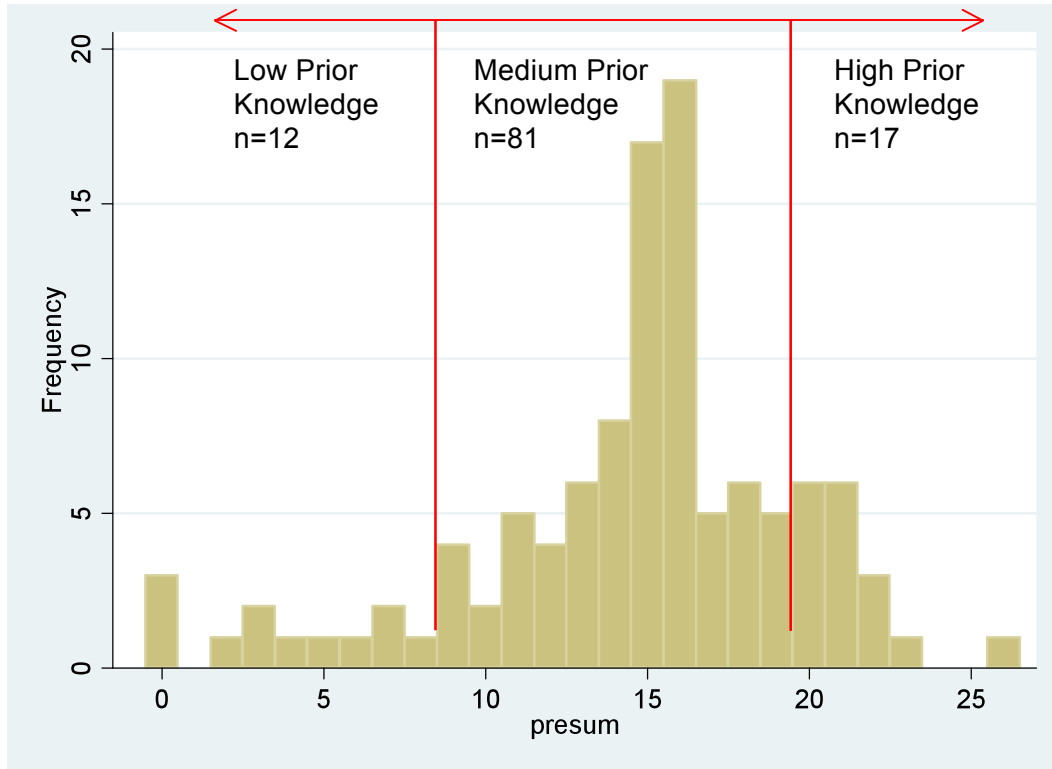


Figure 3.2. Distribution of pretest scores. Score ranges: Low Prior knowledge: 0-8; Medium Prior Knowledge:9-19; High Prior knowledge: 20-26

The pre and post-test means of students with each level of prior knowledge were compared and the effect sizes were calculated (see Table 3.2). The results show that students with different prior knowledge all significantly improved their understanding [High: $t(16)=5.45, p<.0001$; Medium: $t(80)=12.78, p<.0001$; Low: $t(11)=10.57, p<.0001$]. In particular, students who had low prior knowledge on average made the largest learning gains. On the posttest, they achieved similar performance as those who started with medium levels of knowledge. They were able to articulate at least two ideas and establish normative links among them. These findings confirmed that the curricular project that embeds dynamic visualizations within knowledge integration patterns successfully helped the knowledge integration of all participants.

Table 3.2. Means, standard deviations, and effect sizes of pre and posttest scores of all students and students with high, medium and low prior knowledge.

	Students (N)	Pretest		Posttest		Effect Size
		M	SD	M	SD	
Low	12	3.75	2.90	20	5.05	3.05*
Medium	81	14.77	2.53	20.57	3.74	1.42*
High	17	21.24	1.52	24.88	3.02	1.32*
All	110	14.56	5.07	21.17	4.09	1.24*

Note: * $p<.0001$.

Pre and Post-test Item Analysis

Next, I report the data analysis of each individual pretest and posttest item. These items were designed to examine students' knowledge integration from four aspects:

- linking energy diagram with ideas about chemical reactions at the observable level,
- linking energy diagram with ideas about chemical reactions at the molecular level,
- linking idea of energy change in chemical reactions to personally relevant issues,
- linking with other chemistry concepts (e.g., balancing equations).

Table 3.3 presents mean scores, standard deviations, and effect sizes for all the seven pre/posttest items. This section discusses student performance on each item, diagnosing student problems, and possible links to visualizations used in the HFC project.

Table 3.3. Mean scores, standard deviations, and effect sizes of all seven pre/posttest items.

Item	Group	Pretest		Posttest		Effect Size
		M	SD	M	SD	
<u>Connections between energy diagram and molecular reaction processes</u>						
R1	Low	.67	.89	2.75	1.14	1.68*
	Medium	2.44	.74	2.99	.89	.53*
	High	3.12	.49	3.59	.62	.63**
	All	2.35	.96	3.06	.90	.64*
R2	Low	.50	1	2.83	1.27	1.63*
	Medium	2.40	.88	3.07	.85	.66*
	High	3.24	.44	3.82	.39	1.16*
	All	2.32	1.09	3.16	.89	.74*
<u>Connections between energy diagram and observable phenomena</u>						
R3	Low	.67	.98	2.17	.83	1.21*
	Medium	2.19	.55	2.51	.61	.44*
	High	2.65	.61	3.18	.73	.66**
	All	2.09	.81	2.57	.71	.55*
R4	Low	0	0	2	1.04	1.91*
	Medium	1.60	.91	2.42	.85	.67*
	High	2.41	.80	3.11	.99	.67**
	All	1.55	1.04	2.48	.94	.76*
<u>Connections between energy change and personally relevant issues</u>						
A1	All	1.77	1.11	2.6	.96	.65*
A2	All	2.65	.92	3.39	.73	.66*
<u>Connections with the concept of balancing equation</u>						
C1	All	1.83	1.56	3.91	1.07	1.07*

Note: * $p < .0001$; ** $p < .01$

Connections between energy diagram and molecular reaction processes.

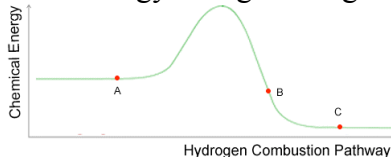
Two questions (R1 and R2) were designed to test whether students can link energy diagram with reaction processes involved in chemical reactions. Students were asked to identify molecular representations of two points in the energy diagram: R1 tested the molecular movement before the reaction (hydrogen combustion), and R2 examined the molecular movement after the reaction is completed. In order to answer these questions correctly, students must comprehend the energy diagram (symbolic representation) and link it to molecular movement at different phases during hydrogen combustion.

Paired t-tests show that all students made significant progress in answering the two items [R1: $t(109) = 6.6903, p < .0001$; R2: $t(109) = 7.7587, p < .0001$]. I also conducted paired t-test on the three groups with different prior knowledge (See Table 3.3). For both items, students with low prior knowledge made relatively greater progress in making connections between the energy diagram and molecular movement. On the pretest, they often had no idea about the diagram or molecular movement. On the posttest, they advanced to correct ideas of at least one level. With regard to students with medium prior knowledge, on average they started with incorrect ideas and ended up with correct understandings about the molecular movement or the diagram. Many of them were able to add one additional idea in their answers to the posttest. For the group with high prior knowledge, they responded with one or two more successful links among ideas on the posttest. These results reflected that all participants made progress in developing and articulating specific connections between the energy diagram and molecular-level ideas.

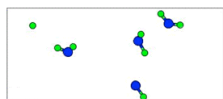
Take the question R1 as an example. On the pretest, some students were able to describe different molecular movement shown in multiple choices. However, they could not establish or explain the connections between the energy diagram and changes at an atomic level. On the posttest, more students successfully articulated connections between ideas at the two levels. Student EM, for instance, identified the energy level of Point A and incorrectly connected to molecular movement on the pretest. He answered the posttest by adding the idea of reaction process to his interpretation of the energy diagram and correctly connected to the corresponding molecular movement at Point A. Table 3.4 displayed student sample responses to this item.

Table 3.4. Student sample responses to pretest and posttest Item R1.

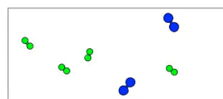
R1: The following diagram shows energy change during H₂ combustion.



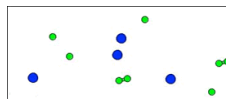
The following pictures are snapshots of molecular movement at different time during the reaction. Which snapshot shows the movement of molecules at **Point A**? Explain your answer.



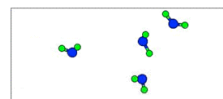
(1)



(2)



(3)



(4)

Student	Pretest (score in parentheses)	Posttest
EM	<i>"I chose 2 because the energy is low, and molecules are resting."</i> (2)	<i>"I chose 2 because the hydrogen and oxygen molecules are just hanging out and doing nothing. They are in the process before the reaction process. In 3 they are starting to separate so they can react."</i> (4)
AG	<i>"I chose 2 because they do not look as active."</i> (2)	<i>"(2) because they have less energy"</i> (2)
CT	<i>"I chose 4 because all of the water molecules are together."</i> (2)	<i>"2 because the atoms are still connected to each other."</i> (3)
EL	<i>"I chose (1), because in point a the reactants are not reacting."</i> (3)	<i>"(2) because the molecules have not bonded yet."</i> (3)

Link to visualizations.

Students' improved performance in these two items may result from the hydrogen combustion visualization (phase three) used in Activity 2 of the project. The visualization illustrates how energy changes (as represented in the energy diagram) with chemical reactions at the molecular level. To help students develop connections, the embedded questions divided the diagram into four parts (see Figure 3.3 for a screenshot of the questions), and required students to identify states during hydrogen combustion, observe molecular movement, and scrutinize how energy changes from one state to another. Students' gains from the pretest to posttest confirmed that students acquired new information from the visualization and these questions provided guidance to help them add new ideas, reconcile conflicts, and sort out ideas. The scaffolded visualization combined with questions supported students to articulate connections between energy diagram and molecular reaction processes.

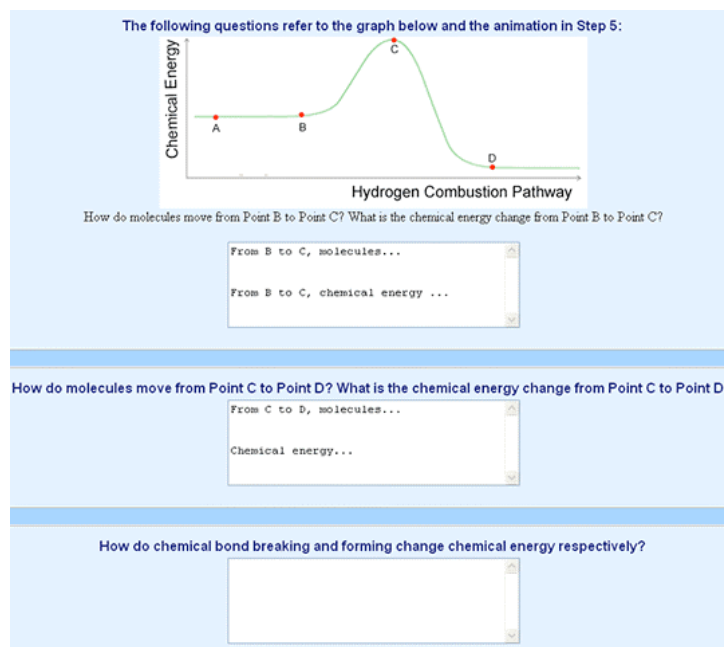


Figure 3.3. Screenshot of embedded questions to scaffold student learning with the hydrogen combustion visualization.

Connections between energy diagram and observable phenomena.

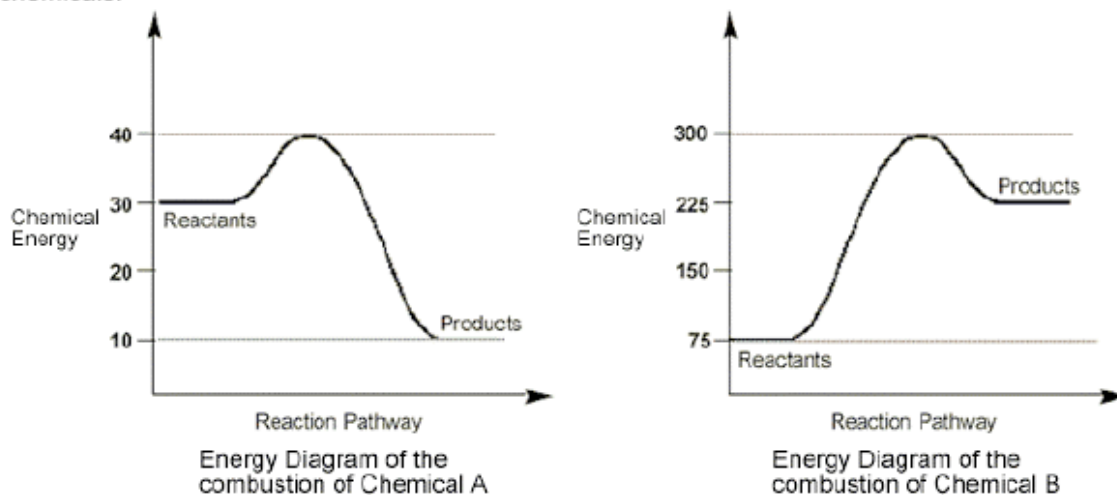
Items R3 and R4 examined whether students could establish connections between energy diagram and observable phenomena. Students made progress in answering these items [R3: $t(109) = 5.71, p < .0001$; R4: $t(109) = 7.94, p < .0001$]. They had a mean pretest score less than 2.0 (no normative ideas at all) and achieved a mean posttest score of 2.5. This result suggests that after the HFC project, most students had one correct idea but could not form any correct links between everyday phenomena and the energy diagram.

To identify students' difficulties in forming connections between the two levels, I analyzed existing ideas student had on the pretest, and compared with their answers on the posttest. A case study is provided with student sample answers from the pretest to the posttest to explain what problems students had in linking energy diagram with everyday phenomena.

Diagnosing students' problems for R3.

R3 provides students two energy diagrams (one for an endothermic reaction and the other one for an exothermic one) and asks them to decide which reaction can be used to power a lawn mower (see Figure 3.4 for the question). To score high, learners need to integrate ideas about macroscopic phenomena (powering lawn mowers requires extra energy) with the energy diagram (distinguishing energy diagrams of exothermic and endothermic reactions). Most students had incorrect ideas on the pretest (Mean=2.09) and progressed to some correct ideas on the posttest (Mean=2.57). Yet the average posttest score was low and few students made successful links between these ideas.

3. You are looking at two new chemicals, A and B, to power a new type of lawn mower. The following diagrams show energy change during the combustion of each of these chemicals.



In terms of energy, which chemical could be used as fuel? Circle all that apply.

A

B

Explain your answer.

Figure 3.4. Pre and post-test item R3.

Categorizing student alternative ideas.

To elucidate the obstacles for students to establish links between ideas in R3, I analyzed students' incorrect answers (scored as 2) on the pretest and compared with their posttest responses. First, I categorized these incorrect answers on the pretest. Students' non-normative ideas were divided into three categories: alternative ideas about the energy diagram, alternative ideas about observable phenomena, and non-normative links between energy diagram and concepts of endothermic and exothermic reactions. Table 3.5 summarizes these categories with student sample responses. Before the project, a majority of students were not able to establish normative connections between the energy diagram and observable phenomena. They could not distinguish energy diagrams for exothermic and endothermic reactions. For instance, one student chose B and explained that *"The energy of the products in graph B (an endothermic reaction) is higher than that of the reactants which means that it creates enough energy to power something."* Instead of using the difference between energy levels of reactants and products (ΔH) to decide whether the reaction is endothermic or exothermic, he believed that all reactions were exothermic and the energy level of the products was the ΔH . His explanation indicates a wrong link between energy diagram and the concept of endothermic and exothermic.

Table 3.5. Categorization of students' alternative ideas to R3 on the pretest.

Category	Description	Sample answers
2a n=13	Incorrect ideas about the energy diagram (understanding the Y-axis as the amount of reactants and products, instead of energy levels of reactants and products)	“Diagram b starts with a low amount of reactants but when it ends up, a lot of products.”
2b n=53	Incorrect connections between the energy diagram and concepts of endothermic and exothermic reactions (unable to distinguish energy diagrams for exothermic and endothermic reactions)	“The energy of the products in graph B is higher than that of the reacts which means that it creates enough energy to power something.”
2c n=5	Incorrect ideas about observable phenomena	“Both can be used, since as long as they are burned inside, the machine can work.”

Examining the performance of students with similar ideas.

Next, I compared these students' performance on the posttest. Figure 3.5 shows the average pretest and posttest scores of these students. After the project, students in all groups made progress in their answers. However, students who could not establish correct connections between energy diagram and exothermic and endothermic reactions made the least gains. Many students with incorrect connections on the pretest still failed to form normative connections among ideas on the posttest.

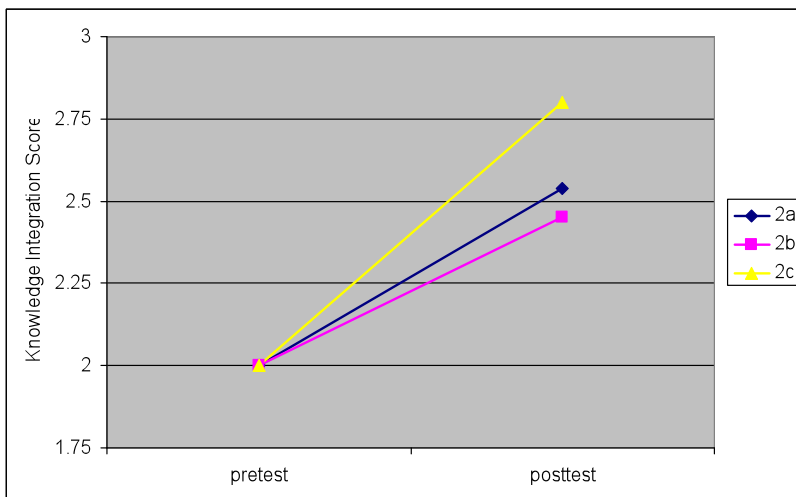


Figure 3.5 Pretest and posttest scores for students who demonstrated incorrect ideas in their answers to R3 on the pretest.

Take student BM's posttest answer as an example, “*Chemical could be used as fuel because the product remains constant in the end. Also, the chemical energy is high so it gives off more energy to power a machine, therefore making it a better fuel than*

chemical A.” BM’s answer was a typical response in the posttest. He demonstrated one correct idea that extra energy was needed. He probably also drew on another existing idea that “higher means more” based on previous experience (p-prim, diSessa 1993). However, when he integrated new ideas of energy diagram with the existing idea, he formed a connection as “higher ending level of energy means more energy released.” The normative link should be “the bigger the difference is, the more energy released or absorbed.” By retaining the intuitive idea and the non-normative connection, he thought that the reaction in the diagram could supply energy to the fuel so that the fuel could potentially provide energy to power a lawn mower. He couldn’t correctly link the chemical reaction depicted in the diagram with the chemical reaction to power a lawn mower. Considering the fact that many students (n=57) were in this group, this may explain why students on average did not make much progress in integrating ideas for this item.

Link to visualizations and suggestions.

The results showed that students’ understanding of the energy diagram was limited in the sense that it was only applicable to the context of cars. When trying to solve problems in a new context (lawn mower), students encountered problems. One conjecture of students’ problems was that their interpretation of the diagram was based on the representation (or symbolic) level and they did not develop connections with underlying concepts of bond breaking and formation. Without integrating ideas about atomic interactions with energy change (that breaking bonds requires energy and forming bonds releases energy), learners could not develop coherent understanding of the energy diagram. Thus, they had difficulties identifying different types of reactions from the diagram and linking with corresponding observable phenomena. The hydrogen combustion visualization was designed to foster links among these ideas. Yet the result suggests that some students still failed to integrate ideas about bond breaking and formation using the visualization. The revision of the project and the visualization should include activities to promote the integration of ideas at the molecular level.

Diagnosing students’ problems for R4.

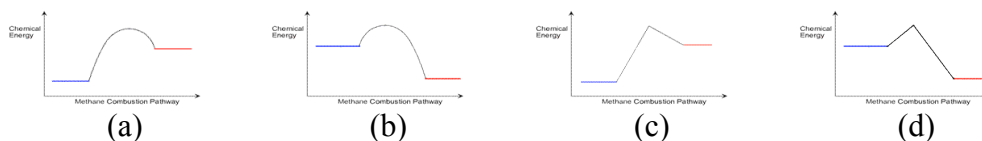
In R4, students were exposed to a scenario question: scientists want to use methane combustion to power cars (the question presents the reaction equation of methane combustion). Learners need to choose an energy diagram that is appropriate to power cars. Table 3.6 presents the question, and student sample answers with knowledge integration scores.

Two possible connections could respectively lead to answers scored as 4 in R4: (a) connection between energy diagram and ideas from everyday life (using methane combustion to provide energy). From the fact that methane combustion could power cars, students could conclude that methane combustion must be an exothermic reaction and release energy, and then link with the appropriate energy diagram. (b) connection between energy diagram and chemical reaction equation. The reaction equation of methane combustion as presented in the question includes energy as one of the products, which indicates that the reaction releases energy and the products are at lower energy level than reactants. Using the link between the two symbolic representations, students can make correct selections and explanations. An answer scored 5 needs learners to explain why the energy diagram was a smooth curve instead of a linear line. Besides the

links required in an answer of 4, students need to connect with other concepts such as chain reaction and the fact that the energy diagram is based on statistical, not individual behavior.

Table 3.6. Student sample responses to pretest and posttest R4.

R4: A scientist wants to use natural gas- methane (CH_4) to run cars. The equation of methane combustion is $\text{CH}_4 + \text{O}_2 \rightarrow \text{CO}_2 + \text{H}_2\text{O} + \text{energy}$. Which of the following graphs shows the energy change in methane combustion? Explain your answer.



Student	Pretest (score in parentheses)	Posttest
KB	“(b) The combustion path goes from a steady pace to low.” (3)	“(b) First, it is exothermic because the reactions need to run the cars release energy, so the energy should be from the higher level to the lower level.” (4)
SC	“(a) (c) because energy is risen when using it after a while.” (2)	“(a) (c) both of these graphs show the methane from when it is started and to after when the reaction has already been taken place and how high the rate of methane is after the reaction has taken place.” (2)
LB	“(d) Because energy is absorbed in engine combustion.” (3)	“(b) I think it is figure two because you start out with CH_4 and O_2 and then you get CO_2 , H_2O and energy. so the chemical energy will be lower as a result.” (4)

Students had similar performance on R4 as on R3. They on average started with incorrect or irrelevant ideas on the pretest (Mean=1.55) and advanced to one correct idea but no links on the posttest (Mean=2.48).

To understand why students had challenges making connections, I performed similar analysis on student responses to R4 on the pretest and posttest as on student answers to R3. The results reveal that many students answered R4 using the same wrong connection as in R3-“higher ending level of energy means more energy released.” To improve their understanding, students need to integrate ideas of molecular reaction processes with their prior knowledge.

Another finding is that among the students who demonstrated valid links on the posttest, they often answered R4 using the first connection noted above. Very few used the second connection. This indicates that compared with linking energy diagram with observable phenomena, establishing connections between two types of symbolic representations (energy diagram and chemical reaction equation) is more challenging to students.

To sum up, student performance on R3 and R4 shows that they had difficulties in applying ideas about energy diagram to decide endothermic and exothermic reactions. One explanation is that their understanding about energy diagram, endothermic, and exothermic reactions is not connected with atomic interactions. Without links with ideas about bond breaking and formation, students cannot develop deep understanding of how and why energy changes during chemical reactions, and thus cannot establish normative links between energy diagram and the ideas of endothermic and exothermic reactions. Adding new contents to emphasize molecular-level ideas can foster connections among various ideas related to chemical reactions. Students could apply the links to solve everyday events.

Connections between energy change and personally relevant issues.

Two questions (A1 and A2) examined whether students could abstract and apply energy concepts to personally relevant issues. A1 asked students the necessary requirements for fuels. A2 asked learners to explain the advantages of hydrogen fuel cell cars over gasoline cars. Both questions required learners to abstract ideas they learned in the project and relate to everyday events such as fuels, global warming, and greenhouse gases.

Students made great progress in linking energy concepts with personally relevant events [A1: $t(109) = 6.76, p < .0001$; A2: $t(109) = 6.89, p < .0001$]. On the pretest, they often explained ideas about fuels and cars based on their previous experience, and could not link with the idea of energy. On the posttest, many students were able to establish links between energy and everyday issues. They explained how the combustion of fuels is used to power cars, how energy is transformed in cars, and why hydrogen fuel cell cars is more environmentally friendly than gasoline cars (different products of the reactions). The improvement may be a result from the discussion at the end of the project. Students discussed the pros and cons of gasoline powered cars and hydrogen fuel cell cars in the discussion, which offers chances for students to reflect and refine connections between energy concepts with everyday events of cars, safety, environment, and economics.

Connections with the concept of balancing equation.

Item C1 asked students to write down balanced equations of the reaction that takes place inside hydrogen fuel cells. Students need to link ideas about chemical reactions with balancing equations. The results demonstrated that students have made apparent progress in linking the two concepts, [$t(109) = 11.25, p < .0001$]. See Table 3.3 for the mean scores, standard deviations, and effect size.

Case Studies

In this section, I we purposely selected three pairs of students' responses to embedded prompts to capture how the scaffolded visualization supported students to establish connections among ideas at different levels. To provide the range of different kinds of connections students make using embedded prompts and visualizations (see Table 3.1 for the prompts and visualizations), the three pairs were selected based on pretest and posttest achievement scores. Pair 1 scored equal to or a little above the class average on the pretest, with big gains on the posttest, Pair 2 scored below the class average on the pretest with little or no increase on the posttest, and Pair 3 scored below the average on the pretest, with moderate gains on the posttest.

Pair 1: AE and DS.

Both AE and DS scored the class average on the pretest (pretest scores: AE: 16 and DS: 15). Their answers to Prompt 1, 2, and 3 demonstrated strong connections from molecular reaction processes to ideas about energy diagram. For example, when asked about how energy changes with chemical bonding (Prompt 3), they responded, *“To break these bonds, we need energy, but once they reach the activation complex, it starts releasing energy, because new bonds in H₂O are formed.”* This suggests that by interacting with the hydrogen combustion visualization, they developed normative links among ideas about energy change, bond breaking, and formation.

Their answers to Prompt 4 suggest links between ideas of bond breaking and formation and observable phenomena. Prompt 4 asks how fuel cell makes hydrogen combustion safe. The purpose is to have students compare two different atomic interactions demonstrated in the hydrogen combustion and the hydrogen fuel cell visualizations and relate to everyday ideas such as the energy is transformed into electrical energy to run hydrogen fuel cell cars. Student pair 1 explained that *“Fuel cells make the hydrogen combustion safe by allowing the hydrogen to flow through without having a spark to ignite the reaction. There is no spark in fuel cells, so there won’t be explosions.”* Their response shows that they made sense of the two visualizations at molecular levels, realized different reaction pathways in the visualizations, and related the difference to everyday issues as the safety of cars. This suggests that they have formed connections between molecular and macroscopic ideas.

Both AE and DS improved their performance from pretest to posttest (posttest scores: AE: 26 and DS: 23). They connected the energy diagram with molecular reaction processes and personally relevant issues. Take AE’s performance on question R1 as an example. On the pretest, although he selected the correct representation to represent molecules before the hydrogen combustion starts, he explained with incorrect ideas, *“because they are resting.”* On the posttest, he still selected the correct picture but explained as *“because the hydrogen and oxygen molecules are still in their natural state. They are not broken bonds yet, though they will after a spark is added.”* This explanation demonstrates normative connections between energy and molecular reaction processes. The scaffolded visualizations with embedded prompts have helped AE and DS integrate new ideas about energy change and chemical reactions into their repertoire.

Pair 2: CM and WL.

CM and WL scored below the class average on the pretest (12 and 13, respectively) and made very little gains on the posttest (15 and 14, respectively). Both remained under the class average on the posttest.

Their answers to the prompts indicate no connections or superficial connections from the visualizations to underlying chemical concepts. For instance, they explained why hydrogen fuel cells make the reaction safe because *“by keeping them in a confined area”* (Prompt 4). This answer suggests wrong connections between the space of reaction and safety issues of cars. They may gain the idea from previous experience *“the more confined area it is, the safer it is.”* They made connections based on the sizes of molecule containers in the visualizations. A correct connection would be that the more confined an area is, the more dangerous hydrogen combustion will be. The pair failed to integrate ideas at the molecular level (that the two visualizations show reactions occurring in

different pathways, and that the reaction in fuel cells takes place more slowly and therefore is safer). The prompts did not help CM and WL make robust connections with ideas underlying the visualizations. Instead, they added incorrect information from this visualization into their repertoire.

CM and WL's failure to make connections may result from their low prior knowledge as well. Considering their low pretest scores, they may not have adequate chemistry knowledge to make sense of the visualizations and the scaffolding could not help add, refine and sort their ideas.

Pair 3: AK and MZ.

AK and MZ scored well below the class average in the pretest (9 and 13, respectively) and progressed to class average in the posttest (20 and 21). Their answers to R3 from pretest to posttest show improvement in making connections among ideas. Take AK's answers as an example. On the pretest, he selected the correct diagram and explained that *"the car is going to be releasing energy because the reactants is greater than the products."* AK's explanation shows that he had non-normative ideas about the energy diagram (understanding the Y-axis as the amount of reactants and products). His answer was classified as Category 2a, Table 3.5. On the posttest, he explained *"In terms of energy release, diagram A is the one in which an exothermic reaction occurs in which energy is released in the reaction. B puts out more products and A takes less energy."* His answer demonstrates mixed ideas. On one hand, he understood what is exothermic reaction. On the other hand, his interpretation of the Y-axis seemed to be a mixture of the energy levels and the amount of reactants and products. His understanding is not stable in terms of jumping back and forth between the two different ways to comprehend the Y-axis. The connection he made between energy diagram and exothermic reaction, therefore, is not robust, either. This indicates that AK is in the process of establishing criteria of distinguishing ideas between new information and previous ideas and trying to sort out normative ideas and links.

