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The efficacy of visual analogy for the instruction of bond energy curves in undergraduate chemistry

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We explored a selection of analogies used for introducing students to the concept of potential energy wells. Two analogy systems were developed, a spring system to explain simple harmonic motion and a novel system consisting of electrostatic spheres. These two, distinct analogies were housed within an interactive tool that allowed students to manipulate the analogous systems and witness changes to potential energy curves in real time. A pre-test/post-test evaluation provided insight into the impact the formatulation of an analogy system can have on understanding. Students modified written descriptions to include new details in accordance to the structure-mapping theory of analogies. However, students failed to correct visual descriptions of energy wells. The failure of participants to apply key concepts after using the interactive and animated analogy systems highlights the importance of carefully designing these tools.

Introduction

The presentation of an analogy is a common teaching strategy that relates familiar concepts and systems to ones that are new and unfamiliar to the learner. Given their utility as an educational tool, instructional analogies have been investigated in multiple studies (Coll, France, & Taylor, 2005; Dagher, 1995; Del Re, 2000; Glynn & Takahashi, 1998; Harrison & Treagust, 1993). Well developed and validated analogies have been demonstrated to have a number of educational advantages, including: (1) providing a base level of understanding for novel concepts (Glynn & Takahashi, 1998; Orgill, Bussey, & Bodner, 2015), (2) providing a visual model upon which to approach abstract concepts (Nersessian & Chandrasekharan, 2009; D. F. Treagust, Harrison, Venville, & Dagher, 1996; Yaner & Goel, 2006), and (3) providing a foundation to motivate students and spark further inquiry (Choi & Chang, 2004; Glynn & Takahashi, 1998; D. F. Treagust et al., 1996). According to the structure-mapping theory proposed by Gentner (1983), a system can serve as an analogy if it shares certain fundamental characteristics with an unfamiliar system. For an analogy to be successful, a base/familiar object must map its higher-order relations to the target/unfamiliar object (higher-order relations include causal, mathematical or function relations). Therefore, an analogy transfers concepts best when the characteristics it shares with the unfamiliar system are fundamental higher order relations rather than simple attributes.

Well-constructed analogies readily lend themselves to instruction within the sciences (Aubusson, P.J., Fogwill, 2006; Del Re, 2000; Novick & Holyoak, 1991). Chemistry in particular contains many abstract principles that are often made accessible through the use of metaphor, analogy or mental models (Gould, 1999; Hajkova, Fejfar, & Smejkal, 2013; Orgill et al., 2015; Thiele & Treagust, 1994). For students, analogies help to make chemistry concepts that are complex and non-intuitive accessible. However, mapping a chemical concept through a single analogy only is not sufficient to create proper understanding (Spiro, Feltovich, Coulson, & Anderson, 1989). The educator must stress to students that the initial insights obtained from analogies must be challenged and refined to truly comprehend chemical concepts (Harrison & Treagust, 2006; D. F. Treagust, Harrison, & Venville, 1998).

Contemporary instructors have access to both interactive and animation technology to produce learning tools capable of conveying concepts that are normally difficult to communicate (Jones, 2013; Wu, Krajcik, & Soloway, 2001; Yang, Greenbowe, & Andre, 2004). Animations have been shown to increase student understanding of atomic phenomenon; for example, animated atomic motion in a description of states of matter led to a significant increase in student comprehension (Ardac & Akaygun, 2004). An added benefit to using interactive educational media is its ability to allow students to learn through exploration (Barak & Dori, 2005; Frailich, Kesner, & Hofstein, 2009). Interactive technology may be useful for the creation of new analogies for the instruction of difficult chemical concepts.

In the present study we wanted to investigate (1) the performance of a newly constructed analogy that relies on interactivity and (2) how the content of the analogy can impact the understanding of a system.