AK and MZ's progress is also reflected in their answers to embedded prompts. Their answers demonstrate correct links among various ideas about chemical reactions and energy, however, these links are still weak and incomplete. Their answers to Prompt 1, 2, and 3 show that they noticed different speeds of molecules and corresponding energy change from the visualization. For instance, they explained that during hydrogen combustion *"the molecules are moving and bouncing with each other, hydrogens move faster and oxygens move slower"* (answer to Prompt 1).

Yet they ignored bond breaking and formation and did not mention them at all. Then in Prompt 4, they explained hydrogen fuel cells are safe *"by allowing the hydrogen to flow through without having a spark to ignite the reaction. The reaction in fuel cells is different from the hydrogen combustion in the air because there is no direct contact between the hydrogen and oxygen."* Their response indicates that they have attempted to relate the new information from visualizations to the issue of car safety. However, their links are still based on the surface phenomena such as direct contact or the spark they have observed in the visualizations. Without the purport from ideas at the molecular level, these connections are weak and may disappear in another visualization without such features. If the curriculum could further support AK and MZ to add more ideas about atomic interactions, these connections are mostly possible to become robust. This pair can be viewed as a case that illustrates the progression of building connections-

starting from superficial phenomena, adding more ideas from underlying mechanisms, and finally ending up with a strong one.

Looking across the three pairs, Pair 1 were able to use the embedded prompts to make connections from the visualizations to relevant concepts and have gained increase in their scores from pretest and posttest. For Pair 2, the scaffolding did not help them integrate their ideas and they did not improve their understanding of energy change in chemical reactions. For Pair 3, the scaffolding and embedded questions did help them incorporate new ideas into their explanations, and they have achieved a better understanding of energy changes in chemical reactions. But the connections were still incomplete and ignore underlying chemistry. They need to add more in-depth chemistry ideas to support these connections.

Conclusion

This chapter discusses how an inquiry-based curricular project that embeds dynamic visualizations with design patterns can support students to develop coherent understanding of chemical reactions and energy by linking ideas at observable, molecular, and symbolic levels. I analyzed student performance on the pretest, posttest, and embedded prompts. Overall, students improved their understanding after learning the HFC project. The instructional prompts that were designed using the knowledge integration framework helped students integrate new ideas from the visualization into their repertoire. In addition, I also used three student pairs to exemplify students who were at different stages of knowledge integration: those who successfully linked ideas, those who failed to link ideas, and those who were in the progress of linking ideas.

Analyzing student performance on each assessment item reveals that students made the least gains in linking energy diagram with endothermic and exothermic reactions. Further analysis shows that students may have an existing idea “higher means more” from previous experience. They cannot reconcile the conflicts between the old idea and the normative way to interpret energy diagrams. They end up with an incorrect connection as “higher ending level of energy means more energy released.” One reason of this difficulty is that students did not link energy diagram with ideas at the molecular level. They understood the energy diagram as an isolated representation and did not link with underlying mechanism such as how bond breaking and formation change energy. Without integrating ideas at the molecular level, learners cannot establish coherent understanding about energy change in chemical reactions. Neither can they formulate normative explanations for endothermic and exothermic reactions.

Implications for Instruction

The findings of this study resonate with claims that technology-enhanced instruction can help students integrate ideas with dynamic visualizations. They confirm the effectiveness of designing instructions that embed dynamic visualizations within knowledge integration patterns.

The results also illustrate the complexity of designing visualizations and instructions. After learning with the hydrogen combustion visualization, some students still ignored important details (bond breaking and formation) and fail to integrate these key ideas. Future revisions of the HFC project and the hydrogen combustion visualization should consider how to support students to integrate ideas at the molecular level into their

repertoire. In the next chapter, I will discuss how a generative activity-generating drawings can help solve this problem and encourage students to integrate ideas.

Chapter 4: Can Generating Drawings Enhance Learning with Dynamic Visualizations?

This chapter discusses the impact of asking students to generate drawings of their ideas about chemical reactions on integrated understanding. Last chapter suggests the benefits of embedding dynamic visualizations within an inquiry-based project with prompts. Learners integrated ideas about energy using the hydrogen combustion visualization and linked them with personally relevant events. However, some students had difficulties integrating ideas about chemical reactions at the molecular level such as bond breaking and formation. They could not establish connections with other ideas.

In this chapter, I designed a generative activity in an attempt to solve this problem. After interacting with the hydrogen combustion visualization, students were asked to draw and explain their ideas about how the reaction takes place at the molecular level. Generating drawings about reaction processes can help focus student attention on the crucial disciplinary knowledge that they need to learn from the visualization. Students were expected to make careful observations of the visualization, add ideas about bond breaking and formation, distinguish with their old views, and connect with other ideas in the repertoire.

To determine the value of the generative activity, I compared the learning of students in the generation group with that of an interaction group. Students in the interaction group were instructed to spend more time interacting with the visualization. I asked them to observe how chemical bonds change during hydrogen combustion and explain the reaction processes. I compared their pre and posttest performance and examined the drawings and explanations they created during the project. The research questions are:

- What are the advantages of generating drawings versus interaction on supporting students to integrate molecular-level ideas from the hydrogen combustion visualization?
- What is the impact of generating drawings on students with different prior knowledge?
- How does generating drawings help contribute to integrated understanding?

To foreshadow the results, this research found that learners in the generation group integrated more ideas about chemical reactions and made more precise interpretations of the visualization than those in the interaction group. Analyzing student drawings and explanations shows that generation motivated students to interpret the visualization more carefully and led to more productive explanations about ideas represented in the dynamic visualization. In contrast, students in the interaction group were less successful in linking the visualization to underlying concepts and observable phenomena and wrote less detailed explanations. Generating drawings is a promising way to help students interpret complex visualizations and integrate information.

One explanation to this result is that generation prompted students to distinguish among normative ideas demonstrated in the visualization and their own intuitive views. Creating drawings of the reaction processes enabled learners to realize gaps in their prior knowledge. Students were observed to revisit the visualization and changed their previous answers to embedded questions. They added new ideas about molecular reaction

processes from the visualization, distinguished with their old views, and developed a more integrated understanding of chemical reactions.

Rationale

Learning chemistry involves understanding and linking representations at the molecular or submicroscopic (e.g., atomic interactions), symbolic (e.g., equations), and observable or macro (e.g., color change) levels (Gabel, 1998; Gilbert & Treagust, 2009; Johnstone, 1993). Students often have difficulty in understanding or making connections across representations (Keig & Rubba, 1993; Kozma, 2003; Nakhleh, Samarapungavan, & Saglam, 2005). For instance, many students understand chemical reactions solely as symbolic equations. They fail to link $2\text{H}_2 + \text{O}_2 \rightarrow 2\text{H}_2\text{O}$ with unseen processes such as atom arrangement, bond breaking, and bond formation (Krajcik, 1991). Textbooks and formal instructions cannot help solve this problem because textbooks often emphasize symbolic representations and observable phenomena and present confusing images of chemical concepts at the molecular level (Ben-Zvi, Eylon, & Silberstein, 1987). Formal instructions often neglect everyday examples, making chemistry overly abstract.

To encourage the development of links among related scientific ideas, phenomena, and levels of representations, I took advantage of the knowledge integration framework to guide the design of the curriculum, assessment, and instructional comparison (Linn & Eylon, 2006; Linn, Eylon, & Davis, 2004; Varma, Husic, & Linn, 2008). The framework emphasizes connecting ideas from multiple perspectives and calls for instructional activities that engage students in knowledge integration processes. For instance, to promote integrated understanding of hydrogen combustion, in this study, I asked students to first explain their experience of burning a hydrogen balloon (eliciting ideas), then to interact with the hydrogen combustion visualization (adding new ideas to build understanding), then to draw molecular reaction processes during the reaction (developing criteria to distinguish ideas), and finally to explain how the molecular view relates to their observations of burning a hydrogen balloon (refining and sorting out ideas). By engaging in these knowledge integration processes, students can see when their ideas conflict with each other and actively refine their knowledge. This study investigates how generating drawings affects student learning and help them distinguish the various ideas demonstrated in the visualization and their old knowledge.

Challenges in Learning Chemical Reactions

For beginning students, making sense of a chemical reaction involves integrating a substantial number of concepts. To form a normative understanding of hydrogen combustion ($2\text{H}_2 + \text{O}_2 \rightarrow 2\text{H}_2\text{O}$), for example, students need to comprehend at least: (a) the structural aspects of chemical reactions, including the molecular structure of reactants and products (hydrogen gas, oxygen gas and water); (b) the symbolic representations of H_2 , O_2 , H_2O , and $2\text{H}_2 + \text{O}_2 \rightarrow 2\text{H}_2\text{O}$, including coefficients, subscripts and conservation of matter; (c) the interactive nature of a chemical reaction, such as bond breaking and formation; and (d) observable phenomena associated with the reaction such as an explosion and fire (Ben-Zvi et al., 1987). They need to understand different types of representations to demonstrate the reaction at the macro, submicro, and symbolic levels and the triplet relationship among the representations (Gilbert & Treagust, 2009). An expert's understanding would include more complex information, such as the chain reaction process and conditions under which explosions would occur.

While expert chemists can move easily between different representations and understand relationship among representations, novice students find it challenging to understand chemical phenomena at the molecular or submicro level and link with other representations (Kozma & Russell, 1997; Kozma, 2003). For instance, students often believe that molecules and atoms have properties of macroscopic matters such as colors, weight, and temperature (Ben-Zvi, Eylon, & Silberstein, 1986). Many learners think of chemical reactions as a static process rather than an interactive one (Ben-Zvi et al., 1987; Krajcik, 1991). They view chemical reactions as an additive equation without atom arrangement, bond breaking, or bond formation..

Such misunderstandings continue to occur throughout high school and college. Liu and Lesniak (2005) analyzed 6th, 8th, and 12th graders' performance on TIMSS items about chemical properties. They found little progress from 6th to 12th grade. Many grade 12 students hold the view that chemical reactions involve static processes, which is common among 8th graders.

Designing Dynamic Visualizations

Dynamic visualizations have great potentials to support chemistry learning. They can demonstrate dynamic unseen processes and offer a complete model of the processes. Compared to static visuals that use indicators such as arrows to symbolize temporal changes, dynamic visualizations bring temporal ideas to life and supports understanding (Park & Hopkins, 1993). Dynamic visualizations often employ multiple representations and support students forming integrated understanding in various ways (Ainswoth, 1999). For instance, multiple representations can complement learning by including pieces of information in each individual representation. By showing coordinated changes in multiple representations simultaneously, dynamic visualizations help students create referential connections between corresponding features of different representations with their knowledge of one representation mapped onto another (Seufert, 2003).

Visualizations have also been demonstrated to broaden participation in science. They offer new ways to represent complex problems and help connect ideas. Adding visualizations to instructions improves student learning of different chemistry topics (Ardac & Akaygun, 2004; Sanger, Brecheisen, & Hynek, 2001; Williamson & Abraham, 1995; Wu, Krajcik, & Soloway, 2001). Further, incorporating visualizations in instruction can increase student interest and insights in science (Boo & Watson, 2001). When asked what helps them learn science, two-thirds of sixth graders chose visualizations over explanations, reading, partners, and teachers (Corliss & Spitulnik, 2008).

Yet researchers also warn that visualizations may not always be powerful. The impact of visualization on student learning remains controversial. Research syntheses report effect sizes for visualizations ranging from -1.5 to +2.3 in recent literature (Chang, Chiu, McElhaney, & Linn, submitted). When learning with visualizations, learners are confronted with complex learning tasks. They need to understand how to interpret the visualization and how the visualization relates to the target concept (Ainswoth, 1999). Meanwhile, visualizations may be cognitively overloading. The transitory nature of visualizations requires learners to keep more information in mind than is required with static visuals. Complex visualizations can overload memory and occlude key details (Ainswoth, 2006; Gilbert, 2007). Some animations may be too perplexing and have no advantage over static diagrams (Tversky, Morrison, & Betrancourt, 2002). Dynamic visualizations need to be implemented and refined iteratively to reduce its complexity.

Further, visualizations can be “deceptively clear”, as coined by Robert Tinker. Some visualizations represent dynamic information in such an apparently simple way that learners may become convinced they understand based on superficial observations (Chiu & Linn, in press).

Visualizations can benefit from supportive instructions that promote connections among ideas. Carefully designed instruction encourages students to reconsider their ideas from the visualizations, refine connections with other ideas, and resolve conflicts among ideas. Successful instruction with visualizations typically takes numerous cycles of refinement (Chang & Quintana, 2006; Clark & Jorde, 2004). It often includes other activities and assessments that guide students to link visualizations and ideas. In this study, I designed the HFC project and the generative activity following proven design patterns. The generation task encourages students to spend more time making sense of the visualization and analyze what they see. They are guided to represent and articulate their ideas, consider new ideas, distinguish among ideas, and reflect on their views.

Generating Drawings to Promote Learning

This study investigates the approach of asking students to draw their interpretations of the visualization. After interacting with a visualization showing atomic interactions during hydrogen combustion, students were asked to create four or five drawings to represent molecular movement at different states of the reaction. This approach is built upon previous research on generation, modeling, learner-generated drawings, and desirable difficulties. It is expected to prompt students to realize gaps in their prior knowledge, revise their interpretations, and develop integrated understanding with the visualization.

Research on inventing drawings or representations suggests that generation promotes integration of new knowledge with prior ideas. Van Meter and Garner’s study (2005) suggests that asking students to draw from an expository text helps them connect information in the text with prior knowledge. Rich and Black (1994) found asking students to draw their views before reading texts elicits students’ background knowledge and promotes discussion. Asking them to draw their views after reading helps integrate ideas from the text with their prior knowledge. According to Chi’s active-constructive-interactive framework (2009), drawing is an interactive learning activity, which can encourage students to recognize conflicts among ideas, examine these conflicts, and “self-repair” differences between ideas.

Other studies suggest that creating drawings helps because it involves reasoning across representations and written language. Ramadas (2009) reviewed previous research and found that creating and reasoning with diagrams or drawings often involves language-based reasoning. Learners reason across representations, texts, and oral languages, which encourages deeper understanding of the underlying idea. In a study asking students to invent graphs about speed and distance, diSessa, Hammer, Sherin, and Kolpakowski (1991) found that learners as a group used their invented graphs to explain real-life scenarios, realized flaws in their graphs, and discussed to revise their inventions. They advanced the understanding of the physics concepts through revision and discussion. One explanation to the success is representational competency (diSessa, 2004). Students drew on representational competency while evaluating and revising the graphs. As a result, representational competence becomes a resource for conceptual development.

Further, research on models and modeling supports the potential benefits of drawing. Creating drawings to model how hydrogen combustion takes place is a modeling practice and “involves students in the critical use of representations of all kinds” (Buckley, 2000, p.928). To create normative drawings, students need to represent not only bond breaking and formation, but also molecular structure of reactants and products. Moreover, learners need to consider the conservation of mass law and conserve the number of atoms in all drawings. To produce their own representations, students need to integrate information learned from the visualization with prior knowledge about chemical reactions and the particulate nature of matter. Through drawing students engage in purposeful modeling practices and simultaneously advance their understanding of scientific concepts. It is unlikely that students create normative drawings without in-depth understanding of chemical reactions.

Another reason that generating drawings helps is that generation is a “desirable difficulty” (Bjork, 1994; Bjork & Linn, 2006). Psychology studies show that conditions that introduce difficulties to a learner may appear to slow down the rate of learning, but can enhance long-term retention and transfer of knowledge. Classroom studies show that generation compared to reading can promote knowledge integration (Richland, Bjork, Finley, & Linn, 2005).

In this research, I expect that students can draw on their prior knowledge and representational competency to create the drawings. As a desirable difficulty, drawing functions as a testing and learning event that enables students to realize the gaps in their previous understanding about chemical reactions. Students are prompted to explore the visualization and integrate more ideas at the molecular level. Consistent with desirable difficulties, the drawing task may slow down learning but help students refine connections between ideas. Specifically, the hypotheses are:

- Generating drawings is better than interaction for helping students integrate ideas from visualizations.
- Drawing may have different impact on students with various ideas. For students who start with high levels of prior knowledge, generation may not have additional benefits compared to interaction.
- Drawing encourages students to realize gaps in their previous understanding about atomic interactions during chemical reactions. Students who draw will gather more precise information from the visualization than those who explore.

HFC Project and the Hydrogen Combustion Visualization

In this research, students learned chemical reactions by interacting with the hydrogen combustion visualization embedded in the Hydrogen Fuel Cell Cars project. Because the participants were 8th graders, I refined the HFC project to make it suitable for middle school students. The major change is that the hydrogen combustion visualization was reduced to only illustrate how molecules, chemical bonds, and the temperature change during the reaction. I removed the energy diagram part from the visualization and the project. One reason for the reduction is that the topics of energy diagram and energy change in chemical reactions are not required by the middle school physical science curricular standards. They are so complicated that 8th grade students do not have enough prior knowledge to understand. Incorporating them in the visualization will increase students’ confusion. Furthermore, results from the last chapter suggest that the main challenge students face when learning with the visualization is that they cannot

integrate ideas at the molecular level. Eliminating the energy part can help focus students' attention on the atomic interactions demonstrated in the visualization, which is the crucial disciplinary knowledge they need to integrate.

Other than the above-noted changes, I did not make further revisions to the project or the visualization. The driving inquiry question remained *Can hydrogen fuel cell cars replace gasoline powered cars in the future?* Students investigated how hydrogen combustion takes place, gathered information about using hydrogen to power cars, and discussed the pros and cons of hydrogen fuel cell and gasoline powered cars.

Methods

Participants

Altogether 133 8th grade students from five physical science classes in a public school participated in this study. The school has a lower than state average for mobility (9% compared to the state average of 14%). Most of the students are Caucasians from working class families. The same teacher (Mr. H) taught all classes. He has five years of experience teaching middle school physical science and three years of teaching projects using the WISE environment. The WISE-targeted professional development program supported Mr. H when he was using the materials (Varma et al., 2008). All students had studied at least another WISE project before and were familiar with the WISE learning environment. The project was implemented after students had learned about the particulate nature of matter, but before any classroom instruction on chemical reactions. Mr. H taught both groups and students worked through the HFC project in pairs.

Study Design

The five classes were randomly assigned to two groups: the generation group (n=81, three classes) and the interaction group (n=52, two classes). The two groups demonstrated similar levels of prior chemistry knowledge on the pretest [$t(131) = .16$, $p = .87$]. During this six-day (a 50-minute period per day) project, both groups spent the first day registering for WISE, completing the pretest, and starting the project. By the end of the second day, all students finished the first half of Activity 2 and were about to start the visualization.

On the third day, students in the generation group explored the visualization, answered embedded questions, and generated paper-based drawings. Students were asked to create four or five drawings to represent interactions among three oxygen molecules and six hydrogen molecules before the reaction, right after the reaction starts, some time after the initiation of the reaction, and after the reaction completes. Because the visualization demonstrates such interactions dynamically with hundreds of frames and over fifty atoms, it is impossible for students to create correct drawings by simply copying the frames. Students need to interact with the visualization to integrate the ideas of bond breaking and formation with prior knowledge about particulate nature of matter, and apply the integrated ideas to create the drawings with the correct number of particles. In addition, we asked students to explain their drawings. The explanations can reveal supplementary information about what students draw. It is unlikely that students create correct drawings and explanations by copying expert views from the visualization.

Students in the interaction group explored the same visualization and answered the same embedded questions as the drawing group. Instead of being asked to generate

drawings, they spent the extra time on the visualizations. Afterwards they were asked to explain how chemical bonds and molecules change during hydrogen combustion.

The teacher gave the same instructions to both groups, including asking to revisit the visualization, to make careful observations about how molecules and atoms move and chemical bonds change during each state of the reaction, and to revise their answers to embedded questions. Both groups finished these tasks within 40 minutes. For the next three days, all students worked on the remaining curricular activities embedded in the project. They finished the project and completed a posttest at the end of the sixth day. Thus only activities on the third day differed for the two groups.

Classroom Observations

During this project, I visited the classroom everyday to observe the project run and provide support to teachers and students. Each time after her visit, the researcher filled out a classroom observation form developed by the TELS center (Varma et al., 2008). The observation form was designed to collect information about student work with visualizations by asking questions such as “What kinds of questions about the visualization do student pairs talk to each other?” and “How do students work with the drawing activity and the visualization?”

Assessments and Scoring

The teacher administered identical paper-based tests to individual students before and after the project. The tests consist of five items and examined links between molecular and symbolic representations for bond breaking and formation. These items include two recognition items and three generation items. The recognition items ask students to identify correct molecular representations of chemicals before and after hydrogen combustion. Students need to make selections and explain their reasoning. The generation items ask students to generate drawings and explain how the reaction between carbon and oxygen gas occurs.

The drawings created by students in the generation group and explanations by those in the interaction group provide further evidence of student learning. Combining these data reveals detailed information about how students developed ideas through the project. Student responses to the pre/posttest, their drawings, and explanations created during the project were scored using the knowledge integration framework (Linn et al., 2006).

Data Analysis

I analyzed student learning about chemical reactions by comparing pretest and posttest scores using paired t-test analyses. To determine the effect of the treatment, I conducted a multiple linear regression analysis, using the mean pretest score and group as explanatory variables, and the mean posttest score as the outcome variable. I calculated the effect sizes between the means of the posttest scores across the treatments to indicate the size of the observed treatment effect.

To compare the effect of generation and interaction on students with different prior knowledge, I categorized students' prior ideas as represented on the pretest. ANCOVA analyses were conducted to compare the pretest-posttest performance of learners with each idea. Further, to understand how students developed their ideas, I examined the work completed by students during the project. I categorized the ideas

represented on drawings created by students in the generation group and those demonstrated in explanations by learners in the interaction group. I calculated and compared the percentages of students holding each category of ideas.

Results and Discussion

Classroom Observations

Overall, the teacher implemented the project successfully in all classes. The difference in treatments occurred on the third day. On Day three, both groups interacted with the visualization by varying the amount of energy provided to ignite the reaction and observing different atomic interactions. Afterwards each pair in the generation group drew five pictures to illustrate the reaction process.

Classroom observations of the generation group revealed that

- Students in the generation group conducted more discussions than those in the interaction group. Many student dyads discussed what ideas should be included in their drawings and how they should plan the sequence of the drawings.
- During the drawing activity, students in the generation group revisited the visualization to check ideas when there was a disagreement between student pairs.
- During the remaining three days of instructions, students in the generation group often returned to the visualization and revised their responses to embedded questions.

Observations of the interaction group showed that

- Compared to those in the generation group, students in the interaction group spent more time interacting with the visualization by changing the energy provided and observing temperature change. They also revised answers to embedded questions.
- Many students in the interaction group completed the third day's work five minutes earlier than those in the generation group.

Advantages of Generation vs. Interaction on Student Integrated Learning

Overall learning gains.

Paired t-test results show that all students benefited from the project (see Table 4.1 for the t-test results). Students in both groups started with comparable levels of prior chemistry knowledge and made significant progress in understanding chemical reactions after the project. On average they had non-normative ideas about chemical reactions on the pretest and progressed to normative ideas on the posttest.

Table 4.1. T-test Analysis Results of Both Groups' Performance on Pre and Post Tests

	N	Pretest		Posttest		Effect size	p-value
		Mean	SD	Mean	SD		
All students	133	1.30	.65	2.33	.58	1.58	p<.0001
Generation group	81	1.31	.61	2.44	.48	1.74	p<.0001
Interaction group	52	1.29	.73	2.15	.67	1.39	p<.0001

On the posttest, students in the generation group demonstrated more complex ideas and links about chemical reactions than those in the interaction group. Most students in the generation group developed normative ideas about bond breaking and formation. More than 50% of students in this group made one or two normative links between the ideas and molecular representations. In contrast, students in the interaction group only developed normative ideas about bond breaking *or* formation. Only a few students were able to make correct links between such ideas and representations.

Advantages of generation vs. interaction.

Multiple regression results show that the generation group achieved significantly higher scores on the posttest than the interaction group, after controlling for pretest scores. There was an interaction between students' pretest score and treatment (see Figure 4.1). For students who had a pretest score below 2.18, generation was more effective than interaction. The difference between the effectiveness of generation and interaction is less significant for students who started the project with a score higher than 2.18. The result indicates that generation is more beneficial than interaction for students who started with wrong or partial ideas about chemical reactions. The treatments are equally effective for students with higher pretest scores.

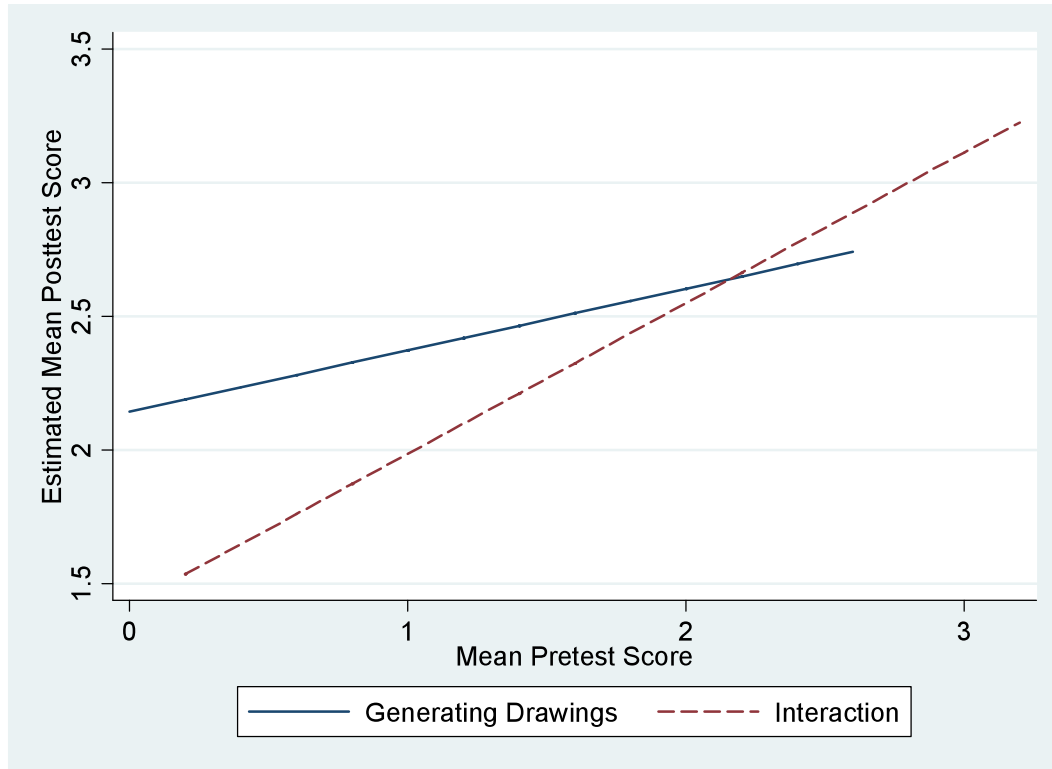


Figure 4.1. Estimated regression line of the two groups' performance from pretest to posttest.

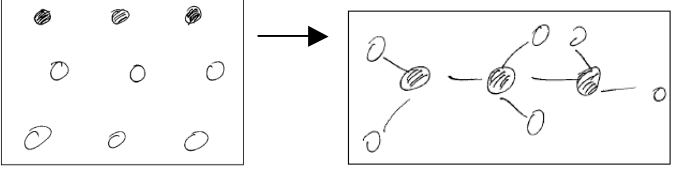
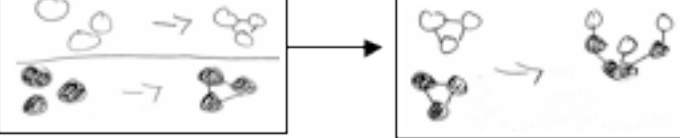
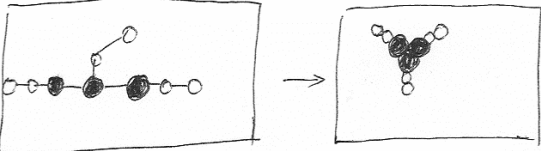
Note. The x-axis shows the mean pretest score, and the y-axis shows the estimated mean posttest score. The multiple linear regression analysis was performed using the mean pretest score and treatment as explanatory variables, and the mean posttest score as response variable. There was an interaction between the mean pretest score and group. The estimated coefficient of drawing was .72 [$t(129)=3.79, p<.001$], and the coefficient of interaction was -.33 [$t(129)=-2.56, p=.01$]. The estimated regression equation was: Mean posttest score = $1.42 + .56$ Mean pretest score + $.72$ drawing - $.33$ Interaction

Impact on Students with Various Prior Ideas

To investigate the impact of generation on students with different prior knowledge, I categorized various initial ideas held by students and tracked how the ideas changed on the posttest. I focused on students who had wrong or partial ideas before the project because drawing is more beneficial to them than interaction. Altogether eighty-three students expressed such ideas on the pretest (35 students, or 71%, from the interaction group and 48 students, or 61%, from the generation group). Their views include: the instantaneous view ($n=56$), element view ($n=13$), and chain view ($n=14$). Table 4.2 presents descriptions of these ideas with student sample drawings. Using the knowledge integration scoring rubric, these ideas were scored 1 on the pretest.

ANCOVA analyses were performed to investigate the effect of the treatment on these students with different ideas. Considering the large percentage of students holding the instantaneous view before the project, I next focused the analysis on the performance of these students.

Table 4.2. Students' Alternative Ideas about Chemical Reaction Processes Demonstrated on the Pretest

Non-normative ideas	Description of the ideas	Sample answers to the drawing question that asks to draw how carbon burning occurs
Instantaneous View (total: n=56, Generation group: n=27, Interaction group: n=29)	Chemical reaction is a static process. The reactants change directly to products, and there are no intermediate phases during a reaction.	 <p data-bbox="662 615 1328 758">"I think the carbons and oxygens will react to form the carbon dioxide. They will rearrange by themselves. There is nothing between (the reactants and products)."</p>
Element View (total: n=13, Generation group: n=10, Interaction group: n=3)	During the reaction, atoms first group by elements, and then different groups are connected to form one big molecule.	 <p data-bbox="662 987 1230 1056">"All atoms are connected first, then they are connected to form a mega molecule."</p>
Chain View (total: n=14, Generation group: n=11, Interaction group: n=3)	Before the reaction, atoms are connected as a chain. They rearrange and become a ring after the reaction.	 <p data-bbox="662 1329 1273 1398">"They (atoms) need to change from a chain to a ring."</p>

Instantaneous view of chemical reactions.

Fifty-six students (generation group: n=27, interaction group: n=29) held an instantaneous view about chemical reaction processes on the pretest. They believed that there were no intermediate phases during reactions. They typically drew two pictures to show how carbon burns at the molecular level, one showing the reactants and the other one representing products. They did not create any drawings about the intermediate phases during the reaction and viewed chemical reactions as an instantaneous process from reactants to products. One student, for example, explained the reaction occurs "like you have reactants, Bang! you get products. This whole thing is magic." Some students

mentioned the term “molecular rearrangement” in their explanations, but their drawings did not represent dynamic processes of rearrangement such as bond breaking and formation.

Compare groups.

The ANCOVA analysis result shows that students who drew outperformed those who interacted on the posttest, after controlling for pretest score [$F(1, 53)=10.12, p<.01$]. Students in the generation group achieved an average score of 2.64 on the posttest, while those in the interaction group had an average score of 2.04 after the unit. For students who had the instantaneous view before the project, generating drawings helped them integrate more ideas about chemical reaction processes from the visualization than spending more time interacting with it.

Element and chain views.

A small number of students demonstrated other non-normative ideas about chemical reactions on the pretest. Students with element view ($n=13$) drew reaction processes as atoms of the same element first forming teams, and then different teams connecting to form a gigantic molecule. Students with chain views ($n=14$) represented all atoms being connected before and after the reaction. During the reaction the atoms change the way they connect. They may be connected as a chain before and form a ring after the reaction.

Compare groups.

Students with element or chain ideas all developed correct ideas about bond breaking and formation on the posttest. The ANCOVA analyses results show that students benefited similarly from generation and interaction [element view: $F(1, 10)=.04, p=.85$; chain view: $F(1, 11)=3.20, p=.10$].

In summary, these results show that all students benefited from the project. Drawing helped students integrate more ideas from the visualization than interaction. Students who had instantaneous view about chemical reactions, in particular, benefited more from generation than interaction. Considering the large percentage of students holding this ideas on the pretest, this helps clarify why generation overall is more beneficial than interaction. For students who started with higher levels of prior knowledge or other non-normative ideas, generation and interaction had similar impact on promoting knowledge integration from visualizations.

Knowledge Integration through Generation and Interaction

To further understand how and what ideas drawing helps students integrate from the visualization, I analyzed students’ drawings and explanations about hydrogen combustion processes. In this section I focus on comparing ideas represented in the drawings created by the generation group with views demonstrated in the explanations created by students in the interaction group. The explanations provided by students in the generation group served as supplementary information to assist our analysis.

According to the numbers of new ideas integrated, we categorized the drawings and explanations into four levels. Table 4.3 presents the categories for drawings and explanations. Students who draw or explained at low level failed to integrate the correct ideas about bond breaking or formation. Responses at single process level indicate that

learners were able to integrate only one idea about bond breaking or formation. Learners who drew or described the complete process integrated both ideas from the visualization. If students drew or explained at the complex process level, they integrated not only ideas about reaction processes but also other related concepts such as temperature change and chain reaction. Compared to students at other levels, they have integrated the most ideas and developed the most sophisticated understanding about chemical reactions.

I calculated the percentage of students with responses at each level. The categorization results show that most students (78%), after interacting with the visualization and creating drawings, were able to integrate at least ideas about bond breaking and formation. Some of them (30%) also paid attention to other features demonstrated in the visualization such as energy and conservation of matter, which were not emphasized in the instruction.

In contrast, twenty students (38.5%) in the interaction group did not pay attention to atomic interactions or changes in chemical bonds at all, even though they spent more time experimenting with the visualization. Other students (n=20, 38.5%) noticed some of the changes, yet they were able to integrate one idea about bond breaking or formation. They often only focused on one idea and ignored the other. Only ten students integrated both ideas. Very few of them (n=2, 4%) were able to integrate bond breaking, formation, and other ideas such as energy or temperature change.

Overall, asking students to draw their ideas prompted them to integrate more ideas about reaction processes from the visualization. Even though students in the interaction group spent more time interacting with the visualization, they still tend to ignore key changes demonstrated in it because of the deceptive clarity. The drawing task, by contrast, provides an opportunity for learners to test and realize gaps in their interpretations of the visualization and prompts them to observe carefully.

Table 4.3. Categories of drawings created by students in the generation group and explanations created by learners in the interaction group

Levels	Category of drawings	Category of explanations
Low	Drawings do not represent any changes in chemical bonds. They do not represent bond breaking or formation.	Explanations do not describe any changes in chemical bonds. They do not address bond breaking or formation.
Simple process	Represent bond breaking or bond formation correctly.	Explain bond breaking or bond formation correctly.
Complete process	Represent bond breaking and formation correctly (i.e. how hydrogen and oxygen molecules break bonds and how hydrogen and oxygen atoms form water molecules).	Explain bond breaking and formation correctly (i.e. how hydrogen and oxygen molecules break bonds and how hydrogen and oxygen atoms form water molecules).
Complex process	Represent not only bond breaking and formation, but also other related ideas correctly. Such ideas include: the conservation of matter (all drawings showing the same amount of atoms), activation energy (drawing a spark to indicate providing energy to start the reaction), and chain reaction (drawing one hydrogen and one oxygen atom forming bonds first, then another hydrogen atoms forming bonds with the oxygen atom).	Explain not only bond breaking and formation, but also other related ideas correctly. Such ideas include: the conservation of matter (there is no loss of atoms), activation energy (need a spark to provide energy to start the reaction), and chain reaction (first one hydrogen and one oxygen atom form one bond, then another hydrogen atoms forms a bond with the oxygen atom).

Case studies.

I used representative students from the generation and interaction groups to characterize how drawing supports knowledge integration. Student A and B started with an instantaneous view of chemical reactions, the most common non-normative idea held by students starting the project. The case tracks A and B's prior ideas, new ideas reconciled through drawing and interacting with the visualization, and ideas demonstrated on the posttest.

Student A from the generation group.

Pretest performance.

Student A was selected because approximately 60% of the students in the generation group who had the same prior knowledge (n=27) achieved similar gains as A. He started with an instantaneous view on the pretest (see Table 4.4 for student A's drawings and answers on the pretest and posttest). On the pretest, student A drew reactants as two groups: one group composed of three oxygen atoms and the other of three carbon atoms. He represented products as a gigantic molecule with all atoms grouped together. He explained the reaction as *“once they (reactants) are put together, they rearrange to form a product. Basically, a start-finish process.”* He neglected intermediate phases and thought that reactants would manage to change directly to products after the reaction started. A's drawings reflect non-normative ideas about reactants, products, and reaction processes before the project.

During the project.

During the project A interacted with the dynamic visualization, answered embedded questions, and then started to draw. He initially explained hydrogen combustion as *“when you hit the spark button, the temperature rises and it's hot enough to form a water molecule. The atoms go crazy from the temperature rising and they are ready to react.”* His explanation did not describe any changes in chemical bonds. This suggests that during A's first interaction with the visualization, he noticed how temperature controlled the reaction but did not attend to the changes of chemical bonds.

During drawing he was observed to re-explore the visualization. Altogether he generated five drawings to illustrate the reaction. The first drawing shows hydrogen and oxygen molecules correctly before the reaction; the second, the third, and the fourth drawings represent the formation of new bonds between oxygen and hydrogen molecules; and the fifth drawing demonstrated the formation of water molecules. He revised his explanations and explained the reaction as *“(1st drawing) hydrogen and hydrogen bond, oxygen and oxygen bond before the reaction...(2nd drawing) Water molecules start forming, the oxygen atom is trying to bond with hydrogen atoms...(3rd drawing) Temperature goes up more and more movement. They are trying to bond with each other...(4th drawing) More bonds are formed between hydrogen and oxygen...(5th drawing) All the molecules are now water molecules. There is a lot of movement now.”* This shows that after drawing and revisiting the visualization A integrated the idea of oxygen and hydrogen forming bond with his prior idea about temperature change. He no longer attributed changes to the increase in temperature.

Consistent with our hypothesis, drawing prompts A to elaborate his idea that “atoms go crazy” and gather more information. He revisits the visualization for new information about interactions between specific atoms, reactants, and products. He integrates these new ideas in a way that extends his previous idea about the role of temperature. Yet student A does not acknowledge the idea of breaking bonds nor does he connect bond breaking to temperature change.

Posttest performance.



On the posttest student A successfully applied these ideas to explain the burning of carbon. He drew three pictures and explained the reaction as *“Before the reaction*

starts, the carbons have no bonds yet and the oxygens are bonded with another oxygen. Both are in their normal state. Then bonds start breaking and the temperature rises (I made an educated guess). At the same time, some oxygen and carbon start bonding. Finally, new bonds are all formed and create carbon dioxide and the reaction completes.” This answer shows normative links between the ideas of bond formation and temperature change. Student A adds the new idea that bond breaking is part of the process. He links bond breaking and temperature change. Classroom observations noted that during the final three days of the project, A continued to re-explore the visualization frequently. He scrutinized the visualization and tracked the interaction between an oxygen atom and a hydrogen atom. This may have helped him integrate ideas about bond breaking. His revisit of the visualization demonstrates his realization that the visualization can help him refine his ideas.

Table 4.4. Student A's drawings and explanations created in the drawing activity and answers to the pretest and posttest drawing item

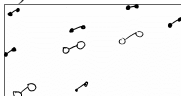
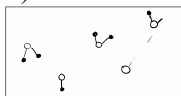
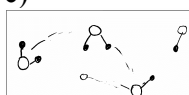
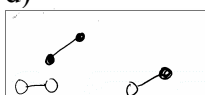
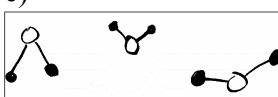
Pretest drawing item:

For the chemical reaction between carbon and oxygen gas, $C+O_2 \rightarrow CO_2$, imagine the reaction starts with 3 carbon atoms and 3 oxygen gas molecules. Draw pictures to show how the reaction happens. Use a black circle to represent a carbon atom and a white circle for an oxygen atom.


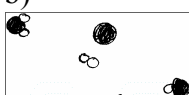

<p>a)</p> 	<p>Explanation: "They are carbon and oxygen before the reaction."</p>	<p>b)</p> 	<p>Explanation: "They all bond together after the reaction finishes. I think once they are put together, they rearrange to form a product. Basically, a start-finish process."</p>
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Drawing activity:

Based on what you have learned from the model, imagine you have a camera taking pictures during the burning of hydrogen. Draw pictures showing different stages during the reaction; explain how molecules change at each stage.

<p>a)</p> 	<p>Explanation: "hydrogen and hydrogen bond, oxygen and oxygen bond before the reaction."</p>	<p>b)</p> 	<p>Explanation: "Water molecules start forming, the oxygen atom is trying to bond with hydrogen atoms."</p>
<p>c)</p> 	<p>Explanation: "Temperature goes up more and more movement. They are trying to bond with each other."</p>	<p>d)</p> 	<p>Explanation: "More bonds are formed between hydrogen and oxygen."</p>
<p>e)</p> 	<p>Explanation: "All the molecules are now water molecules. There is a lot of movement now."</p>		

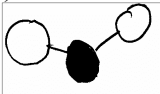
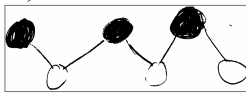
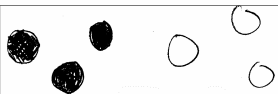


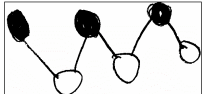
Posttest drawing item: (the same instruction as in the pretest)

<p>a)</p> 	<p>Explanation: "Before the reaction starts, the carbons have no bonds yet and the oxygens are bonded with another oxygen. Both are in their normal state."</p>
<p>b)</p> 	<p>Explanation: "Bonds start breaking and the temperature rises (I made an educated guess). At the same time, some oxygen and carbon start bonding."</p>
<p>c)</p> 	<p>Explanation: "New bonds are all formed and create carbon dioxide and the reaction completes."</p>

Student B from the interaction group.

Student B from the interaction group also started at level 1 with instantaneous view on the pretest. He drew CO₂ as the reactant and described it as “carbon and oxygen”, he described the final state by saying “they are connected after the reaction” but does not unpack the process. He does not mention intermediate phases during a chemical reaction. Table 4.5 presents student B’s answers to the drawing items on the pretest and posttest.

Table 4.5. Student B’s answers to the pretest and posttest drawing item

Pretest drawing item:					
For the chemical reaction between carbon and oxygen gas, $C+O_2 \rightarrow CO_2$, imagine the reaction starts with 3 carbon atoms and 3 oxygen gas molecules. Draw pictures to show how the reaction happens. Use a black circle to represent carbon atom and a white circle oxygen atom.					
a)		Explanation: “I drew carbon and oxygen before the reaction.”	b)		Explanation: “They are connected after the reaction.”
Posttest drawing item: (the same instruction as in the pretest)					
a)		Explanation: “they are separated before the reaction.”	b)		Explanation: “the atoms are moving closer, they want to bond.”
c)		Explanation: “they start forming bonds now.”	d)		Explanation: “They are bonded now.”

During the project, student B spent day three using the dynamic visualization and responding to embedded questions. He answered the Mol-Sym question by describing the reaction as “This reaction did produce water molecules finally and oxygen atoms bonded with two hydrogen atoms.” This suggests that after interacting with the visualization, he investigated the idea of bond formation and established a valid link between bonding and molecular reactions.

Unlike student A, student B did not build on this insight. On the posttest he continues to mention bonding but did not add the idea of bond breaking. He generated four pictures to show the reaction and explained the process as “(1st picture) they are separated before the reaction... (2nd picture) the atoms are moving closer, they want to bond... (3rd picture) they start forming bonds now... (4th picture) They are bonded now.” He implies that bond formation occurs when atoms move together. His drawings reflect the idea that all atoms try to be together to react. He shows atoms in a chain instead of showing separate carbon dioxide molecules as the end state of the reaction. He added bond formation to his repertoire and linked this idea to his view of bonds as a chain connecting all the atoms. It appears that student B also viewed the visualization in the aggregate but never demonstrated specific interactions between single atoms.

In summary, student A and B started the project with similar instantaneous ideas about chemical reactions and initially viewed the visualization as an aggregation of atoms. The drawing task enabled A to recognize problems in his prior ideas and prompted him to revisit and observe the visualization carefully. Drawing functioned as a testing and learning event and helped him develop links between ideas and representations. In contrast, B did not have the chance to test his ideas. Although he added more ideas about bond formation through interaction, he did not gain as nuanced a view as A and was not motivated to explore bond breaking. Therefore, on the posttest, he still had some idea about bonding but returned to the idea of a chain as the end state of a chemical reaction.

Conclusion

This study expands research in designing instructions to help students gain integrated understandings of chemistry with dynamic visualizations. Students learned chemical reactions by interacting with the hydrogen combustion visualization and completing the generation activity embedded in HFC project. Both the project and the generation activity were designed and iteratively refined using the knowledge integration design patterns and principles developed in previous research (Kali, Linn, & Roseman, 2008). These patterns and principles characterize activities that help students use evidence to distinguish ideas and construct coherent arguments. The gains from pretest to posttest of both groups confirm the effectiveness of the design patterns and the success of teaching chemistry with visualizations.

This research shows that generating drawings helps overcome deceptive clarity. Visualizations can be deceptively clear and lead students to believe that they understand (Chiu & Linn, in press). Students may ignore important details and form non-normative interpretations. In this study, learners who drew their ideas took full advantage of visualizations and integrated more ideas than did those in the interaction group. The case studies illustrate how generating drawings motivates students to distinguish among the ideas they bring to science class and the ideas found in the visualization. Generation helps students recognize problems with their initial interpretations and integrate more ideas.

The drawing activity highlights the dynamic nature of a chemical reaction and provides an opportunity for students to add ideas about intermediate states. The generation task encourages them to re-explore the visualization. Drawing helps students refine general observations such as that the molecules “go crazy” or “want to bond” and to gather details about how the process occurs. The visualization adds ideas about chemical bond formation. Overall, students add ideas represented by the visualization, integrate these ideas into their prior knowledge, and distinguish ideas by generating drawings that use evidence from the visualizations. In their explanations, they often reflect on how their ideas fit together. Therefore, drawing strengthens links between visualizations, symbolic representations, and underlying ideas about chemical reactions. It motivates students to revisit the visualizations and enables them to develop more coherent explanations.

Classroom observations of students working on the drawing activity resonate with this view. Before they started drawing, many students discussed the ideas in the visualization with their partners. They determined which ideas should be represented in their drawings. The drawing activity enabled them to generate drawings based on their

interpretations and compare the drawings to the actions on the screen. The comparison helped them distinguish their interpretations from normative ideas supported by evidence from the visualization. In contrast, students in the interaction group with similar experiences were less likely to explain specific bond breaking and formation and use this evidence in their explanations.

Implications for Designers of Instruction with Visualizations

This study suggests a few implications for designers of instruction with visualizations. One implication is that visualization design should consider students' prior knowledge. Dynamic visualizations that are commonly used by scientists and engineers may not be suitable for novices and students. The hydrogen combustion visualization used in last chapter (the original version) was designed for high school students. When implemented in middle school classrooms, it was too complicated and would lead to student confusion. To reduce its complexity and difficulty, I removed the energy diagram. The revised visualization focuses on showing bond breaking and formation during chemical reactions, which is suitable for 8th graders. Students learn with the visualization by investigating how chemical bonds and the temperature change and how adding sparks can make the reaction happen.

Another implication is that instructions surrounding the visualization should focus student attention on the crucial disciplinary knowledge that they need. The generation activity required learners to draw interim phases during the reaction. It engaged students in extensive thinking and representing the molecular reaction processes, which are key concepts demonstrated in the visualization. Students in the interaction group did not create drawings and often ignored these important details.

Limitations

This study suggests the benefits of generating drawings in promoting student integrated understanding about chemistry with dynamic visualizations. The limitations include that the study is quasi-experimental rather than experimental because the teacher was recruited to participate rather than randomly selected. The results may differ from situations involving participants, treatments, settings, and measures not similar to those in the study. In addition, this study measures immediate effects of the treatment using a posttest. Conducting a delayed posttest is a desirable future study and could clarify the long-term effects of generation and interaction on student understanding.

Another limitation concerns the mechanism of generating drawings. This study suggests that generating drawings helps students focus on key information represented in the visualization and distinguish among ideas. However, it is difficult to tease out the effect of generation and distinguishing ideas. Therefore, important questions remain: which one plays a more important role in facilitating student knowledge integration from visualizations, generation or distinguishing ideas? Can an activity that only encourages distinguishing among ideas be as successful as drawing? In the next chapter, I will discuss the study of a selection activity to help clarify the importance of distinguishing ideas.

Chapter 5: Promote Learning with Visualizations: Generating and Selecting Pictures

Powerful dynamic visualizations make unobservable scientific phenomena visible in classrooms and raise questions about how to best guide learners. Previous chapters discuss student difficulties when learning chemistry with the hydrogen combustion visualization. Often they ignored the changes in molecules and chemical bonds demonstrated in the visualization and ended up with superficial or non-normative interpretations.

Generative activities such as generating drawings can promote integrated understanding with visualizations by engaging students in knowledge integration processes of recognizing conflicts among ideas and distinguishing ideas. In Chapter 4, I compared student learning with generation and interaction. Learners who created drawings integrated more ideas from the visualization than those in the interaction group. Yet some important questions remain unanswered: which one plays a more important role in promoting student knowledge integration from visualizations, generation or distinguishing ideas? Can an activity that engages students to distinguish ideas be as successful as drawing?

To clarify the benefits of distinguishing ideas, this chapter investigates a selection activity and compares its impact with that of generation. Students learned chemical reactions using the hydrogen combustion visualization embedded in the HFC project. In the generation condition, learners created four drawings to show interim phases of hydrogen combustion. In the selection condition, students chose four pictures among alternatives to represent the phases. To select, learners need to distinguish among the normative and non-normative ideas represented in the choices based on their understanding from the visualization. It is expected that selection will have similar benefits as generation as they both prompt discrimination among ideas.

This chapter discusses the design, refinement, and implementation of the selection activity. Two versions of selection were developed: simple and complex selection. In study 1, I designed the simple selection (SS) and compared its impact on student learning with that of generating drawings. In study 2, I revised SS, developed the complex selection (CS), and examined its effects with that of generation. The major difference between SS and CS was the choices to be selected. Most choices in SS were snapshots of atomic interactions taken at different time using the visualization. The choices in CS were pictures designed to represent common alternative ideas held by students. Research questions addressed in this chapter are:

- How do selection tasks contribute to integrated understanding of chemical reactions?
- What are the advantages of selection versus generation of drawings of chemical reactions for all learners and for learners with non-normative, mixed, and partially normative ideas?
- What are the implications for designers of instruction with visualizations?

To foreshadow the results, CS had similar impact as generation on promoting student learning. SS was less beneficial than generation because it failed to encourage students to discriminate their naïve ideas from the expert views in the visualization. This

study confirms the importance of designing instructional activities that support students to distinguish ideas.

Rationale

Chemistry students have difficulties making sense of chemical phenomena at the molecular level. They often cannot visualize atom rearrangement, bond breaking, and bond formation (Ben-Zvi, Eylon & Silberstein, 1987; Krajcik, 1991; Yaroch, 1985). One reason is that their conceptions of science are rooted from their observations of everyday phenomena such as setting up campfires (Clark & Linn, 2003; diSessa, 1988; Linn & Hsi, 2000). Without prior experience with the atomic world, learners find it challenging to comprehend unseen processes. As a result, many students apply their experience from everyday life to make sense of the microscopic world. They believe atoms and molecules share the same properties as the tangible materials, *e.g.*, that copper atoms have gravity and temperature (Ben-Zvi, Eylon & Silberstein, 1986). Some students envision chemical reactions as magic processes through which reactants change into products (Zhang & Linn, 2008). Without adequate ideas on atomic interactions, students fail to link with ideas at other levels. Their views about chemical reactions are often fragmented and incoherent.

Designing Visualizations and Instructions to Integrate Ideas about Unseen Phenomena

New technologies such as computer-based visualizations offer a solution by making atomic-level phenomena observable (Ardac & Akaygun, 2004; Schank & Kozma, 2002; Wu, Krajcik, & Soloway, 2001). Yet visualizations can be perplexing and cognitively demanding (Mayer & Moreno, 2003; Moreno & Mayer, 2007; Tversky, Morrison, & Betrancourt, 2002). Learners face great challenges when learning with visualizations. They may ignore important details, develop superficial interpretations, and overestimate their understanding (Chiu & Linn, in press). For instance, the previous implementations of the hydrogen combustion visualization (Zhang, 2006, 2007) show that some students failed to integrate ideas about changes at the molecular level. They did not notice bond breaking and formation and concluded that the visualization showed “*the molecules are moving and bouncing with each other.*” Some other students did not distinguish among new ideas and their prior knowledge and developed incorrect ideas. They explained that “*hydrogen molecules are the small green ones and oxygens are the big blue ones.*”

How to effectively learn from dynamic visualizations poses a challenge to students. To maximize the potential benefits of visualizations, learners need to first understand the format of each representation incorporated in the visualization, including the subtleties of the representations and conventions for interpreting them (Ainsworth, 1999; Winn, 1991). Next, they should select what they perceive to be the most relevant aspects and make careful observations. Third, they must distinguish between the newly conceived ideas and their prior knowledge, recognize when these concepts conflict, demote the naive views, promote the correct ideas, and refine connections with other ideas. Instructional activities can be designed to focus students’ attention on key features of the visualizations and prompt them to discriminate ideas.

Results from Chapter 4 suggest that generating drawings is a promising way to promote knowledge integration with visualizations. When asked to make drawings about

molecular reaction processes, students need to consider details they might otherwise ignore. They recognize gaps in their previous interpretations, distinguish among their previous naïve ideas and new information from the visualization, and integrate normative views into their repertoire. In this chapter, I continue exploring how instructional activities can help students integrate ideas at the molecular level using the hydrogen combustion visualization.

Selecting Pictures to Support Learning

In this research I compare generation with selecting pictures. Students were asked to select and explain four pictures from a large set of alternatives to represent molecular processes during chemical reactions. To make selections, learners were expected to distinguish among the normative and non-normative ideas represented in the choices. Similar as generating drawings, they may realize the problems in their prior understanding if they find it difficult to choose. Students were expected to revisit the visualization and integrate new views from the visualization. Comparing generation with selection helps clarify the role of distinguishing ideas in facilitating student knowledge integration from visualizations and better inform instruction design.

Previous research suggests that selecting pictures promises deeper understanding (Clark & Paivio, 1991; Mayer & Moreno, 2003; Paivio, 1986). According to Mayer and Moreno's (2003) theory, meaningful learning requires significant conscious processing within the verbal and visual channels. Selecting and explaining pictures engage students in actively processing information within the two channels. Compared to studying the pre-organized materials, having students select pictures is cognitively engaging and can lead to an increase in learning.

An effective selection activity may take numerous cycles of refinement. Selection involves learners in working with multiple representations and engages them in several cognitive tasks (Ainsworth, 1999, 2006). To select correct pictures and put them in the correct order, learners need to understand the form of the representations (i.e., how to interpret each picture in the choices), the relation among the representations (i.e., how to sequence these pictures), and the relation between the representation and the domain (i.e., how these pictures represent molecular reaction processes). They may become overwhelmed by these tasks. Some of them may select the pictures by trial and error without understanding the underlying concepts. A successful selection activity should engage students in considering the ideas to be represented, examining each picture to understand the content, and selecting appropriate views from the incorrect ones. The selection activity investigated in this study was pilot tested among researchers and teachers before used in classrooms. I revised and refined the activity based on the results from each implementation.

Design of Generation, Simple Selection, and Complex Selection Activities

This study investigates student learning of the hydrogen combustion visualization with three activities respectively: generation, simple selection, and complex selection. Same as in previous studies, the visualization was embedded in the Hydrogen Fuel Cell Cars project. Students interacted with the visualization to understand hydrogen combustion at the molecular level, investigated how hydrogen and oxygen react in hydrogen fuel cells, and synthesized ideas to discuss the pros and cons of gasoline and hydrogen fuel cell cars.

After interacting with the visualization, students were asked to complete generation or selection activities. These activities engaged students in the same knowledge integration processes (*e.g.*, adding new ideas with the same visualization and sorting out ideas by answering the same embedded question to explain their interpretations) except in distinguishing ideas.

Generation Activity

Students were asked to create digital drawings of atomic interactions at four interim phases during hydrogen combustion: before hydrogen combustion starts, right after the reaction begins, after the reaction has been going for some time, and after the reaction completes. Students created the drawings using the WISE draw tool (Figure 5.1), which provides stamps of different elements. Students constructed the drawings by adding atoms and drawing lines between atoms to represent chemical bonds. After drawing, learners were asked to explain what they draw. The instructions of the generation activity used in this study are identical to those used in last chapter to maintain consistency.

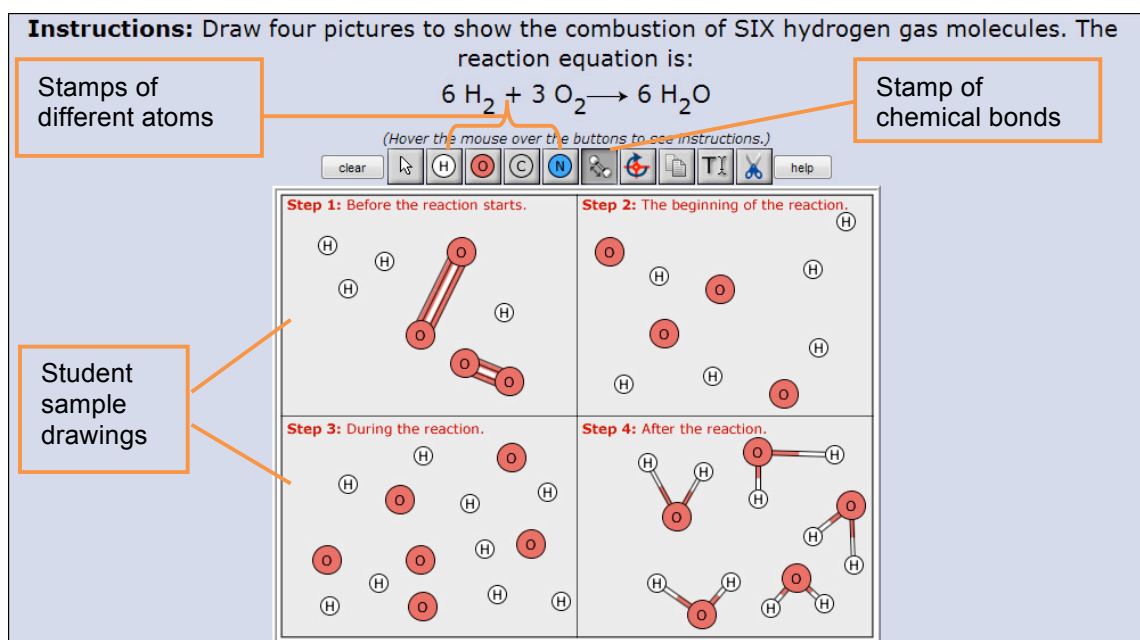


Figure 5.1. Screenshot of the WISE draw tool. The tool provides stamps of different elements and chemical bonds. Students use the stamps to create pictures of four intermediate phases during hydrogen combustion.