Background

Use of analogy in chemistry

Analogies are abundant in the instruction of abstract concepts within the discipline of chemistry (Thiele & Treagust, 1994). Fisher's lock and key for explaining protein-ligand binding, planetary orbits to introduce electron motion, and roller coasters to exemplify the concept of potential energy are

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a few of the many analogies available to educators. These very accessible analogies are useful to naïve students who are trying to comprehend new concepts. While analogies provide a foundation for understanding these concepts, instructional analogies must be refined over time to better reflect reality. Exemplifying this is Fischer's lock and key, which is contrasted with the induced-fit model to better conceptualize protein-ligand binding. Failure to correct these early models can lead to confusion when more complex concepts are introduced (Harrison & Treagust, 2006).

Chemistry is also abundant with visual analogies. To visually communicate chemical concepts, instructors generally use three levels of visual representation: symbolic (Lewis structures), submicro (atomic/molecular level), and macroscopic (chemical reactions) (Gilbert & Treagust, 2009; Johnstone, 2009; D. Treagust, Chittleborough, & Mamiala, 2003). Symbolic and submicro representations are akin to visual analogies since they assign familiar shapes to entities that cannot be observed. While technology has come a long way in its ability to capture images of molecules in real-time (eg. the single-molecule, real-time transmission electron microscope imaging technique), there remains a large reliance on symbolic representations (Nakamura, 2013). However, these representations can unfortunately convey qualities that are not consistent with reality. For example, the line which symbolizes bonds in Lewis representations falsely implies rigid bonds. Without additional corrective descriptions, many visual analogies fall short of reality.

Instructors commonly use analogies in succession in order to build a more complete picture of the concept being taught (Spiro et al., 1989). For example, to modify students' notion that bonds are rigid, as implied by Lewis structures and other static representations, one can use the analogy of two balls (representing the atoms) on a spring (representing the force between them) to provide a dynamic model. These two analogies synergize to give a more elaborate and complete understanding of atomic bonding. Additional analogies, like using "tug of war" for concepts like electronegativity and polar bonds, can scaffold and help to refine the mental model initialized by an earlier analogy.

The spring is an analogy and model readily used by physicists and chemists to describe and simplify difficult systems (Del Re, 2000). When using the spring analogy for atoms in a bond, the system's energy is often discussed. The spring is a simple harmonic oscillator and its energy can be represented by a symmetric, U-shaped energy well. Early descriptions of bonds as simple harmonic oscillators are necessarily replaced by the Morse potential to account for the anharmonicity found in real bonds. Eventually, quantum descriptions can be made to more accurately approximate of the energy of atoms in a bond. Energy plays a fundamental role in chemical phenomena and therefore, the origins and meaning behind energy well shapes found in energy diagrams are important concepts for students to understand.

Interactive energy well analogies.

The energy wells in the Jablonski diagram are a significant component of the diagram and are important features to be understood by students. As mentioned, students are initially introduced to energy wells through a spring model and its corresponding U-shaped energy graph. Students are then introduced to a better approximation of bond energy given by the Morse potential. Unlike the spring system, analogies for the anharmonic Morse potential are not commonplace. In the present study we constructed a system featuring electrostatic spheres that possessed clearly defined regions of attraction and repulsion. This system was proposed to serve as an analogy for the Morse-potential.

In order to aid student's conceptualization of the proposed Morse-potential analogy we created a digital, interactive version of the system (see Fig. 1). The interactive analogy held 3D representations of spheres that students were able to click and drag. Upon dragging the spheres, a Morse potential was drawn simultaneously with respect to the inter-sphere distance on a 2D graph. Arrows clearly demarked the magnitude and direction of the attractive, repulsive and net forces acting on the spheres. We also constructed an interactive digital model of the spring analogy. This model featured an interactive spring with two balls attached to its ends. Students could drag the balls in order to stretch and compress the spring and upon its release the spring system oscillated and dampened. Also, an energy potential was drawn in real time in direct relation to the spring's distance from equilibrium. Pulling the spring too far resulted in the spring breaking.

We wanted to investigate how well these analogies performed in the instruction of potential energy diagrams. In particular, we wanted to investigate if undergraduate students interacting with either analogy would apply this knowledge to their drawings of the Jablonski diagram, where errors in well shape was commonly observed. It was postulated that both systems would alter the student depictions of energy wells found in the Jablonski diagram drawings. Additionally, the electrostatic sphere analogy was investigated for its ability to instruct students about the Morse potential.