Selection Activity

Simple selection (SS).

SS consisted of four multiple-choice questions that asked students to choose pictures for the interim phases during hydrogen combustion (see Figure 5.2). Altogether students need to select from eight alternatives, most of which were snapshots of atomic interactions taken at different time during the run of the visualization. All the choices adopted the same color scheme as the visualization, using green circles to represent

hydrogen atoms and blue ones for oxygen. After the selection, learners need to explain their selections.

Figure 5.2. Screenshot of the SS activity. Students select and explain snapshots to represent intermediate phases during hydrogen combustion. The screenshot shows the questions that ask learners to select and explain a picture for the phase before the reaction start.

Complex selection (CS).

The implementation results of SS show that it was not as successful as generating drawings and failed to engage students in distinguishing non-normative and normative ideas. I revised and developed the CS activity (Figure 5.3) by including more student naive views in the choices. Major changes include:

- The choices of CS include more alternative ideas that students hold to encourage discrimination between ideas. For instance, choice J (in Figure 5) incorporates one non-normative idea about chemical bonding. It represents the molecular structure of H_2O molecule as a hydrogen atom in the middle with an oxygen and a hydrogen atom on each side. To select, students must distinguish this idea with the normative idea about H_2O in choice B (a oxygen atom in the middle with two hydrogen atoms on each side). As another example, choice C and H show reactants with different numbers of hydrogen and oxygen molecules. Students need to select by discriminating normative and non-normative ideas about coefficients.
- CS employs a different color scheme from the visualization. The implementation of SS found that learners often chose based on memorization of the visualization (this will be further discussed in the Study 1 results section). Using different

- colors discourages learners from selecting based on rote memorization and thus ensures that they will scrutinize the ideas represented in the choices.
- CS lays more emphasis on the continuity of molecular processes during chemical reactions than SS. It was designed as a “drag and drop” activity, with four blank boxes connected by arrows to represent the interim phases. Students select four pictures by dragging and dropping the pictures into each box. Once the boxes are filled, students can view all selected pictures on the same page.

Figure 5.3. Screenshot of the CS activity. The background shows the interface of the activity. Students drag and drop four pictures from the choices (at the bottom of this page) into the empty boxes to represent intermediate phases during hydrogen combustion. The foreground shows the question that asks learners to explain their selections.

Methods

This research includes two comparison studies: Study 1 compares the impact of generation and SS on student learning with visualizations, and Study 2 explores generation and CS. In this section I discuss assessments, scoring, and data analysis used in both studies. Information on participants and study design will be reported in the methods section of each study.

Data Resources

Pre and post-test.

In both studies, the teachers administered identical paper-based tests to individual students before and after the HFC project. The assessment includes six items: two recognition items that ask students to select molecular representations for interim phases during hydrogen combustion, and four knowledge transfer items that require learners to select or draw phases during other chemical reactions such as the reaction between nitrogen and hydrogen gas. In all questions, students need to explain their selections or drawings. The recognition items examine student understanding of the processes during hydrogen combustion, and the transfer questions assess whether students can apply their knowledge to new contexts and explain other chemical reactions.

Student drawings and selections.

During the project, students were asked to generate drawings or select pictures, and then explain the drawings or selections. Student drawings, selections, and explanations can provide information of how students develop their understanding about chemical reactions during the project.

Audio recording.

In addition to the quantitative data, I randomly audio taped the conversations of student pairs when they worked on the generation or selection activity. Altogether three student pairs in each condition were taped. The audio data can help capture information about how students worked through the activities.

Data Analysis

Analyzing advantages of selection vs. generation for all learners.

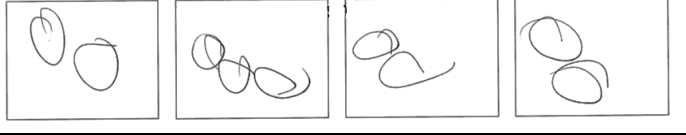
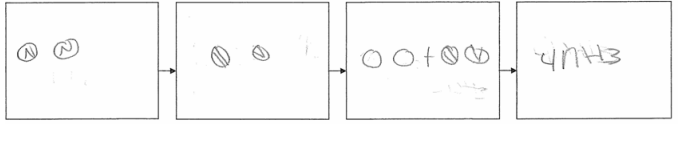
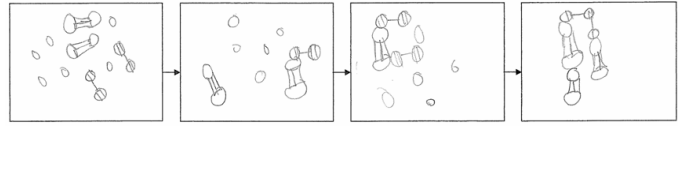
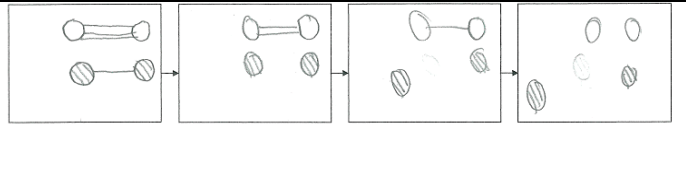
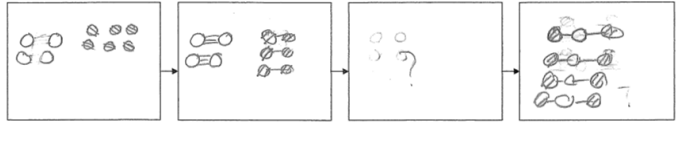
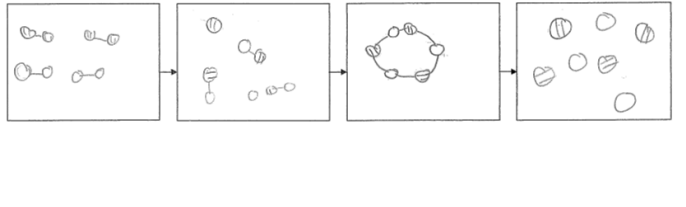
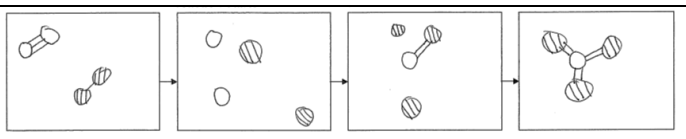
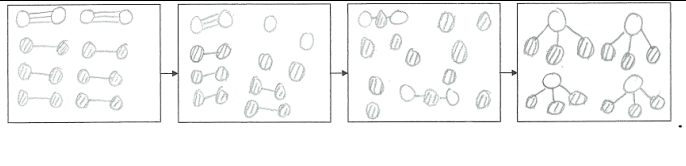
To investigate the advantages of selection over generation on student learning, I examined student performance on the pre and post-tests. Students' responses were coded using the knowledge integration rubrics (Linn, Lee, Tinker, Husic, & Chiu, 2006), focusing on the links students established between ideas and representations. The knowledge integration score ranges from 0 to 4 and higher scores indicate more complex links among ideas.

To compare student learning, I conducted ANCOVA, with the pretest score and treatment as explanatory variables, and the post-test score as outcome variable. I also compared student performance on different types of test questions and calculated effect sizes between the pre and post-test scores for the groups.

Analyzing advantages of selection vs. generation for learners with different ideas.

To explore how the activities affect students with different prior knowledge, I categorized student ideas demonstrated on the pretest. Then I performed a series of t-tests to compare the post-test performance of students with similar prior ideas. Students' prior knowledge was classified into three categories: mostly non-normative, mixed, and mostly normative ideas. Table 5.1 presents the categories, levels, and student sample drawings.

Table 5.1. Categories of student prior ideas. The sample answers include student drawings to represent how the reaction between nitrogen and hydrogen gas takes place at the molecular level.

Student ideas	Sample answers & descriptions			
Mostly non-normative ideas				
<p>No idea: Students don't have any idea about chemical reaction processes. They didn't draw anything meaningful.</p>				
<p>Instantaneous view: Students draw reactants or products, but they don't have any idea about how the chemical reaction takes place.</p>				
<p>Gigantic molecule view: Students think that after the reaction atoms are connected to form one molecule in the shape of a chain or a ring.</p>				
Mixed ideas				
<p>Bond breaking view: Students think during chemical reactions, all molecules try to break apart and the reaction ends up with separate atoms.</p>				
<p>Bonding view: Students think chemical reactions start with separate atoms. During chemical reactions, atoms try to bond to form final products.</p>				
<p>Wrong sequence view: Students have ideas about bond breaking and bond formation. But they often view that bond formation takes place before bond breaking.</p>				
Mostly normative ideas				
<p>No conservation view: Students draw bond breaking and formation correctly, but the pictures don't conserve matter</p>				
<p>Correct ideas: Students draw bond breaking and formation correctly and all pictures follow the law of conservation of mass</p>				

Mostly non-normative ideas.

Students held a repertoire of mostly non-normative ideas about chemical reaction processes. For instance, many students held the instantaneous view, as has been documented in previous research (Andersson, 1986; Krajcik, 1991). They thought chemical reaction as “*a magic process from reactants and products.*” They drew some ideas about reactants and products but did not represent any interim phases during chemical reactions. Some other learners had the gigantic view and drew molecules and atoms forming one gigantic molecule during the reaction.

Mixed ideas.

Students had normative ideas about one of the reaction processes but non-normative ideas in the other (*e.g.*, faultlessly representing bond breaking but making errors in representing bond formation). Some students had correct ideas about both processes but established wrong links between them (*e.g.*, drawing both processes correctly but sequencing them in a wrong order).

Mostly normative ideas.

Learners often demonstrated full or complex links among ideas about chemical reactions. They drew bond breaking and formation correctly. Some students were able to link with ideas about the conservation of matter law (*i.e.*, maintaining the same number of atoms across all the drawings). Some other students linked with the idea of activation energy (*i.e.*, drawing a spark to indicate when bond breaking takes place). Students at this level had complicated understanding about chemical reaction processes. Few students had such ideas on the pretest.

Investigating contributions of selection vs. generation to integrated understanding.

Analyzing student drawings and selections.

To understand how generation and selection facilitate learning, I analyzed the drawings and selections students generated during the project. I developed parallel coding rubrics to analyze student drawings and selections. The rubrics focus on whether students develop valid connections among molecular representations, bond breaking, and formation (see Table 5.2). For instance, if a student generated or selected pictures to represent bond breaking and formation correctly, his response was coded as 3, indicating a full link between reaction processes and molecular representations. Two coders coded student data separately and the inter-rater reliability was 92%. Inconsistent codes were discussed and resolved.

Table 5.2. Parallel scoring rubrics designed to code student drawings and selections.

Knowledge Integration Score	Description of student drawings	Description of student selections
<p>4 Multiple valid links among reaction processes (bond breaking and formation), molecular representations, and relevant ideas such as activation energy and the conservation of matter law.</p>	<p>Draw the reaction processes correctly AND all drawings contain the same number of atoms OR draw spark to ignite the reaction</p>	<p>Select correct pictures to represent reaction processes correctly, AND these pictures have the same number of atoms.</p>
<p>3 One scientifically valid link between reaction processes and molecular representations.</p>	<p>Draw the reaction processes correctly, i.e., draw the reactants, products, bond breaking, and bond formation correctly.</p>	<p>Select correct pictures to represent reaction processes correctly, but these pictures do not show the same number of atoms.</p>
<p>2 Partial ideas about reaction processes, but do not fully elaborate links between them.</p>	<p>Draw partial of the reaction processes correctly, e.g., draw bond breaking or bond formation correctly.</p> <p>Or Create drawings that demonstrate the ideas of bond breaking and formation but does not represent with correct molecular representations.</p>	<p>Select correct pictures to represent bond breaking or bond formation.</p>
<p>1 Incorrect ideas about chemical reaction processes, or invalid links between chemical reaction process and molecular representations.</p>	<p>Create drawings that demonstrate wrong reaction processes, e.g., drawing that during hydrogen combustion the only change is the decrease in the number of oxygen molecules decreases.</p>	<p>Select wrong pictures of the interim phases.</p>
<p>0 No answer or off-task answer.</p>	<p>Does not draw at all, or does not draw anything meaningful about interim phases during hydrogen combustion.</p>	<p>Does not select.</p>

Examining audio data.

In addition to the quantitative analysis, I examined the audio data of student conversations when they worked on the tasks. Examining student conversations can provide qualitative evidence to support conclusions drawn from the statistical analysis.

Study 1: Compare Drawing and Simple Selection

Methods

Participants.

This study involved 110 high school chemistry students (five classes) in a public high school taught by the same teacher (Ms. P). Most students were 10th or 11th graders taking regular high school chemistry. This project was taught before any classroom instruction on chemical reactions. As other WISE project, students worked through the project in pairs. Ms. P had been teaching high school chemistry for five years and this was her second year teaching with WISE projects.

Study design.

The five classes were randomly assigned to generation (three classes, n=64) or simple selection group (two classes, n=46). Students learned the *Hydrogen Fuel Cell Cars* project and completed the pre and post-tests in six days. On the third day, students in both groups spent the entire class period (approximately 45 minutes) learning chemical reactions. They interacted with the visualization, generated or selected pictures, and explained their drawings or selections.

Results and Discussions

Advantages of SS vs. generation for all learners.

Pretest performance.

Students in generation and SS groups started the HFC project with similar levels of prior knowledge. No statistically significant difference was found between their performance on the pretest [$t(108)=.40, p<.01$] (see Table 5.3 for the analysis results). A majority of students held incorrect ideas about chemical reactions before the project. They did not think that there were interim phases during chemical reactions.

Table 5.3. Data analysis results to compare the pre/post-test performance of students in drawing and simple selection (SS) groups.

	Group	Pretest Mean (SD)	Posttest Mean (SD)	Effect Size	ANCOVA Results
All items	Generation	1.03(.83)	2.42 (.65)	1.56	F(1,107)=9.71, $p<.01$
	SS	1.09 (.86)	2.01 (.91)	.99	
Recognition items	Generation	.94 (.74)	1.94 (.72)	1.12	F (1, 107) =.91, $p=.34$
	SS	.87(.83)	2.01 (.72)	1.21	
Transfer items	Generation	1.06 (.97)	2.66 (.78)	1.44	F (1, 107) =17.24, $p<.001$
	SS	1.21 (1.01)	1.99 (1.13)	.72	

Comparing student learning on all items.

After learning the *HFC* project, all students improved their understanding of chemical reactions significantly [$t(109)=13.42, p<.0001$] (see Table 5.3). Students in the generation group advanced to an average post-test score of 2.42, indicating that most of them were able to integrate ideas of bond breaking and formation and link with molecular representations. Learners in the SS group achieved a mean score of 2.01 on the post-test, suggesting that they integrated one idea about reaction processes and few integrated both ideas of bond breaking and formation.

ANCOVA shows that students in the generation group achieved higher post-test scores than the SS group after controlling for pre-test scores [$F(1, 107)=9.71, p<.01$]. Drawing supported students to integrate more ideas of chemical reactions from dynamic visualizations than SS.

Comparing performance on different types of items.

I also examined student performance on different types of assessment items.

- *Recognition questions.* On the post-test, learners in the SS group achieved slightly higher scores on the recognition items than the generation group, yet the ANCOVA result was not significant [$p=.34$]. Most students selected correct pictures and explained how hydrogen combustion takes place at the molecular level.
- *Transfer questions.* Learners in the generation group outperformed those in the SS group on items that assess knowledge transfer [$F(1, 107)=17.24, p<.001$]. Students under the generation condition often were able to explain reaction processes of chemical reactions other than hydrogen combustion. Students under the selection condition often could only explain part of the processes.

Overall, the results show that generation prompted students to integrate more ideas from dynamic visualizations than SS. Students in the generation group performed better on transfer items than those in the SS group. This indicates that generation supports learners to develop more robust connections among ideas so that they can apply to new contexts. SS may help students memorize information from the project but students' understanding was limited within the reaction of hydrogen combustion.

Advantages of SS vs. Generation for learner with different prior ideas.

Before the *HFC* project, 61 students had mostly non-normative ideas about chemical reactions, 32 students had mixed ideas, and 17 students had mostly normative ideas (see Table 5.4).

Table 5.4 Distribution of students with various ideas in generation and SS groups.

	Mostly non-normative	Mixed	Mostly normative
Generation	38	16	10
SS	23	16	7
Total	61	32	17

Generation had more significant impact on students with mixed ideas than SS [$t(30)=3.11, p<.01$] (see Figure 5.4). With regard to learners who had mostly normative

or mostly non-normative, generation and SS had similar effect [Mostly non-normative: $t(59)=1.59, p=.12$; Mostly normative: $t(15)=.04, p=.97$]. This suggests that both activities successfully supported students to integrate ideas about bond breaking and formation from the visualization. Generation was especially beneficial to students who had partially correct ideas about chemical reactions.

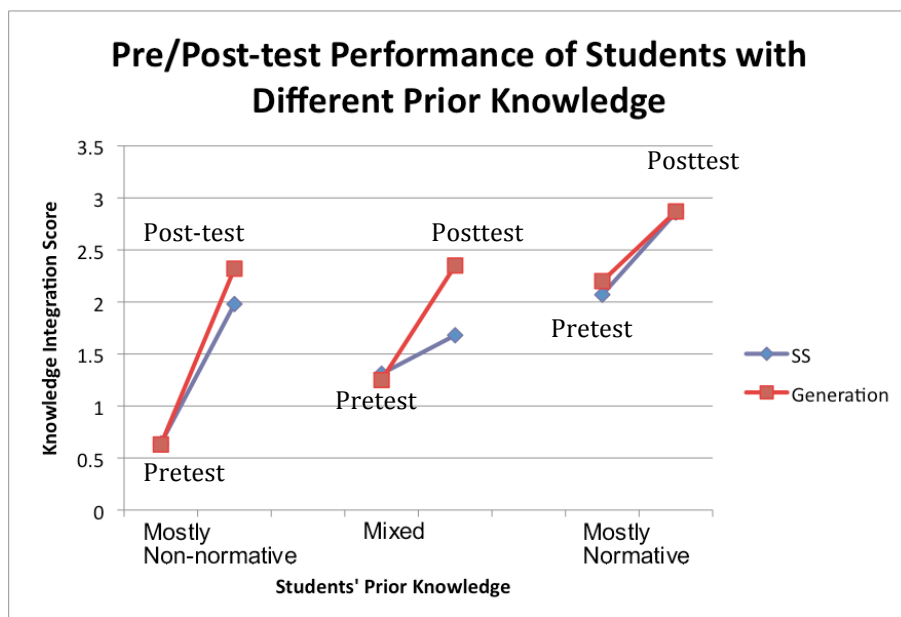


Figure 5.4. Pre/post-test performance of students with different prior knowledge in generation and SS groups.

Contributions of SS vs. generation to integrated understanding.

Examining students' drawings and selections.

To understand how SS and generation facilitated integrated understanding of chemical reactions, I examined student work during the project. Because most students under both conditions drew or selected correctly (generation group: 24 pairs, 71%, SS group: 18 pairs, 72%), I focused the analysis on these students and compared their explanations about hydrogen combustion.

The results show that students who drew correctly explained more ideas about chemical reaction processes than those who selected correctly [$t(40)=2.68, p=.01$]. All students who drew correctly explained bond breaking and formation accurately, whereas 28% of the students who selected correctly did not explain any molecular processes. Often they explained the reaction processes as “*molecules react and form products.*” This suggests that in SS, students were able to make correct selections without deep understanding of molecular reaction processes. They still maintained their prior ideas about chemical reactions. SS did not enable them to realize gaps in their interpretation and integrate new ideas from the visualization.

Analyzing student audio recording.

To find out how students managed to select without deep understanding, I examined the audio data. Among the three pairs of students under SS condition I

audiotaped, two pairs selected and explained correctly. Only one pair selected correctly without explaining any reaction processes. They explained that hydrogen combustion occurs as *“(before the reaction starts) they haven’t reacted yet and they are molecules”, “(right after the reaction begins) then they start to make water”, “(after the reaction has been going for some time) then they continue making water and reacting”, and “(after the reaction completes) at this point the hydrogen molecules have reacted with oxygen molecules forming water.”*

I focused on this student dyad and examined their conversations during the selection. The following excerpt shows their discussion about which picture to select for the phase when bond breaking occurs (Phase two).

Student A: “so, a or b, definitely not a, maybe b or c?”

Student B: “so you remember that they were like this (choice b), then they were like that (choice a)?”

Student A: “I know, so b?”

Student B: “yeah, I guess so.”

Student A: “ok, b, why?”

Student B: “um, they are starting to get attached in b.”

This pair of students ended up choosing the correct snapshot (choice b), yet they did not mention any idea about bond breaking in their discussion. Instead of examining the ideas represented in the snapshots, they made selections based on the sequence of the snapshots that they observed from the visualization. As a result, SS did not enable students to realize gaps in their knowledge. Learners failed to integrate new ideas from the visualization.

This audio recording helps clarify why SS was not as effective as generation. In SS, students were able to choose correct pictures based on superficial information they remembered from the visualization. SS did not encourage students to analyze ideas represented in the choices, distinguish these ideas with their own views, and integrate new ideas from the visualization. Therefore, on the post-test 58% of students who selected correctly returned to their prior ideas and responded with non-normative or partial ideas about reaction processes.

On the contrary, generation required students to represent bond breaking and formation. To decide what to draw, learners need to distinguish between their prior ideas and expert views conveyed in the visualization. Drawing enabled students to recognize when these ideas bump against each other and refine their understanding. On the post-test 70% of the students who drew correctly retained their new ideas from the project and explained bond breaking and formation correctly.

Summary

Study 1 shows that SS was not as effective as generation in helping students integrate ideas from the visualization. On the post-test, more students in the generation group were able to apply their knowledge to explain new chemical reactions than the SS group. Analyzing student explanations and conversations suggests that students were able to select correctly based on their memorization from the visualization. SS failed to enable students to distinguish ideas represented by the choices with their own. Students did not feel the need to revise their understanding. In contrast, generation was successful because it forced students to decide between their prior ideas and expert views they saw from the

visualization. Students were prompted to recognize when the ideas conflict, revise ideas, and refine connections.

Study 2: Compare Drawing and Complex Selection

Based on the results of Study 1, I developed the complex selection (CS) activity, which included more student alternative ideas in the choices than SS. To discourage student from making selections based on rote memorization, particles were represented using color schemes different from those in the visualization.

Methods

Participants.

Study 2 involved 172 8th graders (six classes) in a public school taught by one teacher (Ms. E). She had been teaching 8th grade chemistry for eight years and WISE projects for five years. This project was taught after students learned basics about structure of matter and before any instructions on bond breaking and formation. Similar as in study 1, students worked through the project in pairs.

Study design.

The six classes were randomly assigned to generation (three classes, n=89) and CS groups (three classes, n=83). Students completed the project, pretest, and post-test in six days. On Day 3, students in both groups spent 45 minutes interacting with the visualization, completing the generation or CS activities, and explaining their drawings or selections.

Results and Discussions

Advantages of CS vs. Generation for all learners.

Pretest performance.

Students in both groups started the project with similar levels of knowledge about chemical reactions [$t(170)=.88, p=.38$]. They had an average score of 1.63 on the pretest. Approximately half of the students had non-normative ideas about chemical reactions and the other half had partially correct ideas before the project.

Table 5.5 Data analysis results of drawing and complex selection (CS) groups' performance on pre- and post-test.

	Groups	Pretest Mean (SD)	Posttest Mean (SD)	Effect Size	ANCOVA Results
All items	Generation	1.59 (.66)	2.69 (.56)	1.71	F(1,169)=1.72, <i>p</i> =.19
	CS	1.68 (.64)	2.81 (.51)	1.57	
Recognition items	Generation	1.68 (.68)	2.75 (.56)	1.20	F (1, 169)=.53, <i>p</i> =.47
	CS	1.66 (.69)	2.81 (.56)	1.40	
Transfer items	Generation	1.55 (.80)	2.66 (.63)	1.53	F (1, 169)=1.78, <i>p</i> =.18
	CS	1.68 (.78)	2.82 (.62)	1.25	

Comparing student learning on all items.

Learners in both groups significantly improved their understanding of chemical reactions after the project [$t(171)=21.45, p<.0001$] (see Table 5.5 for the data analysis results). On the post-test, all students achieved an average score of 2.75. Most students established valid links between bond breaking, formation, and molecular representations.

The ANCOVA result shows that that students under both conditions achieved similar performance on post-test. Generation and CS had similar impact on helping students integrate ideas about bond breaking and formation from the visualization. Learners developed coherent understanding about chemical reactions after the project.

Comparing student learning on different items.

No significant difference was found in the two groups' performance on items that assess knowledge recognition or transfer. Large effect sizes of both activities were obtained on all items. Students were able to not only explain interim phases during hydrogen combustion, but also apply their knowledge to explain other chemical reactions.

Advantages of CS vs. generation for students with different prior ideas.

Similar to Study 1, I categorized various ideas held by students before the project and compared the learning of students with similar ideas (see Table 5.6 and Figure 5.5). Altogether 81 students started the *HFC* project with mostly non-normative ideas about chemical reaction processes, 74 students had mixed ideas, and 17 students had mostly normative ideas.

Table 5.6 Distribution of students with various ideas in generation and CS groups.

	Mostly non-normative	Mixed	Mostly normative
Generation	46	34	9
CS	35	40	8
Total	81	74	17

CS was more beneficial to students who had mixed ideas than generation [$t(72)=.19, p<.05$]. On the posttest, 65% of students in the CS group who had mixed prior ideas explained correct molecular processes during hydrogen combustion and other chemical reactions. Only 29% of students in the generation group with similar prior knowledge were able to do so on the post-test. Almost half of them still explained using mixed ideas after the project. With regard to students who held mostly normative or non-normative ideas before the project, CS and generation had similar effect [Mostly non-normative: $t(79)=.20, p=.84$; mostly normative: $t(15)=.19, p=.85$].

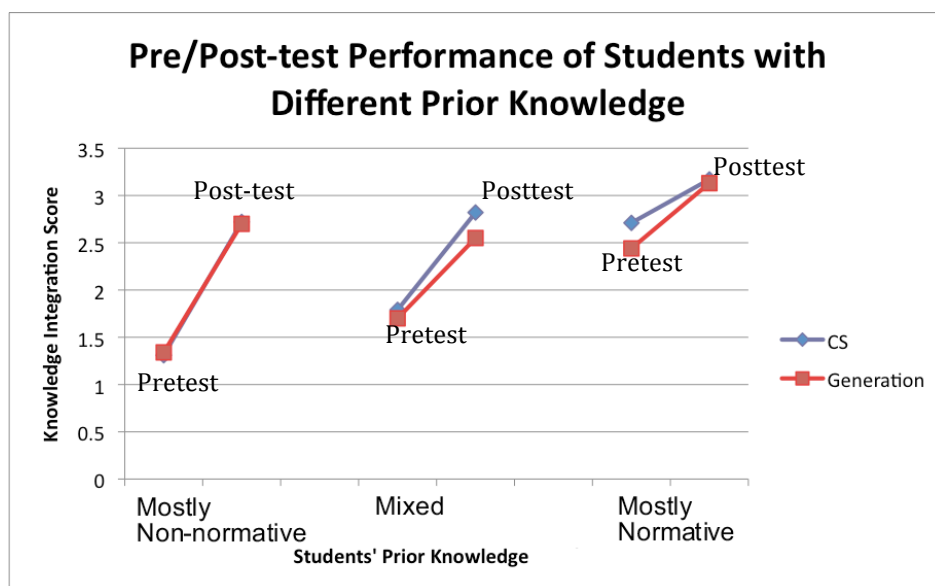


Figure 5.5. Pre/post-test performance of students with different prior knowledge in generation and CS groups.

Contributions of CS vs. generation to integrated understanding.

As in Study 1, I compared the explanations generated by students who drew or selected correctly (generation group: $n=32$, 68%; CS group: $n=34$, 71%). No significant difference was found in the quality of explanations generated by these students [$t(64)=.43$, $p=.66$]. Most students in both groups explained hydrogen combustion with ideas of bond breaking and formation. This confirms that CS and generation had similar impacts on helping students integrate ideas from visualizations.

Summary

Study 2 shows that selection activities that incorporate student non-normative ideas in choices can promote student learning with visualizations. Both CS and generation succeeded in helping students integrate ideas about bond breaking and formation from the visualization. In particular, learners who had partially correct ideas achieved more learning gains from CS than generation. CS may be more helpful to these students than generation.

Conclusion

This chapter extends research in designing instructions to enhance student learning with dynamic visualizations by comparing generation with selection. The results show that generation and CS succeeded in helping students integrate ideas about bond breaking and formation from the visualization. SS was less successful than generation and many students were able to select correct pictures without deep understanding of underlying concepts. A selection activity that engaged students in distinguishing among normative and non-normative ideas can lead to integrated understanding with visualizations.

Results from Chapter 4 and the present study prove the benefits of generating drawings. Interacting with visualizations cannot guarantee that students will learn.

Learners may develop understanding based on superficial information and ignore important detail. To form an integrated understanding, students need to realize gaps in their prior interpretations, distinguish between their old ideas and new information from the visualization, and refine their views. Generation provides students with an opportunity to test and distinguish their ideas. Learners recognize that their initial understanding lack detailed information about molecular processes. They revisit the visualization, add new ideas from the visualization, and distinguish them from their old ideas. Log files of student interactions support this hypothesis. Among the 81 students dyads who generated drawings in study 1 and 2, 72.7% (n=59) returned to the visualization during drawing. Each revisit lasted from more than 4 minutes to 35 seconds. On average they spent 91 seconds (one minute and a half) each revisit, scrutinizing the visualization for detailed information, and distinguishing among new ideas and their non-normative views.

Selection activities also succeeded in encouraging learners to distinguish ideas and therefore enhanced student learning. In CS, learners need to select pictures from twelve alternatives to represent chemical reaction processes. The alternatives were designed to represent common non-normative ideas held by students. To select, students must distinguish among these ideas. They may find it challenging to choose and are motivated to revisit the visualization. They first integrate new ideas by distinguishing their prior knowledge from expert views demonstrated in the visualization. Then, they return to the CS task, analyze ideas represented in the alternatives, and distinguish the normative from non-normative views. SS fails because it does not include student non-normative ideas in the choices and does not engage students in distinguishing ideas. Students select based on their memorization of superficial information from the visualization. They do not realize the necessity of adding new ideas and therefore do not have chances to distinguish ideas.

Student log files reveal evidence for this hypothesis. Students in the CS group on average revisited the visualization more frequently than those in the simple selection group. Two of the 25 student pairs (8%) in the SS group returned to the visualization, whereas 37 of the 48 student dyads (77%) in the complex selection group revisited.

Implications for Designers of Instruction with Visualizations

The results offer several guidelines for designing activities to enhance student learning with dynamic visualizations. First, selection tasks should include common alternative ideas that student hold to encourage distinguishing between non-normative and normative ideas. For instance, the choice J in CS represents a naïve idea about chemical bonding held by students: hydrogen atoms can form more than one bond with other elements. It shows H₂O molecule as a hydrogen atom in the middle with an oxygen atom and a hydrogen atom on each side. To select pictures for chemical bonding, students must distinguish the non-normative (as in choice J) from normative ideas (as in choice B).

Second, instructional activities should focus student exploration of the visualization on the crucial disciplinary knowledge that they need. When learning with the hydrogen combustion visualization, learners often neglect key concepts such as bond breaking and formation. They may focus on details that are not important (*e.g.*, bouncing balls). The selection and generation tasks engage students in representing molecular reaction processes and focus their attention to these important ideas.

Third, visualization design should reduce distracting information. Some features of visualizations may be obvious to scientists and engineers but challenging and misleading to students. For instance, the PhET simulation about chemical reactions was designed with a pump to add molecules to the reaction. While designers may believe that manipulating the pump helps teach about limiting reagents, learners often become confused and do not understand the purpose of the pump. They may think it is related to pressure change and develop incorrect understanding. Therefore this feature should be deleted or revised. Successful visualizations typically take numerous cycles of implementation and refinement.

Limitations

This study shows that selecting pictures to represent the sequence of chemical reactions as well as generating drawings help students learn from dynamic visualizations. The limitations include that the two studies were implemented on students at different grades (study 1 on high school students and study 2 on middle school students). The results may differ from situations involving participants, treatments, settings, and measures different from those in the study.

In the next chapter, I further the understanding of distinguishing ideas by investigating another instructional approach: critique. Critique shares some characteristics with selection as students need to distinguish between their own understanding and the ideas in the responses to be critiqued. I explore how to design a critique activity that can promote integrated understanding with visualizations as generating drawings. Moreover, I take advantage of the new WISE technology and log student interactions with the visualization. Computer log files can provide more detailed information about student interaction patterns facilitated by generation and critique, and therefore can offer better guidance to improve the activities.

Chapter 6: Promote Learning with Visualizations: Generation and Critique

This chapter discusses designing critique activities to promote integrated understanding with dynamic visualizations. Dynamic visualizations can contribute to chemistry learning because they enable learners to visualize unseen processes and phenomena. Students can add ideas about atomic interactions and explain observable phenomena using these atomic-level ideas. Nevertheless, learning with visualizations is challenging. Learners may form interpretations based on superficial information and fail to integrate key ideas. To learn effectively from visualizations, students should distinguish their prior ideas and the expert views demonstrated in the visualizations, sort out, and refine their understanding. Chapters 4 and 5 suggest two promising approaches to promote distinguishing among ideas: generating drawings and selecting pictures from alternatives. They prompt students to recognize gaps in their interpretations, revisit the visualizations with increased attention on key details, distinguish between their own non-normative ideas and normative ideas from the visualization, and integrate new ideas.

In this chapter, I explore the impact of critique on student learning with visualizations. Critique can also potentially prompt discrimination among ideas because to critique, students need to distinguish between their own understanding and the ideas in the responses to be critiqued. They need to develop criteria to decide whether the response is correct. This study compares student learning with visualizations under two conditions: generation and critique. Students learned chemical reactions with the hydrogen combustion visualization. The generation treatment asked learners to create drawings about molecular processes during hydrogen combustion. The critique treatment required students to critique drawings about the processes created by two fictitious peers. I hypothesize that critique has similar impact on student learning with visualizations as generation.

This chapter seeks to answer the following research questions:

- What are the advantages of critique versus generating drawings of chemical reactions for all learners and for learners with non-normative, mixed, and partially normative ideas?
- How does critique contribute to integrated understanding of chemical reactions?

To foreshadow the results, this chapter found that critique supported students to integrate ideas from the visualization as generation. Students in both groups achieved similar learning gains after the project. Student responses to the embedded question and their drawings and critiques show that generation and critique helped them revise their initial interpretations of the visualization and integrate more ideas. Computer log files demonstrate that students frequently revisited the visualization during these activities for new information. Critique activities embedded in an inquiry-based curricular project can support students to integrate ideas from visualizations and develop connections among ideas.

Rationale

Critique to Support Learning with Dynamic Visualizations

Critique is an activity that frequently occurs in our everyday life. Often we can find critiques in newspapers and magazines. Performing a critique involves generating

and applying criteria for evaluating responses to be critiqued. Research shows that students often have a repertoire of criteria. For example, when asked to evaluate representations of motion, 6th graders performed critiques based on whether the representation shows all relevant information, whether it violates accepted conventions, and whether it is easier to explain to other children (diSessa et al., 1991; diSessa, 2004). These criteria are drawn from different concerns including the format, purpose, validity, accuracy, and aesthetics.

Critique has the potential to enhance student understanding of the concepts underlying the response to be critiqued. Several studies have demonstrated that when asked to critique the models built by themselves, students test the model against the reality or scientific facts, distinguish among ideas, and refine their understanding (Gilbert, 2005; Lehrer & Schauble, 2006; Penner, Gilles, Lehrer, & Schauble, 1997). Moreover, critique encourages reflection. When asking middle school students to critique their peer's molecular animations, Chang, Quintana, & Krajcik (2010) found that students examined their own ideas and reflected on their animations during critique. This iteratively reflective process helped learners improve the quality of their animations and their understanding of the discipline.

Further, critique can promote student experimenting with visualizations by encouraging them to distinguish among ideas. Chang & Linn (submitted) compared student learning with a dynamic visualization of heat flow under three conditions: critique, interaction, and observation. In the observation treatment, students observed how heat transfers between hot and cold objects. In the interaction treatment, learners manipulated variables and conducted experiments to understand heat flow. In the critique treatment, students learned by critiquing the experiments conducted by a fictitious student named Mary. The results show that the critique treatment added value to the visualization and enhanced student interpretations of the visualization. Critique required students to distinguish between their own and Mary's ideas about experimenting. Neither the interaction condition nor the observation condition required distinguishing among ideas.

Incorporating critique activities in science classrooms faces several challenges. First, learners are rarely presented with the opportunity to critique (Clark & Slotta, 2000). In formal instruction, science theories and models are often taught as facts in textbooks or by teachers who represent authority. Students are not asked to critique their knowledge. Second, students may not understand the meaning of performing critique. In a study that asked undergraduate students to evaluate a sociology text with their own positions, Mathison (1996) found that only half of the students viewed critique as the task of finding weakness in the text. However, a third of the students focused on summarizing the text and reporting information. In addition, students may not know how to critique and they may not appreciate the role of critique in science (Mathison, 1996; Tabak, Weinstock, & Zviling-Beiser, 2009; Taylor, 2009). Students often use superficial criteria (e.g., spelling, vocabulary, or grammar) rather than scientific facts (e.g., evidence from experiments) (Izsak, 2004).

An effective critique activity requires guidance and structured activities. For instance, in the study by Chang et al. (2010), students critiqued the animations using a set of criteria and prompting questions. White and Frederiksen (1998, 2000) suggest that critique may be more effective if it includes reflective assessment. In Schwarz and White's study (2005), the critique activity was structured such that students first created

and tested their own models of force and motion, they then used explicit criteria to evaluate each other's models, and finally they reflected on the nature of models. These explicit modeling activities improved students' meta-modeling knowledge, i.e., knowledge about the nature and purpose of scientific models.

The present study extends current research in critique by exploring how it can be embedded in an inquiry-based curricular project to promote learning with a dynamic visualization. Students first interacted with a visualization molecular visualization about hydrogen combustion and then critiqued two sets of drawings about reaction processes created by fictitious peers. Critiquing a fictitious student has potential advantages over peer critiquing because students may show reluctance to critique their classmates' artifacts. The fictitious drawings were designed by researchers to encourage students to distinguish among ideas. The drawings represent common alternative ideas held by students. To critique, students need to distinguish their own ideas and the non-normative views in the drawings.

Design of the Generation and Critique Activity

In this study I compare student learning about chemical reactions with visualizations under two conditions: critique and generation. Both treatments were designed to engage students in the same knowledge integration processes except in the area of distinguishing ideas. On the third day of the HFC project, students under both conditions spent the entire class period (~40 minutes) learning chemical reactions. They added new ideas with the same visualization, distinguished ideas through generation and critique tasks, sorted out and refined their ideas by answering the same embedded question to explain their interpretations.

Generation Activity

The generation activity was identical to the one developed in Chapter 5. Students were required to create four digital drawings to show atomic interactions at four interim phases during hydrogen combustion: before hydrogen combustion starts, right after the reaction begins, after the reaction has been going for some time, and after the reaction completes. Using the WISE draw tool, students construct the drawings by selecting appropriate stamps of atoms and chemical bonds and adding them to the blank space in the tool (Figure 5.1 presents a screenshot of the WISE draw tool). After drawing, learners were asked to explain what they draw.

Critique Activity

Students were asked to evaluate two sets of drawings created by fictitious peers (see Figure 6.1 for one set of the drawings and critique questions). They indicated whether the drawings were accurate, partially correct, or wrong, and then explained their evaluations. To encourage students to distinguish ideas, the drawings were designed to represent common non-normative ideas held by students. For instance, one set of drawing (Terry's) represented a common alternative idea: atoms first form and then break bonds during chemical reaction. To critique, students needed to distinguish their own ideas from Terry's non-normative ones. Terry also did not draw the same number of atoms in all his drawings. The critique distinguished between the normative and non-normative ideas about the conservation of matter law.

The critique activity was first pilot tested among researchers, teachers, and sample students to ensure its clarity and whether it was suitable for the audience. I revised the activity based on the feedback before it was used in classroom.

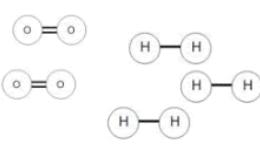
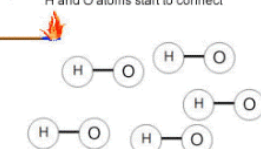
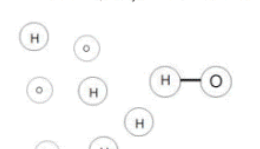
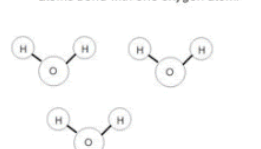
<p>Step 1: Before the reaction starts</p> 	<p>Step 2: A spark is added to start the reaction. H and O atoms start to connect.</p> 	<p>Look at Terry's drawings. Explain what are good and bad in each drawing.</p> <p>1. Is Terry's drawing of Step 1 accurate, partially correct, or wrong? Explain what are good and bad in Step 1 drawing.</p> <p>Terry's drawing of Step 1 is ____ (Accurate/Partially correct/Wrong). Good parts of Terry's drawing:..... Bad parts of Terry's drawing:.....</p> <p>2. Is Terry's drawing of Step 2 accurate, partially correct, or wrong? Explain what are good and bad in Step 2 drawing.</p>
<p>Step 3: The spark makes atoms move faster and faster, many of them break bonds.</p> 	<p>Step 4: Finally, they settle down and two hydrogen atoms bond with one oxygen atom.</p> 	

Figure 6.1. Screenshot of the critique activity. Left: one of the fictitious drawings (Terry). Right: sample critique questions that ask students to evaluate the drawings.

Methods

Participants

This study involved 73 high school students (three classes) taught by the same teacher (Mr. T) at a public high school in the United States. Most students were 10th or 11th graders taking regular high school chemistry. Two classes were randomly assigned to the critique condition (n=48) and the other one was assigned to the generation condition (n=25). This unit was taught before any classroom instruction on chemical reactions. Students studied the unit in pairs while the teacher circulated and responded to questions. Mr. T had been teaching high school chemistry for five years and this was his second year teaching with WISE units. As other WISE projects, students worked in pairs.

Study Design

The study investigates student learning about chemical reactions with the hydrogen combustion visualization and compared generation and critique activities. I gathered data from pre-post assessments, embedded questions, the critiques or drawings generated by learners, and log files of student interaction with the visualization. Student responses to pre-post assessments were analyzed to understand the overall impact of critique and generation on student learning. Student answers to embedded questions, and their critiques or drawings were used to investigate how critique contributes to integrated understanding with the visualization. Computer log files were used to help refine my interpretation of the results.

Assessments and Data Analysis

Advantages of critique vs. generation by comparing pre and posttest.

Design of pre and posttest.

In both implementations, the teachers administered identical paper-based tests to individual students before and after the unit. The assessment consists of nine items:

- two recognition items that ask students to select molecular representations for interim phases during hydrogen combustion;
- three critique items that require learners to critique pre-made drawings about how methane combustion takes place at the molecular level;
- two drawing and explanation questions that ask students to draw and explain molecular processes during the reaction between nitrogen and hydrogen gas;
- two selection items that require students to select representations for interim phases during the reaction between hydrogen and chlorine gas.

Students need to provide reasons for their selections or drawings in all questions. The recognition items aim to examine student understanding of hydrogen combustion. The other seven questions ask students to apply their ideas to new reactions. These questions assess whether students can apply their knowledge to new contexts and explain new chemical reactions. All questions except the critique items were the same as those used in Chapter 5.

Advantages of critique vs. generation for all learners.

I analyzed student performance on pre- and post-tests to investigate the impact of generation and critique on student learning. Consistent with studies in other chapters, students' responses to tests were coded using the knowledge integration rubrics (Linn, Lee, Tinker, Husic, & Chiu, 2006), with a focus on the links students established between ideas and representations. Higher scores indicated more complex links among ideas. Detailed descriptions of the scoring rubrics can be found in Chapter 2 and Appendix B.

To compare student learning under generation and critique conditions, I conducted ANCOVA using the mean pretest score and treatment as explanatory variables, and the mean posttest score as the outcome variable. I analyzed student performance on all test items and different types of test questions. Effect sizes between the pre- and posttest scores for the groups were calculated.

Advantages for learners with different prior ideas

I categorized student ideas in their pretest drawings and compared the learning gains of students who started the HFC project with similar ideas. Using the same categorization developed in Chapter 5, I classified students' ideas about chemical reaction processes into three categories: mostly non-normative, mixed, and mostly normative ideas (see Chapter 5, Table 5.1 for detailed descriptions of each category and student sample drawings). To investigate whether students' prior knowledge affects the impact of generation and critique, I performed multiple regression analysis using learning gains as the outcome variable, student prior knowledge and treatment as the explanatory variables.

Knowledge integration through critique vs. generation.

To track how students developed their understanding about chemical reactions through critique and generation, I analyzed student responses to an embedded question, drawings, and critiques. Student explanations revealed the ideas they had after exploring the visualization. Their drawings and critiques reflected new ideas gained from generation and critique. I also analyzed computer log files to understand student navigation patterns with the visualization under both conditions. I gathered data from all

student pairs involved in this study (total: 39 pairs, critique group: 26 pairs, generation group: 13 pairs).

Analyzing student explanations, drawings, and critiques.

Immediately after exploring the visualization, students were asked to answer an embedded question, “*Describe how chemical bonds change during hydrogen combustion.*” To answer this question, students needed to explain their observations of the visualization. Their responses reveal interpretations of chemical reaction processes based on interacting with the visualization. After the embedded question, students generated digital drawings or critiqued pre-made drawings about molecular reaction processes shown in the visualization. Their drawings and critiques provide evidence of new ideas gained from generation and critique.

I developed parallel scoring rubrics to code student explanations in the embedded question, drawings, and critiques (Table 6.1). These rubrics assessed valid connections between reaction processes and molecular representations. For instance, if a student generated or critiqued pictures of bond breaking and formation correctly, his response was coded as 3, indicating a full link. I averaged student critique score on each set of drawings to obtain a mean score for their critiques. Two coders coded student data separately, and the inter-rater reliability was 98%. Inconsistent codes were discussed and resolved.

Analyzing computer log files.

In the previous implementations of the generation condition, I observed that students often returned to the visualization for new ideas while generating drawings. In this study, I took advantage of new technologies in WISE and logged how students navigated around the visualization. Specifically, I analyzed student revisits to the visualization. I analyzed whether students revisited the visualization to integrate new ideas, how many times they revisited, and the amount of time they spent during each revisit. Analyzing the log files allows me to examine the similarities and differences in student navigations under the two conditions and helps explain conclusions drawn from statistical analysis.

Table 6.1. Parallel scoring rubrics designed to code student answers to the embedded question, drawings, and critiques. The embedded question asks, “*Describe how chemical bonds change during hydrogen combustion.*” The drawing task asks students to represent chemical bonds change during the reaction. The critique task requires students to critique fictitious drawings about chemical bond changes. The scoring rubric for critiques presented here is designed to analyze student critiques about Terry’s drawings, one of the fictitious drawings.

Knowledge Integration Levels	Description of student answers to the embedded question	Description of student drawings	Description of critiques about Terry’s drawings
4 Two valid links among reaction processes, molecular representations, the conservation of matter law, or energy.	Explain that <ul style="list-style-type: none"> • bond breaking and bond formation occur • there is no increase or decrease in the number of atoms OR the reaction needs a spark to start bond breaking OR chain reaction occurs during hydrogen combustion	Create drawings that <ul style="list-style-type: none"> • show bond breaking and formation correctly • all drawings contain the same number of atoms OR include a spark to indicate the beginning of the reaction OR show chain reaction process during hydrogen combustion	Explain that Terry’s drawings <ul style="list-style-type: none"> • show correct bond breaking and formation but in an incorrect sequence • do not conserve matter OR correctly include a spark to indicate the beginning of the reaction OR show correct chain reaction process
3 One valid link between reaction processes and molecular representations	Explain that <ul style="list-style-type: none"> • bond breaking and bond formation occur 	Create drawings that show bond breaking and formation correctly	Explain that Terry’s drawings show correct bond breaking and formation but in an incorrect sequence

<p>2 Partial ideas about reaction processes, but do not fully elaborate links between them</p>	<p>Explain that</p> <ul style="list-style-type: none"> • bond breaking occurs but do not explain and bond formation • OR bond formation occurs but do not explain bond breaking 	<p>Create drawings that</p> <ul style="list-style-type: none"> • show partial of the reaction process correctly, i.e., show bond breaking or formation correctly • OR show the ideas of bond breaking and formation but represent with incorrect molecular representations 	<p>Explain that Terry's drawings show correct bond breaking and formation, do not comment on the incorrect reaction sequence.</p>
<p>1 Incorrect ideas about chemical reaction processes, or invalid links between chemical reaction process and molecular representations.</p>	<p>Do not explain molecular processes during the reaction</p>	<p>Create drawings that demonstrate wrong reaction processes, e.g., draw that during hydrogen combustion the number of oxygen molecules keeps decreasing.</p>	<p>Explain that Terry's drawings show conserved matter, or Terry's drawings should not include a spark to indicate the beginning of the reaction, or the chain reaction included in the drawings are incorrect.</p>
<p>0 No answer or off-task answer</p>	<p>Do not answer, or do not explain anything related to hydrogen combustion</p>	<p>Do not create any drawings, or do not draw anything meaningful about interim phases during hydrogen combustion.</p>	<p>Do not create any critiques, or do not critique anything meaningful about reaction processes, e.g., comment on the format or the color scheme of the drawings.</p>

Results and Discussions

Classroom Observations

The teacher successfully implemented the project. On Day three, both groups explored the visualization by observing different atomic interactions with or without clicking the spark button. Afterwards, students created four drawings to illustrate the reaction processes or critiqued two sets of drawings made by fictitious peers Terry and Dunhong.

Students in both groups were observed to discuss with their partners during generation or critique. Learners in the generation group discussed what ideas should be included in their drawings and how they should plan the sequence of the drawings. Students in the critique group discussed what and how they should critique. Some students did not know how to critique in the beginning and asked for the teacher's help.

Students in both groups revisited the visualization when there was a disagreement between the pairs. During the remaining three days of instruction, students in both groups often returned to the visualization and revised their responses to embedded questions. Students in the critique group were also observed to revisit and revise their critique to the first set of drawings (Terry's) when they critiqued the second set of drawings (Dunhong's).

Advantages of Critique vs. Generation for All Learners

Pretest performance.

Most students started the HFC project with non-normative or partially correct ideas about chemical reaction processes (see Table 6.2). Often they had some normative ideas about reactants and products, but naïve ideas about molecular processes. Some believed that chemical reactions are “magic processes” without any interim phases. No significant difference was found between the pretest performance of students in the generation and critique groups [$t(71)=-.11$, $p=.92$].

Learning gains from pretest to posttest.

After the project, students under both conditions improved their understanding about chemical reactions [Generation group: $t(24)=10.72$, $p<.001$; Critique group: $t(47)=10.39$, $p<.001$] (Table 6.2). On the posttest, students on average achieved a score higher than 2, which suggests that they integrated at least one correct idea about reaction process. Many learners were able to integrate both ideas of bond breaking and formation.

No significant difference was found between student post-test performance across groups after controlling for the pretest score [$F(1,70)=.09$, $p=.77$]. Generation and critique had similar impact on supporting students to integrate ideas about chemical reactions from the visualization.

Table 6.2. Pre/post-test performance of students in generation and critique groups.

Group	Pretest		Posttest		Effect Size	ANCOVA result
	Mean	SD	Mean	SD		
Generation	1.49	.57	2.43	.51	2.14	F(1, 70)=.09,
Critique	1.35	.60	2.41	.57	1.50	p=.77

Learning gains on different types of assessments.

I examined student performance on each type of questions (see Table 6.3). As noted earlier, the pre/post assessments include four types of questions: recognition, critique, drawing, and selection.

Table 6.3. Student pre/posttest performance on different assessment items.

	Generation			Critique			ANCOVA result
	Pretest Mean (SD)	Posttest Mean (SD)	Effect size	Pretest Mean (SD)	Posttest Mean (SD)	Effect size	
Recognition	1.76 (.66)	2.82 (.75)	1.31	1.58 (.56)	2.38 (.68)	.95	F(1, 70)=5.41, $p<.05$
Critique	.91 (.80)	1.6 (.91)	.97	.97 (.74)	2.16 (.79)	1.10	treatment: F(2, 69)=17.03, $p<.001$; interaction: F(2, 69)=8.94, $p<.01$
Drawing	1.5 (1.1)	2.76 (.72)	1.20	1.58 (.93)	2.70 (.77)	1.24	F(1, 70)=.28, $p=.60$
Selection	2.08 (1.22)	2.94 (.53)	.88	1.44 (1.06)	2.54 (.87)	.85	F(1, 70)=2.25, $p=.14$

Recognition questions.

Learners in the generation group outperformed their peers in the critique group on the posttest [F(1, 70)=5.41, $p<.05$]. Before the project, half of the students selected wrong pictures and explained incorrect ideas about hydrogen combustion (n=36, 51%). For instance, they thought that hydrogen combustion started with separate hydrogen and oxygen atoms. They selected the picture that shows bond breaking as the first phase during the reaction.

After the project, a majority of the students (n=23, 92%) in the generation group were able to accurately sequence the pictures and explain how bond breaking and bond formation take place during the reaction. Sixty percent of students in the critique condition selected correct pictures but had incomplete ideas about reaction processes (n=30, 62.5%). They often only explained one idea about bond breaking or formation, but

not both ideas. Generation helped students integrate more ideas about hydrogen combustion from the project than critique.

Critique questions.

Students in the critique group performed significantly better than those in the generation group on critique items. There was an interaction between students' pretest score on critique items and the treatment [treatment: $F(2, 69)=17.03, p<.001$; interaction: $F(2, 69)=8.94, p<.01$]. For students who had a pretest score lower than 1.7, critique was more beneficial than generation. For students who started the project with a score higher than 1.7 on critique questions, generation supported them to integrate more ideas about chemical reactions from the visualization than critique. Only six students (8%) had a pretest score higher than 1.7 on critique items. Table 6.4 presents one of the critique questions, student sample critiques on the pre and posttest, and the knowledge integration scores.

On the pretest, most students in both groups demonstrated no idea or incorrect ideas about chemical reaction processes in their responses (with an average score lower than 1). Many students summarized the drawings and did not critique on anything related to the drawings, e.g., "*the drawings show how methane combustion happens*" (generation group: $n=15, 60%$; critique group: $n=25, 52.1%$). They did not know how to critique. Some students critiqued about trivial issues such as the color or the size of the molecules represented in the drawings, e.g., "*the hydrogen and oxygen have different colors*" (generation group: $n=8, 32%$; critique group: $n=22, 45%$). Their critiques showed that they had non-normative ideas about the particulate nature of matter. They did not critique the underlying chemistry concepts including bond breaking and formation.

On the posttest, students in the critique group advanced to an average score of 2.16. Eighty percent of them were able to accurately critique whether the drawings represent bond breaking or formation correctly ($n=39, 81.2%$). In contrast, students in the generation group had an average score of 1.6. One third of them still summarized the drawings ($n=7, 28%$) without performing critiques. Almost half of students in the generation group critiqued irrelevant issues and did not evaluate whether the drawings showed correct molecular reaction processes ($n=13, 42%$). Only five students critiqued whether the drawings represent the reaction processes (20%).

Table 6.4. A critique question, student sample critiques on the pre and posttest, and the knowledge integration scores. The question asks students to critique a picture that shows what molecules look like when methane combustion starts.

<p>Question 5: Li drew pictures to show how the burning of methane happens. The following box shows the reactants.</p> <p style="text-align: center;">$2\text{CH}_4 + 4\text{O}_2 \rightarrow 2\text{CO}_2 + 4\text{H}_2\text{O}$</p> <div style="text-align: center;"> <p>(Carbon=●, hydrogen=○, oxygen=○)</p> </div> <p>Li drew another three pictures to explain how methane burns.</p> <p>5.1) Li's drawing of what the molecules look like when the reaction starts.</p> <p>Picture 1:</p> <div style="text-align: center;"> </div> <p>Is Li's drawing correct? (Check one) <input type="checkbox"/> accurate <input type="checkbox"/> partially correct <input type="checkbox"/> wrong</p> <p>Explain what is correct and incorrect about this drawing.</p>		
Student sample answers (knowledge integration score in parentheses)		
Student	Pretest (score in parentheses)	Posttest
12216	Correct, it shows what the molecules look like when the reaction starts. (0)	Incorrect, Correct: the hydrogen molecules are not breaking apart, Incorrect: the carbon and hydrogen atoms shouldn't be broken down (1)
12371	Correct, I guessed they are logical. (0)	Correct: because the particles are splitting (2).
12308	Incorrect, the oxygen should be the biggest. (1)	Correct: there are most bonds broken but there are still some bonds similar to the original picture (2).
12156	Correct, because the particles are starting to group together. (1)	Partially correct, Correct: the particles are splitting. Have the right amount of carbon. Incorrect: but the wrong amount of hydrogen and oxygen (3)
12233	Partially correct, Correct: the molecules are breaking their bonds and separating. Incorrect: the hydrogen atoms are still bonded. (2)	Partially correct, Correct: the number of carbon atoms she has. The particles are separating. Incorrect: the number of bonds of hydrogen atoms and a different number of oxygen atoms are incorrect. She needs a spark. (4)

Drawing questions.

No significant difference was found between the two groups' performance on drawing questions [$F(1, 70)=.28, p=.60$]. On the pretest, students often held incorrect or incomplete ideas about chemical reaction processes. Some drew the reactants and products correctly and left the middle boxes blank (generation group: $n=10, 40\%$, critique group: $n=19, 39.6\%$). They did not think there were any processes during the reaction between nitrogen and hydrogen gas. Some students had incomplete ideas about the processes and represented bond breaking or formation (generation group: $n=12, 48\%$, critique group: $n=24, 50\%$).

After the project, most students drew bond breaking or formation correctly (generation group: $n=16, 64\%$, critique group: $n=34, 70.8\%$). About one third of students developed complicated understanding about the reaction processes. They represented both processes and relevant concepts correctly (generation group: 36% , critique group: 27%). For instance, they drew sparks to show that bond breaking requires external energy or kept the same amount of atoms in all their drawings. These students not only connected reaction processes with correct molecular representations, but also linked with other chemistry concepts such as activation energy and conservation.

Selection questions.

Students in the generation and critique groups performed similarly on selection questions [$F(1, 70)=2.25, p=.14$]. After the project, they selected correct pictures and explained molecular processes during the reaction between hydrogen and chlorine gas.