Methods

Participants and context

The study included undergraduate students enrolled in a 3-year advanced analytical chemistry course taught during a single semester (N = 39) at University of Toronto Mississauga. All students in the study were previously enrolled in a 2nd year analytical chemistry class and were taught the Jablonski diagram as part of their 2nd year curriculum. The Jablonski diagram was reviewed at the beginning of the 3rd year course. Students were randomly assigned to either a "spring analogy" (N = 19) treatment group or an "electrostatic sphere analogy" (N = 20) treatment group. Each group interacted with an analogy that was intended to instruct students about the energy found within a molecular bond. The study was conducted over an hour period, where students completed a pre-test, interacted with the tool, and then completed post-test.

Pre-experimental and Post-experimental Procedures

As part of the recruitment process students were surveyed in order to collect background information on age, gender, study habits, previous chemistry courses completed and comfort level with digital devices. Participants logged into an online system to complete the survey and were provided the information needed to obtain informed consent. Students were assigned random numbers to ensure their anonymity throughout the course of the experiment. Following the use of the interactive tool students were asked to complete a post-use survey which used an ordinal scale to rate their experience with the interactive tool.

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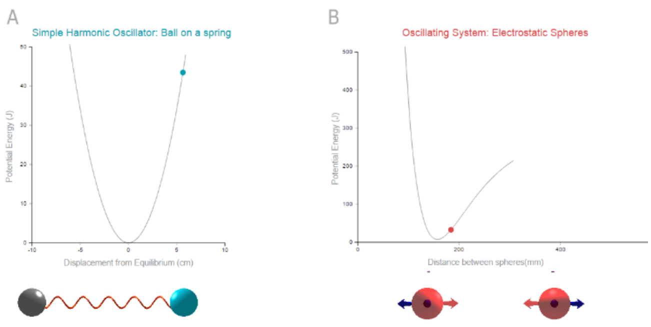

Figure 1. (A) Spring analogy (B) Sphere analogy.

Experiment

All participants completed a pre-test featuring six multiple-choice questions about molecular excitation. They were also asked to draw a Jablonski diagram depicting fluorescence and to provide an explanation for the shape of their drawn energy curves. Students were then prompted to interact with their assigned interactive analogy. One representation featured the traditionally used "ball on a spring" analogy for conveying simple harmonic motion. The animated, three-dimensional spring along with its corresponding potential energy graph can be observed in Figure 1A (link to spring analogy). A brief description on the significance of simple harmonic motion and molecular bonds was included with the metaphor. The second representation featured a system of "electrostatic spheres" that introduced anharmonic oscillatory motion. The electrostatic spheres were also 3D, interactive, and presented with a graph drawn in real time (Figure 1B) (link to sphere analogy). The module featured a text description that was marginally modified from the spring analogy's text for consistency with the sphere model.

Following tool usage, participants were asked to complete a post-test consisting of six questions that followed the same format as the pre-test. Students completed four multiple choice questions and were asked to draw a Jablonski diagram showing phosphorescence and were asked to explain the energy well shape. The total time needed to complete the testing was less than one hour.

Data Analysis

The pre- and post-tests' multiple choice questions featured material that wasn't discussed in the analogy system. Thus, these questions served as a baseline measure to ensure equivalency between the two groups. Non-parametric methods were used to detected differences in performance between the treatment groups as well as to compare total participant performance before and after intervention.

Analysis of student diagrams was conducted by evaluating the graphs component parts. These components are listed in Table 1 along with the evaluation criteria for these features. Diagrams were given an average mark based on the quality of the different components. Features were also examined independently, with focus placed on the well-shape featured in the Jablonski diagram. Responses from two students who drew Jablonski diagrams without including energy curves and using only energy levels demarked by lines, were excluded from consideration.

Analysis of written descriptions was initiated by separating student responses into idea units. An idea unit is generated by dividing a student's written response into a singular thought or idea. In this way, a single sentence could be broken down into multiple idea units each addressing a single fact. Idea units were further designated as either explanatory or descriptive in nature. As per Lowe's (1999) definition, a descriptive idea unit outlines a feature on the graph without giving the underlying cause for that shape (ex. the curve had a vertical asymptote as distance decreased). For an idea unit to be considered explanatory, it must establish a link between an element of the graph and a rationalization for this observed feature (ex. the vertical asymptote was established due to large repulsive forces at short distances). Idea units that did not discuss the well shape were excluded from consideration. Additionally, idea units were evaluated for their correctness.