Overall, generation and critique had similar effects on items measuring knowledge integration. Students under both conditions integrated ideas of bond breaking and formation from the visualization. Analyzing student performance on specific questions shows that students in the generation group outperformed their peers in the critique group on recognition items. Learners in the critique group performed better on critique questions. This suggests that the generation task may be more effective at focusing students' attention on the nuances of hydrogen combustion represented in the visualization. More students in the generation group were able to represent bond breaking and formation correctly on the posttest than those in the critique group. The critique activity better prepared students to apply their ideas to critique new chemical reactions. They critiqued the drawings of methane combustion more accurately than those in the generation group.

Effect of Prior Knowledge

According to the nature of their repertoire of ideas, students were divided into three groups. I used the same categorization as the one developed in Chapter 5 (see Chapter 5 Table 5.1 for detailed descriptions of the categories and student sample drawings). Table 6.5 shows the distribution of students with various ideas.

Table 6.5 Number of students with various ideas in generation and critique groups.

	Mostly non-normative	Mixed	Mostly normative
Generation	10	12	3
Critique	21	21	6
Total	31	33	9

To investigate whether student prior ideas affect the impact of generation and critique, I performed multiple regression analysis using student learning gains as the outcome variable, the treatment and student prior ideas as the explanatory variables. The result shows that generation and critique had similar impact on promoting the learning of students with various ideas [$t=.22$, $d.f.=69$, $p=.83$]. Figure 6.2 shows the learning gains of students with different ideas.

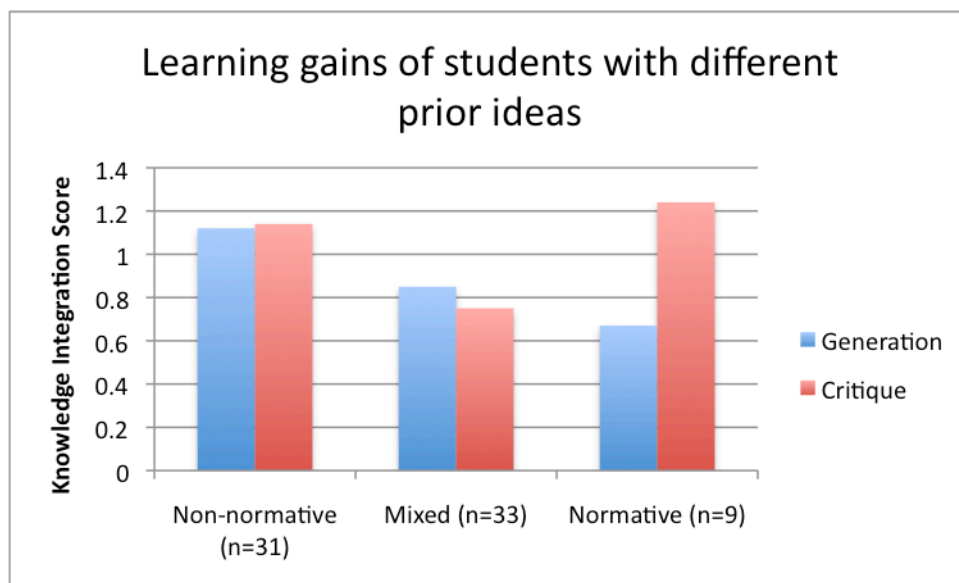


Figure 6.2. Learning gains of students with different prior knowledge in generation and critique groups.

Students with mostly non-normative ideas: They had a repertoire of mostly non-normative ideas about chemical reaction processes (n=31, 42.5%). They may have some ideas about reactants, products, and the particulate nature of matter. Yet they did not have normative ideas about how chemical reactions take place at the molecular level. Their pretest drawings were scored below 1.

These students had the most learning gains after the project. They increased their scores by over 1 from pretest to posttest. On average, they integrated at least one normative idea about reaction processes from the project.

Students with mixed ideas: They had partially correct ideas of reaction processes (n=33, 45.2%). They often had some normative and non-normative ideas about bond breaking or formation. Some students had correct ideas about both processes but did not link them correctly. For instance, they drew both processes in a wrong sequence, e.g., drawing that bond formation occurs first and breaking later during the reaction. Their pretest scores ranged from 1 to 2.

After the project, these students increased their score by slightly less than 1. Many students integrated a new idea about reaction processes, but some learners still had difficulties integrating new ideas.

Students with mostly normative ideas: They started the project with sophisticated understanding about chemical reactions (n=9). They drew both reaction processes with

correct molecular representations. Some even represented activation energy and conserved the number of atoms in their drawings, indicating complex links with relevant concepts. Their pretest scores were above 2.

After the project, learners in the generation group increased their scores by .67, which indicates that some students still struggled to integrate new ideas from the project. Students in the critique group increased their scores by 1.24. They integrated at least one more idea such as energy and conservation into their repertoire. This suggests that critique may be more beneficial to students with high prior knowledge. However, because of the small sample size, the difference was not significant.

Knowledge Integration Through Critique vs. Generation

To track how students developed their ideas, I coded student explanations, drawings, and critiques using the parallel coding rubrics developed in Table 6.1. The increase in student scores from explanations to critiques or drawings suggests that critique and generation helped students integrate normative ideas.

Explanations of the visualization.

Students achieved scores of 2 or above on the embedded question (see Table 6.6), which suggests that most students integrated some ideas about chemical reaction processes by exploring the visualization. Of the 39 student pairs who completed the question, 20 pairs (51%) were able to explain one of the reaction processes correctly (bond breaking or bond formation). Fifteen pairs (39%) integrated both ideas and explained both processes correctly. Four pairs (10%) failed to explain any ideas about the chemical reaction processes. No difference was found between students in the two treatments [$t(37)=.64, p=.53$].

Table 6.6. Student scores on the embedded question, drawings, and critiques.

	Generation	Critique	t-test results
Embedded question (SD)	2.31 (1.03)	2.50 (.81)	$t(37)=.64, p=.53$
Drawing/Critique (SD)	3.69 (.63)	3.40 (.53)	$t(37)=1.51, p=.14$

Student critiques and drawings.

Students improved their understanding of chemical reactions through critique and generation (see Figure 6.3 for the scatter plot). Generation and critique helped students distinguish between their old and new ideas. They were able to integrate the new ideas. No significant difference was found between groups for student understandings of chemical reactions demonstrated in their critiques and drawings [$t(37)=1.51, p=.14$].

Learners in the generation group achieved a mean score of 3.69 in their drawings. Generation helped them integrate new ideas from the visualization: all student pairs who did not integrate ideas or integrated partial ideas through exploration ($n=8, 62%$) gained at least one idea through generation. Students who integrated ideas of bond breaking and formation through exploration ($n=3$) linked with relevant ideas such as energy and conservation after generation.

Students in the critique group achieved a mean score of 3.40 in the critiques. Critique also supported them to integrate new ideas from the visualization: all students who did not gain any ideas through exploration ($n=16, 62%$) integrated at least one idea

of bond breaking or formation through critique. Half of the students who gained ideas about bond breaking and formation ($n=3$) linked with relevant ideas through critique. Interestingly, of the four student pairs who expressed complicated ideas about reaction processes in their explanations (scored 4), three pairs had a mean score of 3.5 in their critiques. This may suggest that although exploration helped these students establish links between reaction processes and relevant ideas such as energy, the connections were weak. Students may not be able to apply these links to distinguish the normative and non-normative ideas demonstrated in the drawings to be critiqued.

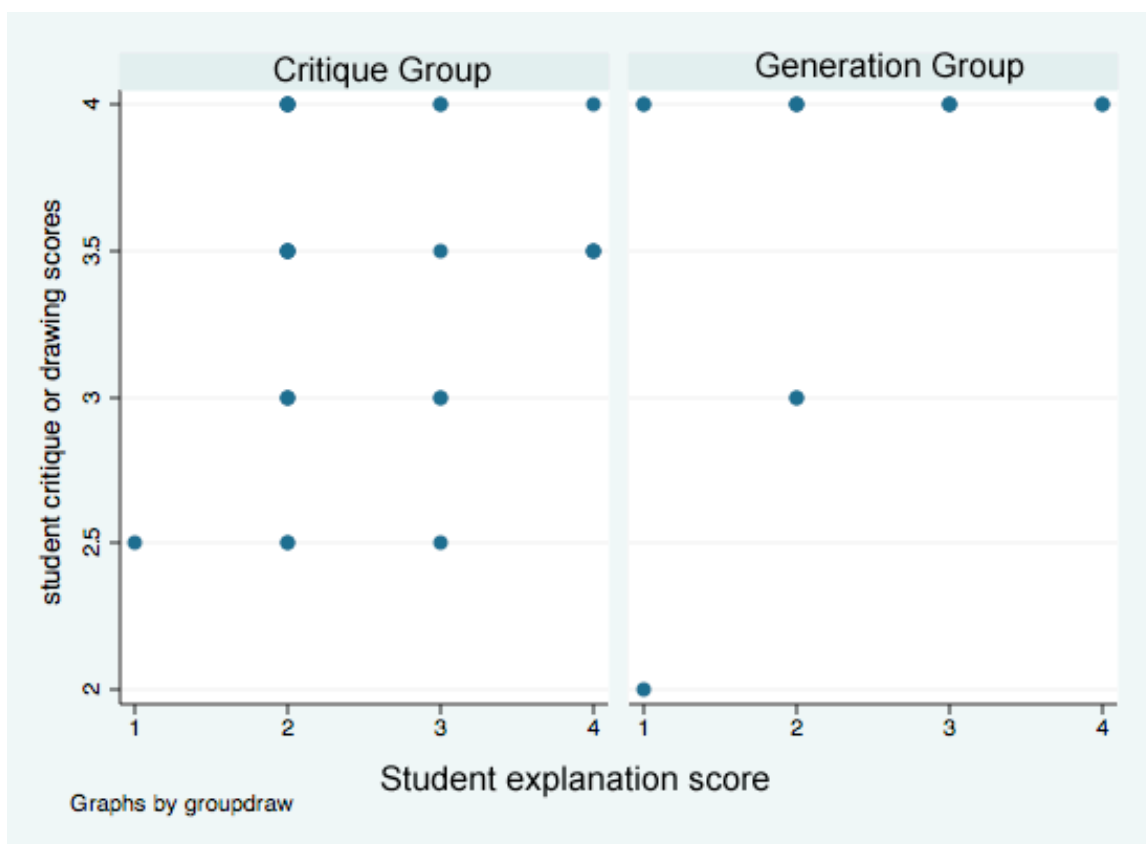


Figure 6.3. Scatter plot of student critique/drawing scores and their explanation scores.

Student interactions with the visualization.

I examined the log files to understand student navigations during generation and critique. Table 6.7 presents the results from the 39 pairs who participated in this study. Sixty percent of the students revisited the visualization. Among the 13 pairs in the generation group, 8 pairs (61.5%) revisited the visualization during drawing. They revisited the visualization from once to four times. On average they spent more than half a minute on each revisit, re-running the visualization and making careful observations. Seventeen student pairs (65.4%) in the critique group revisited the visualization. Many pairs returned to the visualization three or four times. On average they spent more than one minute (65 seconds) on each revisit.

Table 6.7. Student revisit of the visualization facilitated by generation and critique.

	Number of pairs who revisited (percentages)	Times of revisits per pair	Average time spent on each revisit (in seconds)
Generation	8 (61.5%)	1.5	37
Critique	17 (65.4%)	1.94	65

Taken as a whole, the results show that exploring the visualization had some impact on student understanding but was not sufficient to ensure the understanding of bond breaking and formation. Student drawings and critiques show that generation and critique helped learners fill some gaps in their knowledge and improve their understanding. Computer log files demonstrate that students under both conditions frequently revisited the visualization for new ideas.

Conclusion

This chapter discusses two instructional alternatives for exploring a dynamic visualization of a chemical reaction. Students either critiqued pre-made drawings or created digital pictures to represent molecular processes involved in the reaction. The results show that critique and generation had similar impact on supporting students to integrate ideas with the visualization. Students in both groups achieved similar learning gains after the project. Specifically, students in the generation group performed better on questions that accessed understanding about hydrogen combustion. Learners in the critique group performed better on critique questions. Generating drawings helped students focus their attention on nuanced information represented in the visualization. Critique better prepared students to apply their ideas about chemical reactions to critique.

Further, I examined student understanding about reaction processes right after exploring the visualization and after the critique and generation activities. The results show that exploring the visualization helped students add some ideas of bond breaking or formation, but often their ideas were incomplete. Many students failed to integrate both ideas and develop connections. Generation and critique helped them improve understandings about chemical reaction processes and integrate new ideas. Computer log files show that students under generation and critique conditions navigated around the visualization similarly: they revisited the visualization frequently to integrate new ideas.

Overall these findings suggest that critique is another promising approach to promote integrated understanding of chemical reactions with dynamic visualizations. It engages students in the knowledge integration process of distinguishing ideas. Learners often ignore important details when learning with dynamic visualizations. Critique presents students an opportunity to test their understanding. Learners need to decide and explain whether the fictitious drawings are correct, wrong, or partially correct. The drawings to be critiqued are designed to represent common alternative ideas held by students. To critique, learners need to distinguish the normative and non-normative ideas represented in the drawings. They are prompted to realize gaps in their previous understanding. Thus they return to the visualization, make more careful observations about molecular reaction processes during hydrogen combustion, distinguish with their naïve ideas, and integrate the new views into their repertoire.

Critique also draws student attention to the crucial disciplinary knowledge

demonstrated in the visualization. Visualizations may include too many features for students to make sense of. The critique task required learners to evaluate drawings about molecular processes during hydrogen combustion, which were the key concepts of the visualization. Critiquing the drawings helped learners focus on these important details, make careful observations, and integrate important ideas.

Implications for Instructional Designers

Results from this study offer insights for instructional designers. First, an effective critique activity should include common non-normative ideas so as to engage students in distinguishing normative and non-normative ideas. The two sets of drawings used in this study were designed based on alternative ideas identified from previous studies. Students had difficulties to decide whether these alternative ideas were correct or wrong, realized gaps in their prior knowledge, and therefore returned to the visualization to integrate normative ideas.

Second, instructions can combine critique and generation activities to benefit all learners. Students come to science classrooms with diverse background and prior knowledge. One approach may be especially effective to students with certain prior ideas. For instance, critique may be more beneficial to students with high prior knowledge than generation. Instructions that employ critique and generation can provide students with ample opportunities to recognize gaps in their knowledge and ensure that all learners will benefit from visualizations.

Future Studies

This study suggests the benefits of distinguishing ideas facilitated by generation and critique. However, distinguishing ideas often involves students in developing criteria and applying them to evaluate. This study did not analyze what criteria students developed to distinguish among ideas. Examining the criteria generated by students would provide more insights on how students discriminate among ideas. This issue will be addressed in the next chapter.

Chapter 7: What Criteria do Students Use to Distinguish Ideas?

This chapter discusses the criteria students develop to distinguish ideas when learning with dynamic visualizations and activities of generation, selection, and critique. Dynamic visualizations are potentially powerful tools for chemistry learning. Yet they pose challenges to students. Learners may ignore important details conveyed in the visualizations and establish non-normative interpretations. To maximize the effects of visualizations, they need to observe carefully, distinguish the normative ideas from their intuitive views, and establish valid connections with the prior knowledge.

This chapter extends previous research in exploring the nature of criteria developed by students. In previous chapters, I conducted a series of comparison studies to explore the benefits of embedding visualizations within instructions that aim at engaging students in productive knowledge integration processes such as distinguishing ideas. Students learned chemical reactions with the hydrogen combustion visualization and activities such as generating drawings, selecting pictures, and critiquing pre-made drawings. Compared to interaction, these activities all successfully prompted students to attend to details about atomic interactions demonstrated in the visualization, add these molecular-level ideas, distinguish them from their old conceptions, and refine understanding about chemical reactions. These activities confirm the important role that distinguishing ideas plays in promoting integrated understanding with visualizations. Further, they suggest different approaches that can engage students in distinguishing ideas for instructional designers.

Yet one question remains from previous studies: distinguishing ideas often involves developing criteria and applying them to evaluate ideas. What is the nature of the criteria students developed with generation, selection, and critique? Is there any difference in the criteria developed by students under the three conditions? Previous research suggests that students hold a repertoire of criteria to evaluate (diSessa et al., 1991; diSessa, 2002, 2004). When asked to evaluate representations of motion, 6th graders spontaneously used criteria including completeness, compactness, precision, and learnability. High school students generated similar criteria when judging representations for spatially distributed data. Most of these criteria were drawn from different concerns of everyday life. In this study, I was interested in exploring if generation, selection, and critique change the criteria students used. Do these activities help students develop more complicated criteria to distinguish ideas about chemical reactions?

This study seeks to answer these questions by asking students to explain three most important things to be represented in drawings of chemical reactions. Students learned the Hydrogen Fuel Cell Cars project under three conditions: generation, selection, and critique. After the activities, they explained their criteria. I categorized student answers, focusing on the criteria they developed to distinguish various ideas about chemical reactions. This chapter seeks to answer the following two research questions.

- How do generation, selection, and critique impact learners? Do student prior ideas make a difference in their performance?
- What criteria do students develop to distinguish ideas in selection, critique, and generation?

To foreshadow the results, first, this chapter found that generation, selection, and critique had similar impact on promoting student knowledge integration with

visualizations, which resonates with results from previous chapters. Second, these activities helped students develop valid criteria to evaluate ideas about chemical reactions. Examining the criteria in detail reveals that generation helped students develop more complex criteria than critique and selection. Learners in the generation group on average developed more complicated criteria than those in the selection and critique groups. Many students developed multiple valid criteria to distinguish ideas about chemical reactions. In addition, generation drew students' attention to representing molecules and atoms. Some students in the generation group established criteria about representing the molecules (e.g., whether representing oxygen molecules with double bonds and hydrogen molecules with single bonds), whereas none of learners in the selection or critique group had such criteria.

Methods

Participants

This study was implemented among 109 8th graders (five classes) in a public middle school taught by the same teacher. The teacher had over six years of experience using WISE projects. The project was taught after students learned basics about chemical reactions and students worked through the project in pairs.

Study Design

Student classes were randomly selected into the generation group (n=41, two classes), selection group (n=21, one class), and critique group (n=47, two classes). All three groups learned *Hydrogen Fuel Cell Cars* project with the same visualization of hydrogen combustion. On the third day of the implementation, students in all groups spent the same time (around 40 minutes, a whole class period) interacting with the hydrogen combustion visualization and completing the activities.

In the generation treatment, students were asked to create digital drawings of atomic interactions before hydrogen combustion starts, right after the reaction begins, after the reaction has been going for some time, and after the reaction completes. Students created the drawings using the WISE draw tool, which provides stamps of different elements. Students constructed the drawings by selecting appropriate stamps for elements and chemical bonds. They need to explain their drawings afterwards. To maintain consistency with previous studies, the generation activity was identical to that studied in Chapter 5 and 6.

In the critique treatment, students need to evaluate two sets of drawings created by fictitious peers. They need to evaluate whether the drawings are accurate, partially correct, or wrong, and explain their evaluations. The drawings were designed to represent common non-normative ideas held by students. The critique activity was the same as the one used in Chapter 6.

In the selection treatment, students need to select four pictures from twelve alternatives to represent the interim phases during hydrogen combustion. The selection activity was designed as a “drag and drop” activity, with four blank boxes connected by arrows to represent the interim phases. Students select four pictures by dragging and dropping the pictures into each box. Once the boxes are filled, students can view all selected pictures on the same page. Students also need to explain their selections. All the twelve choices in the selection task were designed to represent common intuitive ideas

held by students to encourage discrimination among ideas. The selection task was the same as the complex selection activity investigated in Chapter 5.

Assessments & Data Analysis

Impact of the activities on all learners.

The teacher administered identical paper-based tests to individual students before and after the unit. The assessment consists of the same nine items as employed in Chapter 6. It includes two recognition items that assess student understanding about hydrogen combustion, three critique items, two drawing questions, and two selection items that examine students' ability to critique, draw, and select representations to explain other chemical reactions. Students need to provide reasons for their selections or drawings in all questions.

To compare the impact of generation, critique, and selection on student learning, I performed ANCOVA, using student pretest score and treatment as explanatory variables and posttest score as outcome variable. I examined student performance on all items and different types of assessment questions. Students' responses to pre and posttests were coded using the knowledge integration rubrics (Linn, Lee, Tinker, Husic, & Chiu, 2006), focusing on the links students established between ideas. The knowledge integration score ranged from 0 to 4, higher scores indicating more complex links among ideas.

Impact of the activities on learners with different prior knowledge.

I categorized student ideas demonstrated on the pretest using the same category developed in Chapter 5. Students' prior knowledge was classified into three categories: mostly non-normative, mixed, and mostly normative ideas. To investigate how the activities affect students with different prior knowledge, I performed ANCOVA to compare their posttest performance for students with similar prior ideas.

Criteria students developed to distinguish ideas.

Design of the embedded question.

An embedded question was designed to capture information about what criteria students use to distinguish ideas about chemical reaction processes. After the generation, selection, and critique activities, students in all groups were asked "*Ms. ChemTchr asks students to draw four phases to how chemical bonds change during hydrogen combustion. Explain what should be represented in good drawings for Phase 2 (after the reaction starts) and Phase 3 (after the reaction has been going for some time)? List the three most important things.*" Students need to report the criteria for good drawings about chemical reaction processes. These criteria include ideas that students consider the most important for chemical reactions. They can reveal information about what criteria that students use to distinguish ideas about chemical reactions under the generation, critique, and selection conditions. I gathered data from all student pairs who completed these activities.

Categorizing student-reported criteria.

I first identified different criteria demonstrated in student answers to the embedded question, and then grouped them based on whether they are valid criteria to distinguish ideas about chemical reaction processes. To investigate the difference in the criteria students developed under the three conditions, I developed an emergent scoring rubric to score student answers. The scoring rubric focused on how many valid criteria students developed to distinguish ideas. More valid criteria indicate that students developed sophisticated criteria to distinguish ideas. Table 5.1 shows the scores, criteria, categories, and student sample answers.

Students' responses to the embedded question suggest the following criteria and categories:

- General criteria: the criteria did not address any information that is related to representing chemical reactions. Often students focused on issues such as accuracy and understandability, e.g., they explained that good drawings “should be accurate” and “show what is going on.” These criteria were too general and did not reveal any information about the criteria students used to distinguish ideas.
- Representation criteria: the criteria focused on representational issues and did not address any scientific concepts relevant to chemical reactions. For instance, some students focused on labeling and clarity, and explained that good drawings should “label all separate parts and atoms, (with) lots of details.” Some students focused on sequence and detail, e.g., “the drawings should have a good pace, should have things in correct chronological order, (and) should have very detailed description.” These criteria were useful in terms of distinguishing ideas about representations. Yet they were invalid in terms of distinguishing ideas about chemical reactions.
- Molecular criteria: the criteria focused on how to represent the molecules and atoms correctly. Often students focused on representing chemical bonds, e.g., “the drawings should show hydrogen molecules with single bond, oxygen molecules with double bonds, (and) water molecules with single bond.” Instead of representing the changes in the aggregate, these criteria emphasized whether the drawings represent the molecules and atoms with correct molecular structures or numbers. They can reveal information about the criteria students used to distinguish ideas about the particulate nature of matter, but not about chemical reaction processes.
- Reaction criteria: the criteria focused on representing correct reaction processes. Students developed four criteria concerning different aspects of chemical reaction processes:
 - Bond breaking criteria: focusing on whether the drawings represent correct bond breaking, e.g., the drawings should “show them (the molecules) breaking apart.”
 - Bond formation criteria: students attended to whether the drawings represent bond formation correctly, e.g., the drawings should “show (the atoms) starting to bond, they should be going to form water molecules and not have any atoms that aren't bonded.”
 - Energy criteria: focusing on representing energy related issues, such as adding activation energy to start the reaction or temperature change during the reaction. For instance, the drawings should “let the audience know how the reaction happens, SPARK and temperature rises!”

Conservation of matter criteria: focusing on whether the reaction follows the conservation of matter law, e.g., the drawings should “*show an equal amount of atoms from the beginning.*”

Next, I developed a scoring rubric to score student criteria demonstrated in their answers to the embedded question. The score ranged from 0 to 4. Higher score indicates more valid criteria students developed to distinguish ideas.

- Invalid (scored 0): student answers only included general or representation criteria and did not address any underlying chemical concepts. Learners with such answers did not develop any valid criteria to distinguish ideas related to chemical reactions.
- Molecular (scored 1): student answers only included molecular criteria. Learners with such criteria developed valid criteria to distinguish ideas about the particular nature of matter. However, they failed to establish valid criteria to discriminate ideas about chemical reaction processes.
- Partial (scored 2): student answers included one of the reaction criteria. Some learners may respond with mixed criteria, e.g., with bond breaking and molecular criteria. Students with such criteria were able to distinguish ideas about one aspect of the reaction processes. They developed incomplete criteria to distinguish ideas about chemical reactions.
- Complete (scored 3): student answers included two of the reaction criteria. Students were able distinguish ideas about two ideas about the reaction processes. Many students reported criteria about representing bond breaking and formation, which suggests that they have developed complete criteria to distinguish key ideas about processes during chemical reactions.
- Complex (scored 4): student answers included more than two reaction criteria. Their criteria could not only distinguish ideas about bond breaking and formation, but also discriminate other ideas such as energy and conservation. They have developed sophisticated criteria to distinguish ideas about chemical reaction processes.

Table 7.1. Categories of criteria demonstrated in students responses to the embedded question. Students were asked to describe what they consider the most important things to represent chemical reaction processes.

Categories	Different types of Criteria		Sample answers to the embedded question
Invalid criteria (scored 0)	General criteria	Focusing on general issues such as accuracy	<i>“Clearly shows what is going on” “be related to the model we saw” “accurately show the reaction” “be neat and understandable, show understanding of the topic”</i>
	Representation criteria	Focusing on representation issues such as formatting, labeling, and sequence	<i>“label all separate parts and atoms, lots of details” “should have a good pace, should have things in correct chronological order, should have very detailed description.”</i>
Molecular criteria (scored 1)	Most of the criteria focus on representing single molecule and atom with correct structures or numbers, instead of representing the changes of the aggregate		<i>“should show hydrogen molecules with single bond, oxygen molecules with double bonds, water molecules with single bond” “should show 2 hydrogens and 1 oxygen for each water molecule, should have 6 water molecules”</i>
Partial criteria (scored 2)	Bond Breaking	Focusing on how to represent bond breaking	<i>“show them breaking apart”</i>
	Bond Formation	Focusing on how to represent forming new chemical bonds	<i>“show starting to bond, they should be to form water molecules and not have any atoms that aren't bonded”</i>
	Energy	Representing energy related issues, such as energy change in the reaction and activation energy	<i>“let the audience know how the reaction happens, SPARK and temperature rises!”</i>
	Conservation of matter	Representing the reaction with consistent numbers of atoms	<i>show an equal amount of atoms from the beginning”</i>
Complete criteria (scored 3)	include TWO valid reaction criteria		<i>“shows the atoms splitting up, shows the atoms forming together” (bond breaking and formation criteria)</i>
Complex criteria (scored 4)	include THREE OR MORE valid reaction criteria		<i>“show the molecules being sparked, Show the molecules breaking apart, Show the atoms forming new molecules” (bond breaking, formation, and energy criteria) “Has same number of hydrogen and</i>

oxygen; Has formed a water molecule as a product; For step 2, bonds start breaking. For step 3, there should be only few bonds that didn't break”
(bond breaking, formation, and conservation criteria)

Results and Discussions

Impact of Generation vs. Critique vs. Selection on All Learners

Pretest performance.

Students in all groups started the HFC project with low prior knowledge. They had an average score of 1.38 on the pretest, which suggests most of them held a repertoire of non-normative ideas about chemical reactions. Often they believed that chemical reaction is an instantaneous process that does not involve bond breaking or formation. Students in the selection group started with the lowest prior knowledge, yet the difference was not significant [$F(2, 105)=.51, p=.60$].

Comparing performance from pretest to posttest.

After learning the HFC project, all students significantly improved their understanding about chemical reactions (see Table 7.2). They advanced to an average score of 2.06 on the posttest. Most students integrated at least one new idea about bond breaking or formation. Many students linked these ideas with relevant concepts such as conservation of matter and activation energy. The effect sizes were large for students under each condition. There was no difference in student posttest performance across groups after controlling for the pretest score [$F(2, 106)=2.45, p=.09$]. The three activities successfully promoted integrated understanding about chemical reactions with the visualization. They had similar impact on student learning, which resonates with the results from our previous studies.

Table 7.2. Pre/post-test performance of students in generation, critique, and selection groups.

	Generation (n=41)	Critique (n=47)	Selection (n=21)
Pretest Mean (SD)	1.46 (.55)	1.42 (.60)	1.14 (.51)
Posttest Mean (SD)	2.08 (.72)	2.15 (.66)	1.80 (.85)
Effect Size	1.15	1.28	1.00

Students in all groups improved their performance on different types of assessment items except that learners in the selection group did not make much gains on the critique questions [$t(20)=.39, p=.71$]. Figure 7.1 presents the learning gains of students under the three conditions on different assessment questions. While they demonstrated integrated understanding in their responses to the recognition, selection, and drawing questions, students in the selection group performed poorly on the critique items. They on average had a pretest score of 1.08, and a posttest score of 1.16. On the posttest, many students in the selection group still critiqued the color and representation of molecules in the drawings, instead of the underlying chemical reaction processes.

Taken together, these results suggest that students who selected may have developed normative ideas about hydrogen combustion from the project and applied them to select, draw, and explain other chemical reactions. However, they could not apply the ideas to critique representations about chemical reactions.

One conjecture of the selection group's poor performance is that they had relatively low pre and posttest scores. On the pretest, most of them had irrelevant or incorrect ideas about chemical reactions. They may not have enough prior knowledge to perform the critique. On the posttest, they on average developed partial ideas about the reaction processes. Yet they may still have difficulties in critiquing because the selection treatment did not provide them with any training on critique. They may not know how to critique the drawings and focus their critiques on trivial issues instead of underlying chemical concepts.

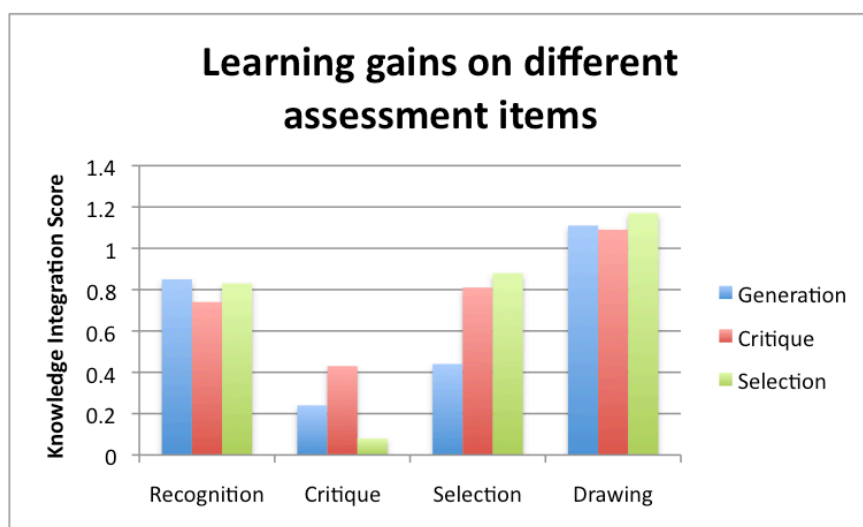


Figure 7.1. Student learning gains on recognition, critique, selection, and drawing pre/post-test questions. Students in the selection group did not make significant gains on critique items.

Impact of the Treatments on Learners with Different Prior Ideas

To investigate whether the three activities have different impact on students with different ideas, I categorized students' prior knowledge demonstrated in their pretest drawings. Then I performed ANCOVA to explore compare the posttest performance of students who started the HFC project with similar ideas. I also calculated the effect sizes of each treatment on students with each type of ideas. Table 7.3 presents the analysis results.

Table 7.3 Distribution of students with different prior ideas, effect sizes, and ANCOVA results

	Generation		Critique		Selection		ANCOVA results
	# of students	Effect size	# of students	Effect size	# of students	Effect size	
Non-normative	23	1.19	32	1.37	15	1.01	F(2, 67)=1.09, $p=.34$;
Mixed	18	1.16	15	1.37	6	.91	F(2, 35)=.04, $p=.97$;

Seventy students started the HFC project with mostly non-normative ideas. They often thought that chemical reactions do not involve any interim processes such as bond breaking or formation. Some students believed that during chemical reactions all atoms tried to form one gigantic molecule as the end product. Altogether 39 students demonstrated mixed ideas about chemical reactions on the pretest. Over half of them (54%, $n=21$) held correct ideas about one interim process but incorrect views about the other one. For instance, they drew molecules breaking bonds accurately, but drew bond formation incorrectly (all atoms forming a gigantic molecule). Approximately 20% of the students ($n=7$) had correct ideas about both reaction processes but did not conserve matter in their drawings.

No significant difference was found in student posttest performance across groups [Non-normative: $F(2, 67)=1.09, p=.34$; Mixed: $F(2, 35)=.04, p=.97$]. The treatments had similar impact on students who started with similar prior knowledge. The effect sizes of the three treatments on students with various prior ideas were large (more than .75). This suggests that generation, critique, and selection significantly helped students with diverse views integrate ideas about chemical reaction processes from the visualization. Further, the effect sizes of selection were the smallest among the three activities, which indicates that compared to generation and critique, selection may be less effective.

Criteria Students Used to Distinguish Ideas

I categorized the criteria students used to distinguish ideas as reported in their responses to the embedded question. Altogether 68 student pairs completed the project and the embedded question (Generation group: $n=26$, Critique group: $n=28$, Selection group: $n=14$).

Overall the three activities facilitated students to develop at least one valid criterion to distinguish ideas about chemical reactions. Students in the generation developed the most complicated criteria than learners in other groups. They achieved a mean score of 2.77, which suggests that students on average developed complete criteria to distinguish ideas about chemical reaction processes. Students in the critique group had a mean score of 2.29 and learners in the selection group had a mean score of 2.21. They on average only developed partial criteria to distinguish ideas.

Further, to investigate the nature of the criteria developed under the three conditions, I examined student criteria in detail and calculated the percentages of students with each level of criteria. Figure 7.2 presents the distribution of student criteria developed under each condition.

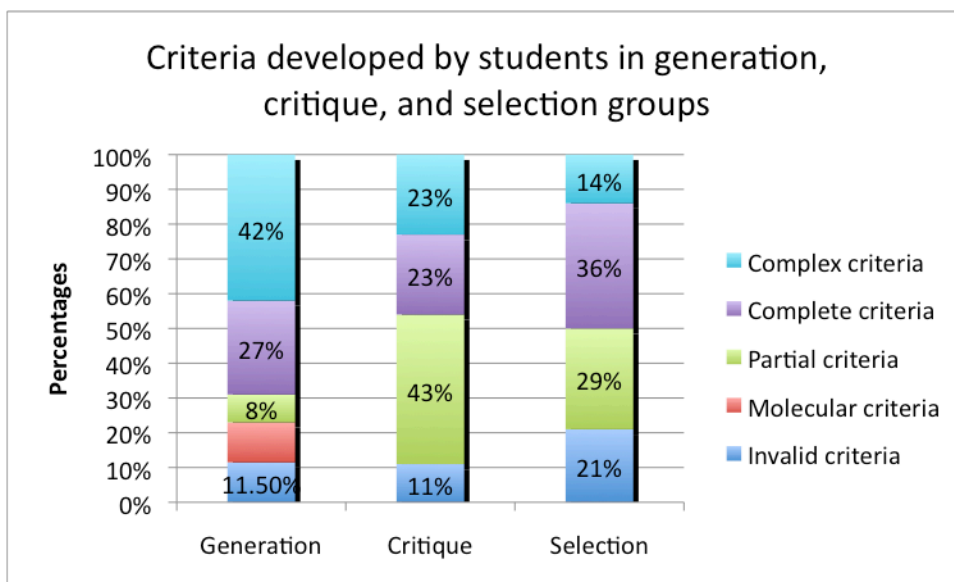


Figure 7.2. Criteria students developed to distinguish ideas under generation, critique, and selection conditions.

The results show that

- A majority of students developed at least one valid reaction criterion to distinguish ideas about chemical reactions after the project (Generation group: 77%, Critique group: 89%, Selection group: 79%).
- More students in the generation group developed complex criteria than those in the critique or selection groups (Generation group: 42%; Critique group: 23%; Selection group: 14%). Generation was the most effective approach to help students develop complex criteria to distinguish ideas about chemical reaction processes. Many students in the critique and selection group developed partial criteria and only were able to distinguish ideas about one reaction process.
- Students in the generation group developed a wider range of criteria than those in the critique and selection group. Approximately 12% of learners in the generation group focused their criteria on representing molecules and atoms, whereas none of students in the selection or critique group generated criteria about this aspect. Compared to generation, selection and critique activities may be more effective in terms of focusing student attention on the changes of the aggregate. Some students in the generation group attended to how to represent each single molecule and ignored the behavior of the aggregate.

One possible reason is that only the generation treatment engaged students in representing molecules in detail. Using the WISE draw tool, students need to construct the drawings by selecting appropriate stamps for chemical bonds (single, double, or triple) and elements (hydrogen, oxygen, or nitrogen). Choosing from the stamps may draw student attention to representing the singles. They may realize the importance of representing the molecules with correct structures and prioritize it over showing the changes of the aggregate. Critique and selection did not require students to consider whether the pictures represent hydrogen and

oxygen molecules with correct chemical bonds. Students focused on how to represent the reaction processes.

- Less students in the selection group developed valid criteria to distinguish ideas about chemical reactions than those in other groups. After the project, only 15% of students in the selection developed complex criteria to distinguish ideas about bond breaking, formation, and conservation (generation group: 42%, critique group: 23%). Twenty-one percent of students in the selection group (versus 10% of students in the critique or generation group) did not establish any valid criteria. Compared to critique and generation, selection was less successful in helping students develop valid criteria to distinguish ideas. On the posttest, students in the selection group on average had mixed ideas about chemical reactions. Selection did not help them develop criteria that can effectively distinguish among ideas.

This result and findings from other studies suggest that selection may not be as effective as generation and critique at helping students distinguish ideas and refine understandings of the visualization. In this study, the effect size of selection was the smallest among the three activities. It was smaller than the effect sizes of generation and critique found in Chapter 6 (the effect sizes of generation and critique were 2.14 and 1.50 in Chapter 6). Further, selection may have different impact on students with diverse ideas. For instance, it had much less impact on students who started the project with mixed ideas than those who had non-normative ideas. In Chapter 5, the effect size of selection on students with non-normative ideas was 2.02, whereas that of selection on those with mixed ideas was only 1.37. Selection may not be sufficient to help students with various prior ideas. To support students at all levels to develop criteria to distinguish ideas, instructions should combine selection with other patterns such as critique and generation.

Conclusion

This research demonstrates the benefits of generation, selection, and critique activities in enhancing student learning with visualizations. After interacting with the visualization, students created digital pictures, selected pictures, or critiqued pre-made drawings to represent molecular processes involved in the reaction. The results show that the three treatments had similar impact on supporting students to integrate ideas with the visualization. Students in all groups focused on key ideas demonstrated in the visualization and improved their understanding about chemical reactions. Further, examining the impact of the activities on students with different prior ideas demonstrates that they had similar impact on students who started with similar levels of prior knowledge. In addition, analyzing student responses to the embedded question shows that all three activities helped students develop valid criteria to distinguish ideas. These results suggest the importance of designing instruction that engages students in knowledge integration processes. Students need to recognize gaps in their prior knowledge, revisit the visualization to add new ideas, develop criteria to distinguish their old and new ideas, and integrate normative views.

Recommendations for Instructional Design

Results from this study offer valuable insights for instructional designers and

teachers. Generation, selection, and critique support students to develop different criteria to distinguish among ideas from visualizations and their own views. Relying solely on one activity may not be sufficient to support students with different prior knowledge. Instructions should consider combining these activities so that students at all levels can develop complicated criteria to distinguish ideas. For instance, instructions can employ selection and critique activities. They can first ask students to select among alternative sequences of the drawings and auto score their selections as an indicator of their understanding. Then they can require learners to critique one set of drawings that show the sequence of hydrogen combustion. The critique activity can supplement selection by forcing students to distinguish their own ideas against those in the drawings to be critiqued. Students may recognize more gaps in their knowledge and develop more robust understandings of chemical reactions.

Teachers can use the criteria generated by students as an opening or starting activity of the second day instruction. At the end of the first day, teachers can review student responses and select some representative criteria developed by students. In the beginning of the second day, they can show the criteria to the whole class and lead a discussion about them and how to apply them to evaluate drawings. These activities can support both student and teacher learning. Students can learn from each other through discussion, recognize problems in their knowledge, revise their answers, and refine their understanding. Teachers can become more aware of student learning during the project, including their challenges and progresses. In the summer professional development workshops, teachers can work in groups to discuss how to better use student data. They can share experiences, learn from other teachers, and plan instructional guidance or activities that can better assist teaching in the next year.

Chapter 8: Conclusion

Summary of Findings

This dissertation investigates how instructional activities designed following the knowledge integration framework improve chemistry learning with dynamic visualizations. The overarching question is: *How can we design instructional activities that can support students to develop integrated understanding of chemical reactions with dynamic visualizations?*

Students hold a repertoire of ideas about chemistry concepts such as particulate nature of matter and chemical reactions from everyday experience (Linn & Eylon, 2006). They often have difficulties visualizing chemical phenomena at the molecular level and linking the molecular-level ideas with observable phenomena and symbolic representations (Johnstone, 1993; Gilbert & Treagust, 2009). Dynamic visualizations help students add ideas about atomic interactions by demonstrating these unseen processes. Instruction designed following the knowledge integration framework allows students to build understandings based on their prior knowledge, to distinguish among the normative and their naïve ideas, and to develop connections among ideas. A focus of this dissertation was to explore how to design these instructional activities that can enhance student learning with visualizations.

Study 1 Impact of an inquiry-based curricular project featuring dynamic visualizations with prompts

The first analytical study described the design and refinement of an inquiry-based curricular unit on chemical reactions. The learning goals of the unit were to help students establish links among ideas about energy change during chemical reactions on molecular, observable, and symbolic levels. Informed by the knowledge integration framework (Linn, Davis, & Eylon, 2004), this project introduced energy diagram and chemical reactions within the context of hydrogen fuel cell cars. Students explored energy change during hydrogen combustion to decide whether hydrogen can be used to power cars in the future. The visualization employed in this study showed synchronous changes in chemical bonds, temperature, potential energy, and energy diagram during hydrogen combustion. Instructions and embedded prompts surrounding the visualization were designed following design patterns of *predict, observe, and explain* and *reflection*. Their purpose was to encourage students to link the energy diagram with observable phenomena and molecular reaction processes such as bond breaking and formation.

This project was implemented and tested by two teachers and 110 high school chemistry students. I gathered data from classroom observations and student responses to the pretest, posttest, and embedded prompts. Students achieved significant learning gains after the project. On the posttest, they on average established at least one normative link among ideas about chemical reactions. This suggests that the HFC project that featured dynamic visualizations and prompts successfully helped students improve their understandings of chemical reactions by linking ideas. I also examined the impact of the project on students with different levels of prior knowledge. The results show that while students at all levels benefited from the project, those who had the lowest prior knowledge made the most learning gains.

Examining student performance on each pre and posttest question demonstrated that a majority of students were able to establish connections between energy diagram with personally relevant issues and other chemical concepts such as balancing equations. However, many of them struggled to link the energy diagram with molecular-level ideas such as bond breaking and formation. Without normative connections, they could not understand why energy changes during chemical reaction. To develop integrated understandings, they needed support to integrate ideas about atomic interactions from the visualization.

The case studies exemplified the importance of focusing student attentions on key details such as bond breaking and formation demonstrated in the visualization with three student pairs. The first pair carefully observed how bond breaking and formation took place during the chemical reaction, successfully integrated these ideas, and established normative links with the energy diagram. They achieved great learning gains after the project. The second pair did not focus on changes in chemical bonds. Instead, they attended to the changes in the speed of molecular movement and temperature. They did not integrate the ideas of bond breaking and formation and failed to link with energy diagram. The visualization and prompts did help them gain some ideas, but the new ideas were not as important as bond breaking and formation. They needed help to pinpoint the key ideas demonstrated in the visualization. The third pair did not pay attention to atomic interactions in the visualization and made the least learning gains. They did not notice how chemical bonds change during the reaction and did not improve their understanding. One reason for the poor performance was that their prior knowledge was too low. They started the project without any ideas about chemical reactions such as molecules, reactants, and products. Without adequate background knowledge, they might not know how to interpret the visualization and therefore could not benefit from it.

Classroom observations also revealed that students often did not pay attention to key details demonstrated in the visualization and thus failed to integrate important ideas. Many students were observed to focus on superficial information such as color change. Some of them did not know what to observe and asked the teacher what they should do with the visualization. They needed more guidance to integrate ideas about molecular reaction processes.

Study 2 Impact of Generating drawings on Student Integrated Understanding

Findings of Study 1 suggest that inquiry-based curricular projects that feature dynamic visualizations and instructions designed using the knowledge integration framework can help students add new ideas and connect with relevant ideas about chemical reactions. The results also shed light on the complexity of designing instructions with visualizations. Students may ignore important details demonstrated in visualizations and develop superficial interpretations. They played the visualization too fast to notice changes at the molecular level and therefore failed to integrate these crucial ideas. The design patterns employed in Study 1 with embedded prompts were useful but insufficient to ensure that students can integrate ideas about bond breaking and formation from the visualization. Students needed more support to carefully observe changes at the molecular level, to distinguish new ideas with their prior knowledge, and to refine connections among ideas.

In the second analytical study, I explored improving student learning with dynamic visualizations by designing instructions that followed other patterns such as

generation. After students explored the visualization that shows bond breaking and formation during hydrogen combustion, they were asked to create drawings to illustrate how the reaction takes place at the molecular level. Specifically, learners needed to draw atomic interactions at four interim phases during hydrogen combustion: before hydrogen combustion starts, right after the reaction begins, after the reaction has been going for some time, and after the reaction completes. Designed following the pattern of *generation*, this activity was expected to draw student attention on key information in the visualization (e.g., bond breaking and formation), encourage them to make careful observations, and integrate these ideas. To determine the value of this activity, I compared student learning under two conditions: generation and interaction. Students in the generation group created the drawings. Learners in the interaction group were instructed to spend more time interacting with the visualizations and observing how chemical bonds change during the reaction.

The results showed that students in the generation group outperformed their peers in the interaction group on the posttest. Generation supported students integrated more ideas about bond breaking and formation from the visualization than interaction. Most students (78%) in the generation group integrated both ideas of bond breaking and formation after drawing. Only 40% of students in the interaction group integrated one of the ideas after the interaction. Approximately 39% of learners in the interaction group still focused on superficial information such as temperature change and ignored molecular-level ideas even though they were instructed to make careful observations about bond breaking and formation.

Case studies exemplified the knowledge integration of two students who started the project with instantaneous ideas about chemical reactions (i.e., thought there were no interim phases during chemical reactions). The generation task enabled student A to recognize problems in his prior ideas. A revisited and observed the visualization carefully and successfully integrated ideas of bond breaking and formation. Student B did not draw and did not test his understanding. He did not gain as nuanced understanding as A did and therefore did not integrate ideas about reaction processes.

One explanation for the benefits of generating drawings was that generation engaged students in the knowledge integration processes of adding ideas and distinguishing their old and new ideas. Dynamic visualizations presented learners with enormous amount of information. Learners often had difficulties deciding what features were important and ended up focusing on superficial information. They might hold conflicting ideas at the same time. Generation required students to articulate and represent the reaction processes, which provided an opportunity for the learners to test their knowledge and recognize gaps in their interpretations. Students needed to consider how chemical bonds and molecules changed during the reaction. They also needed to consider relevant concepts such as molecular structure and conservation of matters. The generation task prompted them to realize problems in their previous understanding. Students revisited the visualization to add new ideas, distinguished between their old ideas and the expert views in the visualization, and integrated normative ideas. In contrast, interaction did not provide learners with such opportunities to test their ideas and therefore was not as effective as generation.

Classroom observations resonated with this view. Students were observed to revisit the visualization for new ideas during generation. They discussed which ideas

should be represented in their drawings with their partners and compared the drawings they created to the actions demonstrated in the visualization, discussed, and revised their drawings. In contrast, few students in the interaction group were observed to revisit the visualization and revise their explanations. Generation helped learners take full advantage of the visualization and integrated ideas about bond breaking and formation.

Study 3 Designing Selection Activities to Promote Integrated Understanding

Findings of Study 2 suggest that generation was a promising approach to promote integrated understanding of chemical reactions with dynamic visualizations. It prompted students to recognize conflicting ideas and distinguish among their old and new ideas. Yet important questions remain from the study. For instance, which one plays a more important role in promoting student knowledge integration from visualizations, generation or distinguishing ideas? Must instructional activities that promote knowledge integration from visualizations be generative? Can activities that encourage distinguishing ideas be as successful as generating drawings?

To investigate these questions, in Study 3, I studied the impact of selection activities on helping students integrate ideas from dynamic visualizations. Students learned chemical reactions with the hydrogen combustion visualization embedded in the HFC project. I compared the learning of students who generated drawings with those who selected. The generation treatment was similar to the one in Study 2. After exploring the visualization, students created drawings to show atomic interactions at four interim phases during hydrogen combustion. In the selection treatment, students needed to select pictures from alternatives to represent the four phases. The selection activity was expected to be as effective as generation because it required students to distinguish among the normative and non-normative views represented in the choices. Students would recognize gaps in their knowledge when they found it difficult to choose. They would add new ideas from the visualization, distinguish their old and new ideas, and establish normative views.

This study reported the design and refinement of the selection activity. I devised two selection activities: simple selection and complex selection. Simple selection consisted of four multiple-choice questions, each asking students to choose a picture for one interim phase during hydrogen combustion. Students needed to select from eight snapshots of atomic interactions taken at different time during the run of the visualization. In complex selection, students needed to select and sequence four pictures from twelve alternatives to show atomic interactions during hydrogen combustion. The twelve choices were designed to represent common alternative ideas that students held. I compared the effects of the two selection activities with that of generation respectively.

The results showed that simple selection was not as effective as generation at supporting students to integrate ideas about reaction processes from the visualization. Students in the generation group achieved higher scores on the posttest than those in the simple selection group. After the project, students in the generation group on average integrated both ideas of bond breaking and formation. Students in the simple selection group only integrated one of the ideas. In particular, students in the generation group achieved higher scores on questions requiring learners to apply their knowledge to explain other chemical reactions. This suggests that generation supported students to develop robust connections among ideas so that they could apply their ideas to solve problems.

Simple selection failed to produce similar effects as generation because it did not enable students to realize gaps in their knowledge and to distinguish ideas. I examined student selections and explanations and found that students in the simple selection group often selected correct pictures without integrating any new ideas from the visualization. They chose the pictures based on their memorization of the snapshots from the visualization. Simple selection did not encourage students to distinguish the ideas represented in the choices with their own. In contrast, generation forced students to decide between their old ideas and the new views from the visualization. All students in the generation group who drew the reaction processes correctly integrated ideas about bond breaking and formation.

Based on the results of simple selection, I developed complex selection, which incorporated intuitive ideas students held in the choices. The complex selection had similar impact on supporting students to integrate ideas from visualizations as generation. Students under both conditions achieved similar learning gains after the project. Most students who selected correct pictures during the project successfully integrated ideas of bond breaking and formation from the visualization. Complex selection prompted students to distinguish their own ideas with those represented in the choices. It enabled learners to recognize gaps in their prior knowledge and integrate new ideas.

These studies confirmed the importance of encouraging students to distinguish ideas when designing instructions with visualizations. Complex selection incorporated student alternative ideas in the choices. Learners were required to select by distinguishing the normative and non-normative ideas in the choices. They recognized conflicts between ideas, added new ideas, and distinguished between their old and new views. Complex selection was as successful as generation in promoting integrated understanding of chemical reactions with the visualization. In contrast, simple selection did not include student alternative ideas in the choices. Students were not encouraged to select by distinguishing ideas represented in the pictures. They selected based on their memorizations of the visualization. Thus, they did not realize the necessity of filling gaps in their knowledge and did not gain new ideas from the visualization.

Study 4 Designing Critique Activities to Promote Integrated Understanding

In the fourth analytical study, I took advantage of the design pattern of *critique* and investigated how to design critique activities that can effectively enhance student learning with dynamic visualizations. Critique shares some characteristics with selection, as learners need to distinguish between their own understandings and the ideas in the responses to be critiqued.

The critique activity required learners to critique drawings about molecular reaction processes created by fictitious peers (Terry and Dunhong). Students were required to critique the correct and incorrect aspects of the drawings. To encourage students to distinguish ideas, the drawings were designed to represent common intuitive ideas held by students. Students needed to compare the ideas in the drawings with their own ideas and decide which one was correct. For instance, Terry's drawing showed a common idea: atoms first formed and then broke bonds during chemical reaction. To critique, students needed to distinguish among their ideas and Terry's non-normative ones. I compared the performance of students who critiqued with that of learners who generated drawings.

The results showed that the critique activity was as effective as generation at promoting integrated understanding of chemical reactions with the visualization. Students in both groups achieved similar learning gains after the project. In particular, students in the generation group had better performance on questions that assessed student understanding of hydrogen combustion. Learners in the critique group outperformed their peers on questions that asked them to critique drawings of other reactions. This suggests that generation may be more effective at focusing students' attention on bond breaking and formation demonstrated in the visualization. Critique may better support students to apply their ideas to critique.

The analysis of student work during the project demonstrated that visualizations helped students add some ideas but could not ensure that they would develop coherent understanding about chemical reactions. After exploring the visualization, approximately 60% of the students in both groups did not integrate or integrated partial ideas about bond breaking and formation. They developed incomplete understanding of how chemical reactions take place at the molecular level. Critique asked learners to critique drawings about the reaction processes. Students needed to distinguish their own ideas with the views represented in the drawings to be critiqued. Similar as generation, critique enabled learners to realize gaps in their knowledge and prompted them to integrate more ideas from the visualization. All students in the critique group integrated new ideas about the reaction processes from the visualization through critique. Computer log files demonstrated that students under the critique and generation conditions had similar navigation patterns: they frequently revisited the visualization for new ideas during critique and generation.

Study 5 Criteria Students Used to Distinguish Ideas

The purposes of Study 5 were to replicate the results from previous empirical studies and to explore the criteria students developed to distinguish ideas. Generation, selection, and critique all encouraged learners to recognize gaps in their understandings and distinguish among their old ideas and new views from visualizations. Distinguishing ideas involves developing criteria and applying them to evaluate ideas. Students often hold a repertoire of criteria from their previous experience, e.g., completeness and learnability (diSessa, 2002, 2004). In this study I was interested in investigating what criteria generation, selection, and critique helped students develop to distinguish ideas about chemical reactions, and whether there was any difference in the criteria developed by students under the three conditions. Students learned the HFC project in three groups: generation, complex selection, and critique. After completing these activities, they were asked to explain the criteria for good drawings about chemical reaction processes. I categorized the criteria reported by students and examined whether the treatments helped students develop different criteria.

The pre- and posttest results showed that students in the three groups achieved similar learning gains through the project. They all successfully integrated ideas of bond breaking and formation from the visualization. This resonated with my previous studies and confirmed the effectiveness of instructions that engaged learners in knowledge integration processes.

Analyzing student criteria revealed valuable information on how students distinguish ideas. First, all three activities successfully supported students to develop valid criteria to distinguish ideas about chemical reactions. Students on average

established at least one valid criterion to distinguish ideas about bond breaking or bond formation after the project. Second, generation helped students develop the most complicated criteria to distinguish ideas about chemical reaction processes. Students in the generation group on average developed two or more valid criteria to distinguish ideas about bond breaking and formation. Whereas, students in the selection and critique groups often only developed one valid criterion. Generation was the most effective approach at supporting students to distinguish ideas. Third, generation supported students to develop criteria to distinguish ideas about particulate nature of matter. Approximately 10% of students in the generation group focused their criteria on how to represent atoms and molecules with correct molecular structures, whereas none students in other groups had criteria concerning this aspect. One possible explanation was that students in the generation group drew what molecules looked like during the interim phases. This task involved them in considering how to represent molecules and atoms accurately. Students in other groups did not draw and instead focused on representing changes in the aggregate instead of structures of single particles. Besides distinguishing ideas about chemical reaction processes, generation also supported students to distinguish ideas about particulate of matter.

Overall, this study confirmed findings from previous studies and offered insightful guidelines for teaching and instruction. Teachers and researchers can examine the criteria to better understand student learning. For instance, if a student had invalid criteria about bond breaking but valid criteria about bond formation, he probably struggled to integrate the idea of bond breaking but did not have problems in integrating the idea of bond formation. Teachers can lead a whole-class discussion about the criteria. Students can discuss and revise the criteria, and advance their understanding of the underlying chemistry concepts simultaneously. In addition, instructional designers can employ the three activities in the instructions. Because each activity may facilitate students to develop different criteria, combining them may help students develop complete criteria to distinguish various ideas about chemical reactions.

Knowledge Integration Implications

This dissertation offers great implications to the knowledge integration framework. First, the success of the *Hydrogen Fuel Cell Cars* project exemplifies the power of using knowledge integration framework to design technology-enhanced curricular projects that feature computer visualizations. Students enter chemistry classes with multiple non-normative ideas about chemical reactions. To develop coherent understandings of chemistry, researchers advocate instructions that build upon student existing knowledge and employ an inquiry context so that learners can apply their knowledge to solve real-life problems (Linn & Eylon, 2006). Informed by the knowledge integration framework, *Hydrogen Fuel Cell Cars* was built upon student prior knowledge about cars and guided them to integrate new ideas with their prior views. Students investigated chemical reactions within the context of hydrogen fuel cell cars and connected atomic interactions with everyday events such as car safety. To promote knowledge integration, this project employed design patterns such as reflection and predict-observe-explain. Embedded questions were designed to elicit students' existing ideas, a dynamic visualization was embedded to help add normative ideas about bond breaking and formation during chemical reactions, and a series of activities were developed to help students distinguish among various ideas and refine their

understandings about chemical reactions. The design of the project shows how to embed dynamic visualizations within inquiry-based curricula that take advantage of the knowledge integration framework. Student learning gains after learning the HFC project demonstrate the effectiveness of technology-enhanced curricular projects that engage students in knowledge integration.

Second, this dissertation suggests some refinements to the knowledge integration framework by investigating approaches that can engage students in distinguishing ideas. Dynamic visualizations can help students add ideas about atomic interactions during chemical reactions. Yet learners often do not distinguish among their intuitive ideas and the normative ones from the visualization and end up with mixed ideas. For instance, in this research, many students were found to stick with their non-normative ideas (e.g., believing there were no interim phases during chemical reactions) even after exploring the visualization that shows bond breaking and formation during hydrogen combustion. They did not distinguish the expert views in the visualization with their prior ideas and failed to integrate new ideas from the visualization.

To solve this problem, three different approaches were explored: generating drawings, critiquing drawings by fictitious peers, and selecting among alternative drawings. Generating drawings required students to draw the sequence of events in the visualization, which forced them to distinguish between the details demonstrated in the visualization and their own prior knowledge. Critique asked learners to critique drawings about the sequences, which were designed to show common non-normative ideas held by students. To critique, learners must distinguish among their ideas with those represented in the drawings. Selection required students to select among alternative sequences. Learners need to distinguish among the normative and non-normative ideas represented in the alternatives to make choices. The results suggest that these tasks all succeeded in supporting students to distinguish among ideas. Students realized gaps in their knowledge and explored the visualization to integrate normative ideas. These approaches suggest the importance of distinguishing ideas when supporting students to integrate ideas from visualizations. The research adds value to the knowledge integration perspective by demonstrating different instructional approaches that can engage students in the process of distinguishing ideas.

Principles for Designing Instructions with Visualizations

This dissertation demonstrated the success of designing instructions with dynamic visualizations using knowledge integration principles and patterns. Visualizations help students visualize unobservable phenomena and processes. Curricular activities guide students to add ideas at the atomic level, distinguish with their old views, and connect with relevant concepts. This dissertation investigated three different instructional patterns and suggested directions for instructional designers. Next, I propose the following design principles for effective instructions with visualizations (Kali, Fortus, & Ronen-Fuhrmann, 2009).

Reduce Distracting Features of Visualizations

Dynamic visualizations can help students learn abstract scientific concepts. They allow learners to explore or experiment with phenomena that are too small or too big to investigate in classrooms and labs. For instance, they can demonstrate atomic interactions during chemical reactions and help learners understand these unobservable phenomena

and processes. Research has suggested the benefits of incorporating visualizations in instruction, including adding ideas at the atomic level and linking with other levels (Ardac & Akaygun, 2004), motivating learners to discuss the microscopic processes with peers (Wu, Krajcik, & Soloway, 2001), and increasing students' interest and insights in science (Corliss & Spitulnik, 2008).

Designing effective visualizations poses great challenges to researchers. Students and teachers often complain that visualizations are too complex and confusing. To be successful in classrooms, visualizations must remove distracting features. Many visualizations are designed for/by experts and engineers. They may include features that are obvious to experts but confusing to novice students. Consider the Phet chemical reactions simulation (Wieman, Adams, & Perkins, 2008) as an example. The visualization aims at teaching chemical reactions and limiting reagents. It features a representation of a pump. Learners can add molecules to the reaction by clicking on the pump. Designers may believe that students can develop deep understanding about chemical reactions by manipulating the pump and observing how adding molecules changes the reaction. Yet this feature can be distracting to students. Learners often become confounded and struggle to understand the purpose of the pump. Some may think that pushing the pump means increasing the pressure and investigate how pressure affects the reaction rate. This feature must be revised or removed when we implement the visualization in real classrooms.

When determining whether features are distracting, designers should take into consideration of student prior knowledge and needs. Features that experts appreciate may require too much prior knowledge and are confusing to novices. Such features should be removed when we adopt the visualizations in classrooms. The design of the hydrogen combustion visualization involved eliminating a lot of these kinds of features. The Molecular Workbench software (Xie & Tinker, 2006) provides designers with many options, such as graphing real-time potential and kinetic energy of all particles demonstrated in the simulation and tracking attractive forces between particles. Experts may think these features can vividly illustrate how energy and forces change during chemical reactions. Middle school students are confused. They do not have adequate prior knowledge about energy and struggle to make sense of the graphs. They may ignore other key ideas such as bond breaking and formation demonstrated in the visualization. While these features may be more helpful to students who have higher prior knowledge, they are distracting and confusing to middle school students. I removed them when designing the visualization for this research.

Successful visualizations typically take numerous cycles of implementation and refinement. In this project, before being used in classrooms, the hydrogen combustion visualization was first pilot tested with teachers, sample students, and researchers to reduce the complexity and confusing features. I revised the visualization based on their feedback. I kept revising the visualization based on results from each implementation in classrooms.

Focus Student Exploration on Crucial Disciplinary Knowledge

Dynamic visualizations typically present students with enormous amount of information because of their transitory nature. When learning with visualizations, students need to select important features, add ideas by observing the changes, and organize their thoughts (Mayer & Moreno, 2003). Students may attend to features that are

irrelevant and develop superficial understandings. Implementing the hydrogen combustion visualization in classrooms found that students often focused on superficial information such as color and size of the atoms. They did not notice changes in chemical bonds and did not gain ideas about molecular-level changes.

Instructions should draw student attention to the crucial disciplinary knowledge they need to learn and guide them to add new ideas. In this dissertation, students generated, selected, or critiqued pictures that showed atomic interactions and changes in chemical bonds during four interim phases: before the reaction, right after the reaction starts, later during the reaction, and after the reaction completes. These activities highlighted the dynamic nature of chemical reactions and forced learners to concentrate on key ideas such as bond breaking and formation. Students investigated the visualizations to add new ideas and refined their understanding about chemical reactions. Such activities helped students select important features of the visualization and attracted their attention to these important details.

Design Desirable Difficulties to Help Overcome Deceptive Clarity

Dynamic visualizations can be deceptively clear. They illustrate complex science in such an apparently simple way that students may underestimate the demands of interpreting visualizations. They may become convinced that they understand based on superficial observations and stop further exploration of the visualizations (Chiu & Linn, in press). For instance, students often observed the movement of molecules using the hydrogen combustion visualization and concluded that the visualization demonstrated “*molecules moving during the reaction.*” They thought they had learned from the visualization and did not further investigate reaction processes of bond breaking and formation. To enhance learning with visualizations, students need to recognize problems of their interpretations, distinguish new ideas with their prior knowledge, and refine their understandings.

To help students distinguish ideas, I took advantage of desirable difficulties. Research on desirable difficulties (Bjork, 1994, 1999) suggested that students benefit from certain difficult activities that generally slow down or prolong learning by increasing errors. Ultimately resolving these errors or revisiting the instruction leads to better understanding. Bjork’s studies show that activities such as generation resulted in more errors but better long-term retention. Desirable difficulties include asking students to generate explanations, to draw their ideas, to critique an argument, or to generate an argument. Classroom studies show that generation compared to reading can be more effective for learning science concepts (Richland, Bjork, Finley, & Linn, 2005).

The generation, selection, and critique activities studied in this dissertation can be potential desirable difficulties. These activities all provided students with opportunities to test their understandings and encouraged them to distinguish among ideas. Generation required learners to draw the interim phases during hydrogen combustion. Students needed to distinguish their own ideas with the expert views demonstrated in the visualization in order to decide what should be represented in each phase. In selection, students needed to select from a large set of alternatives to represent the phases. The choices to be selected represented common ideas held by students. Learners must select by distinguishing the normative and non-normative ideas represented in the choices. In critique, learners needed to critique drawings of the interim phases by distinguishing normative and non-normative ideas in the drawings to be critiqued. All three activities

created learning difficulties that prompted learners to realize gaps in their knowledge. They avoided students from being beguiled by their superficial interpretations. Learners distinguished their own ideas with new views from the visualization, added new ideas, sorted out, and refined their understanding.

Implications

Results from this dissertation offer important implications for researchers and designers. First, the dissertation investigates using dynamic visualizations in real classrooms. The results contribute to the educational dialogue by providing means to make technology effective in classrooms. They also offer ways to design activities such as generation, selection, and critique that help students distinguish and refine ideas in technology-enhanced settings.

Second, this research explores designing instructions that follow the selection, generation, and critique patterns. It exemplifies embedding visualizations within these patterns and demonstrates the effects of these patterns on students with various levels of prior knowledge. The findings suggest that critique may be more beneficial to students with high levels of prior knowledge than generation, selection may be more effective for learners with partial ideas, and generation may be more suitable for learners with low prior ideas. Designers can consider combining all or partial of these patterns to help students at all levels of prior knowledge.

Third, results from this research can inform teaching. Student drawings, selections, and critiques offer teachers opportunities to understand the difficulties and challenges that students face in learning with visualizations. Teachers can gain a better idea of student learning by examining student work and use this information to improve their teaching. They can ask students to share their drawings with peers, discuss, and revise their understandings of the underlying chemistry concepts.

Limitations

This research has limitations. For instance, this dissertation includes a series of quasi-experimental studies because the teachers and students were recruited to participate instead of being randomly selected. The results may differ from situations involving participants, treatments, settings, and measures different from those in the study. This research involves seven teachers. Although I stayed in all classrooms when implementing this research, instructions may differ slightly across teachers because of their different teaching styles.

Another limitation is that this study measures immediate effects of the treatments using posttests. Conducting a delayed posttest may be a desirable future study and could clarify the long-term effects of these activities on student understanding. In addition, the dissertation does not lay emphasis on analyzing the videos when students worked on the generation, selection, and critique tasks. Video analysis can add value to the research by providing more details about the cognitive processes involved in these tasks.

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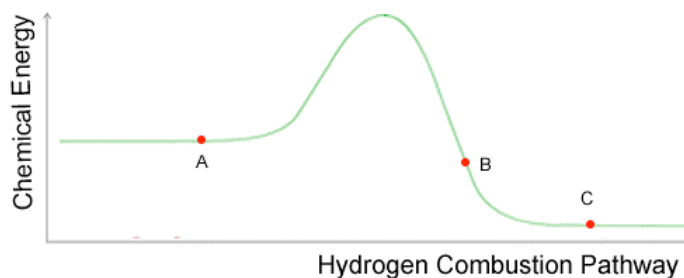
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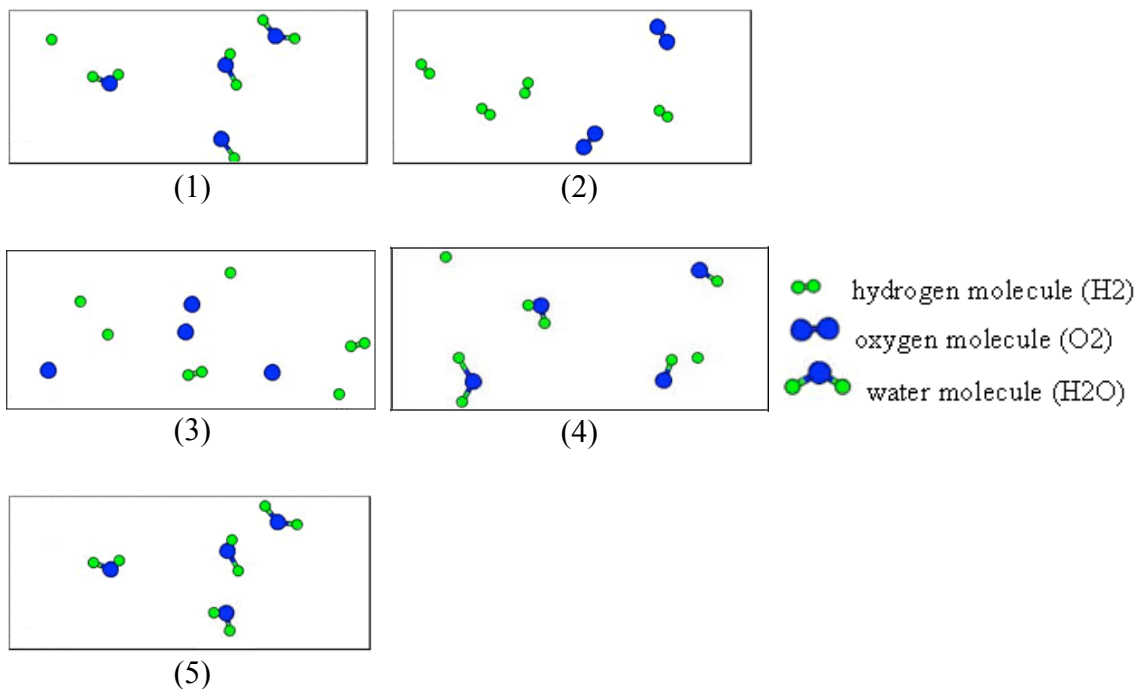
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Appendix A: Pretest and Posttest questions used in studying the impact of HFC project (Chapter 3)

Questions R1 & R2 refer to the diagram below. The diagram shows energy change during H₂ combustion.



The following pictures are snapshots of molecular movement at different time during the reaction.



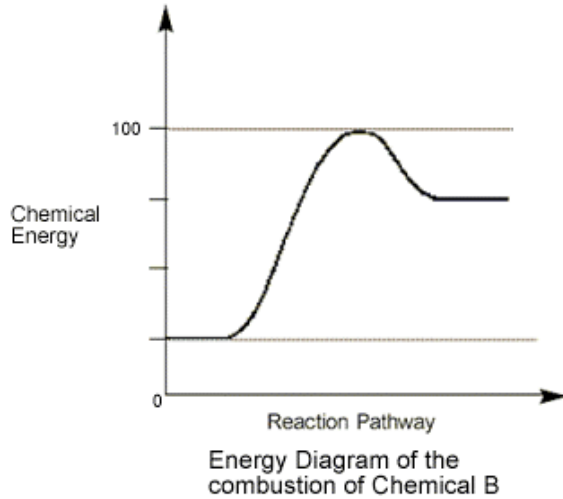
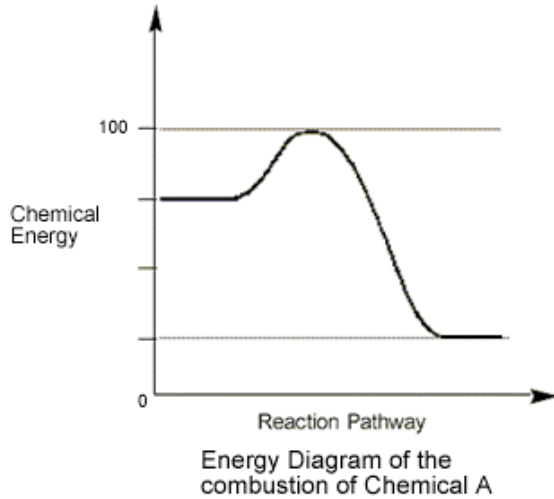
R1. Which snapshot shows the movement of molecules at **Point A**? Circle all that apply.

- (1) (2) (3) (4) (5)
- Explain your answer.

R2. Which snapshot shows the movement of molecules at **Point C**? Circle all that apply.

- (1) (2) (3) (4) (5)
- Explain your answer.

R3. You are looking at two new chemicals, A and B, to power a new type of lawn mower. The following diagrams show energy change during the combustion of each of these chemicals.



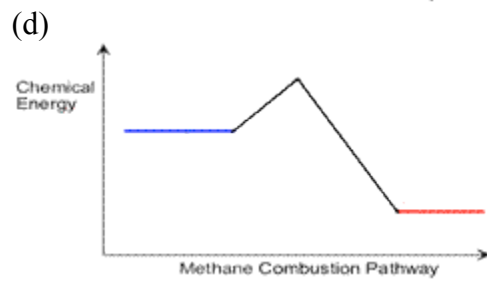
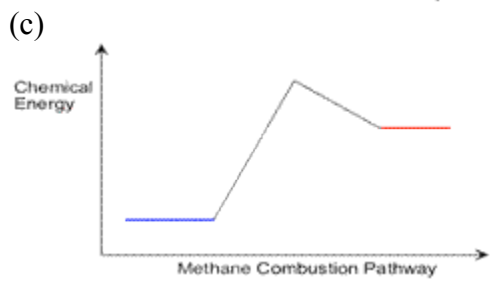
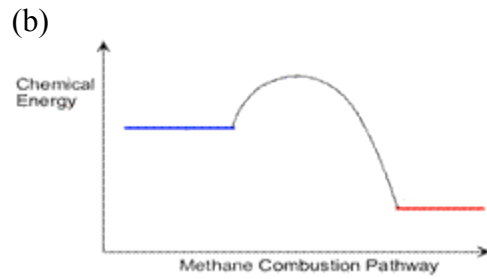
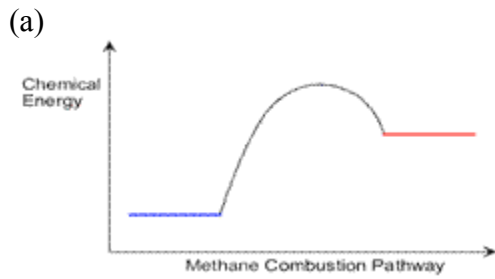
In terms of energy release, which chemical could be used as fuel? Circle all that apply.

A

B

Explain your answer.

R4. A scientist wants to use natural gas- methane (CH_4) to run cars. The equation of methane combustion is $\text{CH}_4 + \text{O}_2 \rightarrow \text{CO}_2 + \text{H}_2\text{O} + \text{energy}$
Which of the following graphs shows the energy change in methane combustion? Circle all that apply. Explain your answer.



A1. Of the following requirements, which is **NECESSARY** for all types of fuels used in cars? **ONLY** check those **NECESSARY** requirements.

- release energy when burn
- produce CO₂
- absorb energy when burn
- non-polluting reaction when burn
- produce H₂O
- burn spontaneously
- require a spark to start burning
- produce O₂

Explain your answer.

A2. Compared to gasoline powered cars, what are the advantages of using hydrogen fuel cell to run cars?

C1. Scientists claim that liquid hydrogen can be used as fuel to power cars. What chemical reaction(s) is involved if hydrogen is used in cars? Specify the reactants and products. Write down balanced equation(s) of the reaction(s).

Reactants: _____

Products: _____

Balanced equation(s): _____

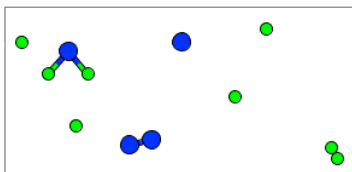
Appendix B: Pre and Posttest Questions and Knowledge Integration Scoring Rubrics

Recognition Question 1:

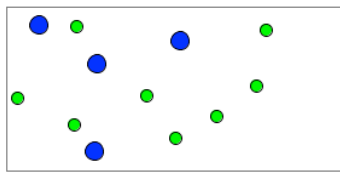
The following pictures are snapshots of particles at different times during the burning of hydrogen (Oxygen=●, Hydrogen=●).

1.1) Circle the snapshot that shows the particles **before the burning of hydrogen gas starts**.

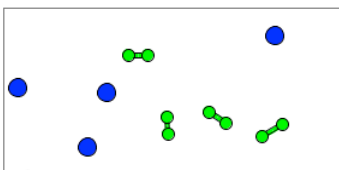
a.



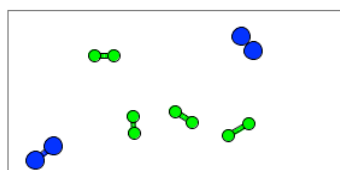
b.



c.



d.

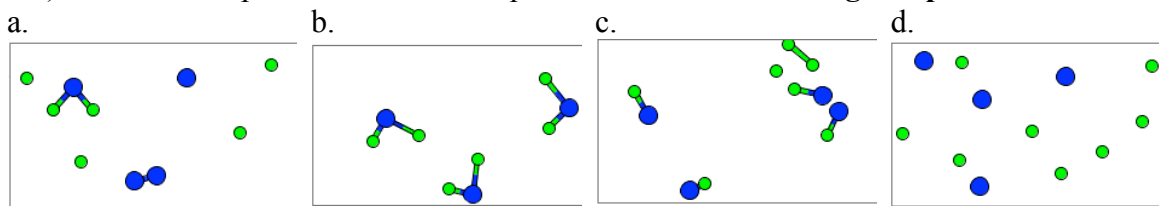


Explain your answer.

KI level	Score	Characteristics
none	0	blank;
invalid	1	Wrong or incorrect ideas <i>"b, they start separately and then attach to each other."</i>
partial	2	Only make the correct selection, explanation did not address the reaction state or activation energy <i>"d, the oxygen and the oxygen are connected together, and the hydrogen and the hydrogen are connected together"</i> OR Explained the reaction state or activation energy but made wrong selection
simple	3	One complete link of molecular representations and reaction state (correct selection +reaction state) <i>"d, the hydrogen and oxygen molecules don't break their own bonds before the burning. They are still together."</i>
Two links	4	Two or more links between the three ideas <i>"d, the temperature has not speed up the particles yet, so they are still bonded together."</i>

Recognition Question 2

1.2) Circle the snapshot that shows the particles **after the burning completes**.

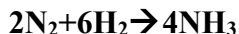


Explain your answer.

KI level	Score	Characteristics
none	0	blank;
invalid	1	Wrong or incorrect ideas “d, because the molecules separated after burning.”
partial	2	Only make the correct selection, explanation did not address the reaction state or released energy OR Explained the reaction state or released energy but made wrong selection “b, it shows the products H ₂ O when the reaction finished.”
simple	3	One complete link of molecular representations and reaction state (correct selection +reaction state) “b, well during the burning some of the hydrogen molecules are still not connected to the oxygen molecules. But I think after two hours the hydrogen molecules connect to the oxygen molecules.”
Two links	4	Two or more links between the three ideas “b, the temperature speeds up hydrogen gas and they start detaching from their original bonds and they attract to the oxygen atoms.”

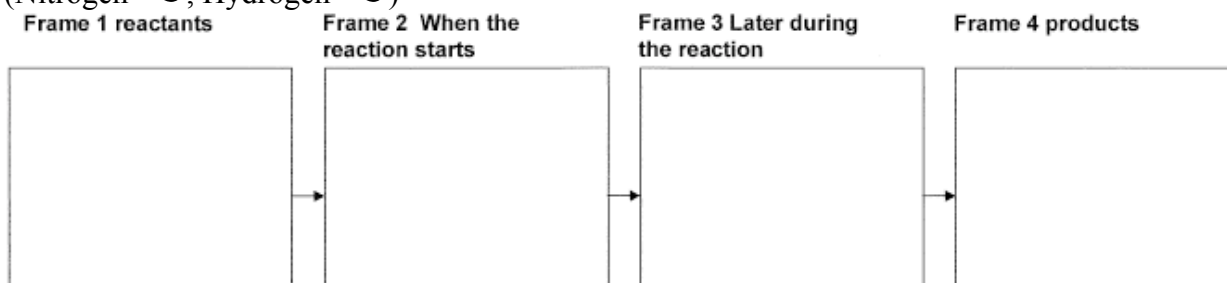
Drawing Question 1 & 2:

Nitrogen (N₂) and hydrogen (H₂) react to create ammonia (NH₃) according to the following reaction equation:



2.1) Frame 1 shows the reactants. Draw intermediate steps in Frame 2 and 3 to show how the reaction happens, and draw Frame 4 to show the end products.

(Nitrogen = ○, Hydrogen = ⊙)



KI level	Score	Characteristics
none	0	blank; Did not draw anything that makes sense
invalid	1	Wrong or incorrect ideas e.g., draw element view, or static view
partial	2	Draw bond breaking correctly (break only view) OR Draw bond formation correctly (bond only view) OR Draw some ideas of bond breaking or bond formation, but none of them is completely correct (incorrect bond breaking + correct bond formation OR correct breaking + wrong formation) OR Did not draw breaking or formation, but all pictures contain the same numbers of atoms
simple	3	Draw bond breaking and formation correctly
Two links	4	Draw bond breaking and formation correctly AND all pictures have the same numbers of atoms

2.2) What happens during the reaction? Describe how the chemical bonds change.

KI level	Score	Characteristics
none	0	blank;
invalid	1	Wrong or incorrect ideas
partial	2	Explain only bond breaking or bond formation
simple	3	Explain bond breaking and bond formation in the right sequence (first breaking, then formation)
Complex links	4	Explain bond breaking and formation And other ideas, such as the increasing temperature makes molecules moving faster, or energy change

Selection Question 1 & 2:

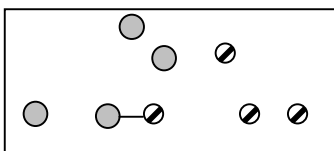
Sasha is trying to make a movie with 4 frames to show how the reaction between H_2 and Cl_2 happens ($H_2 + Cl_2 \rightarrow 2HCl$). Frame 1 shows the reactants, and Frame 4 shows the end products. (C= , H=)



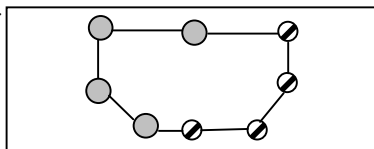
Sasha needs to select pictures to **show the intermediate steps** in for Frame 2 and Frame 3.

3.

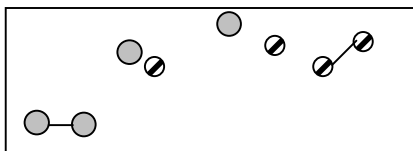
a.



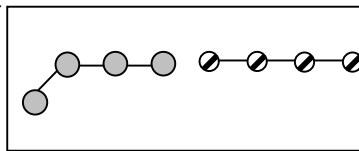
b.



c.



d.



3.1) Which picture should she choose for Frame 2? (Circle one)

a

b

c

d

Explain your choice.

KI level	Score	Characteristics
none	0	blank;
invalid	1	Wrong or incorrect ideas
partial	2	Only explain the bond breaking and wrong selection
simple	3	One valid link between the correct molecular representation and bond breaking <i>"c, because the reaction just starts, the bonds are not all broken and the atoms are trying to separate."</i>
Two links	4	Valid links between molecular representation, bond breaking and bond formation Other links to relevant ideas such as temperature or heat <i>"c, they are breaking the bonds, the atoms will be free to combine with each other to form new molecules"</i>

3.2) Which picture should she choose for Frame 3? (Circle one)

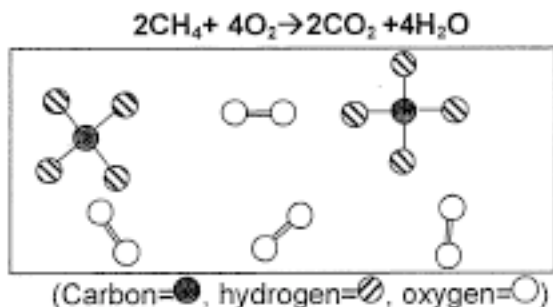
a b c d

Explain your choice.

KI level	Score	Characteristics
none	0	blank;
invalid	1	Wrong or incorrect ideas
partial	2	Only explain bonding and wrong selection OR Only make correct selection, don't mention bonding
simple	3	One valid link between the correct molecular representation and bond formation <i>"a, they are forming new bonds between h and cl. There are three h atoms, three free cl atoms, and one hcl molecule. They are floating around."</i>
Two links	4	Valid links between molecular representation, bond formation, and relevant ideas such as temperature or heat <i>"the hs and cls combine and become hcl molecules. It will release heat and the temperature will increase."</i>

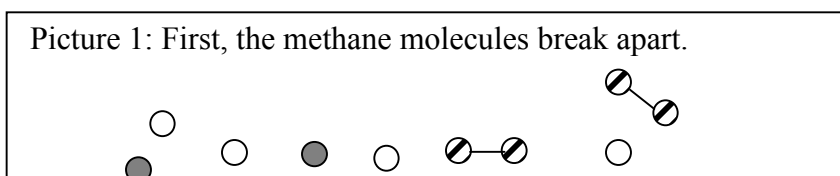
Critique Question 1, 2, & 3:

Li drew pictures to show how the burning of methane happens. The box below shows the reactants.



Li drew another three pictures to explain how methane burns.

4.1) Li's drawing of what the molecules look like **when the reaction starts**.



Is Li's drawing correct? (Check one)

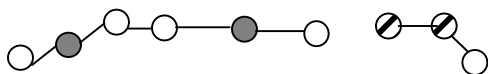
accurate partially correct wrong

Explain what is good and what is bad about this drawing.

KI level	Score	Characteristics
none	0	blank;
invalid	1	Wrong or incorrect ideas
partial	2	Only explain breaking bond and don't mention the incorrectness of hydrogen atoms being connected Or only mention correct bond-breaking of oxygen and methane molecules
simple	3	A complete link of bond breaking and molecular representation (mentions methane and oxygen molecules break correctly, and hydrogen atoms should not connect) OR A complete link of conservation of mass (explain that atoms are not conserved, miss oxygen atoms and hydrogen atoms) OR A complete link of conservation of mass and mentions breaking bonds, but fail to point out the incorrectness of hydrogen atoms being connected
Two links	4	Valid links between molecular representation, bond breaking, and conservation of mass

4.2) Li's drawing of what the molecules look like **later during the reaction**.

Picture 2: Then the free atoms are trying to get connected.



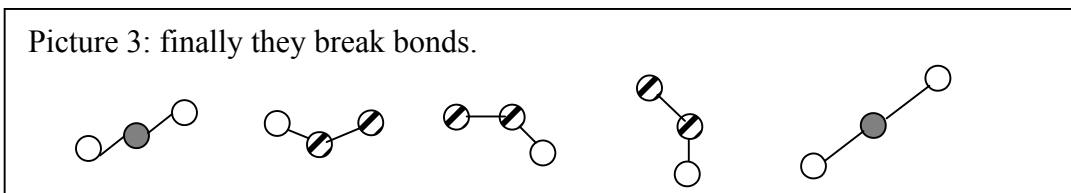
Is Li's drawing correct? (Check one)

accurate partially correct wrong

Explain what is good and what is bad about this drawing.

KI level	Score	Characteristics
none	0	blank;
invalid	1	Wrong or incorrect ideas
partial	2	Only mention the incorrect chain structure or only point out the wrong structure of water molecules
simple	3	A complete link of bonding and molecular representation (explains the chain structure is wrong, molecules are starting to bond with fixed ratio, and the wrong structure of water molecules) OR A complete link of conservation of mass (explain that atoms are not conserved, miss oxygen atoms and hydrogen atoms) OR A complete link of conservation of mass and mentions bond formation, but fail to point out the wrong chain structure or the wrong structure of water molecules
Two links	4	Valid links between molecular representation, bond formation, and conservation of mass

4.3) Li's drawing of what the molecules look like **after the reaction**.



Is Li's drawing correct? (Check one)

accurate partially correct wrong

Explain what is good and what is bad about this drawing.

KI level	Score	Characteristics
none	0	blank;
invalid	1	Wrong or incorrect ideas
partial	2	Only mention the incorrect chain structure or only point out the wrong structure of water molecules
simple	3	A complete link of bonding and molecular representation (explains the wrong structure of water molecules and the correct structure of carbon dioxide molecules) OR A complete link of conservation of mass (explain that atoms are not conserved, need two more water molecules) OR A complete link of conservation of mass and mentions correct structure of carbon dioxide molecules
Two links	4	Valid links between molecular representation, bond formation, and conservation of mass