Table 1. Evaluation criteria for student Jablonski diagram

Component	High Quality (3)	Medium Quality (2)	Low Quality (1)
Axis	- Both y and x axis present - y axis is labelled potential energy and x is labelled internuclear distance	- Both y and x axis present - Incorrect labels for a single axis	- Missing one or more axes - Missing or incorrect labels for both axes
Energy curve shape	- Clear energy minimum - Distinct vertical asymptote at low internuclear distances - Unambiguous horizontal asymptote as x value approaches infinity	- Clear energy minimum - Vertical asymptote indistinct (ie. features curly end) - Horizontal asymptote has indistinct curly end	- Missing energy minimum - No indication of vertical asymptote - Missing or ambiguous horizontal asymptote
Vibrational States	- Horizontal lines representing different vibration states present -Lines are properly spaced and end at the horizontal asymptote	- Horizontal lines representing different vibration states present - Lines aren't properly spaced and end incorrectly	- Horizontal lines absent - Horizontal lines extend beyond the confines of the energy curve
Electron transitions	- Excited state depicted - Excitation event demarked and correct states occupied - Relaxation events clearly marked	- Excited state depicted - Excitation event attempted though not necessarily correct - Relaxation events marked but not necessarily correct	- No excited state presented - Excitation event not indicated - Relaxation event not indicated

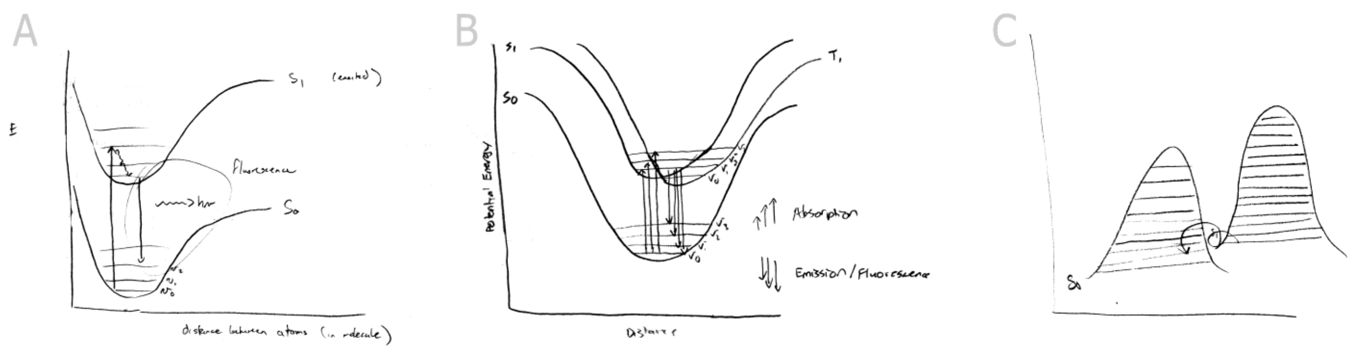

Figure 2. Representative examples of student drawn Jablonski diagrams. A) A high quality example, B) an average quality response and C) a low quality response.

Two neutral inter-raters assigned idea units as either explanatory or descriptive in nature. Inter-raters were trained with a sample set of idea units before categorizing idea units independently. The reliability of the sorted responses was established using Cohen's kappa coefficient, a statistical measure that accounts for random chance. Relatedly, marking idea units as correct or incorrect was performed by the authors after establishing an objective criteria. Furthermore, the number of idea units generated by students before and after intervention were evaluated for significance. Changes in the proportion of correct idea units after intervention were also investigated.

Results

The results from both treatments (N = 39) were collected and analysed in identical fashion. The pre-test's multiple choice questions were graded and the grade averages were compared between the two groups. A Mann-Whitney test performed on the results determined no significant difference existed between the groups (Mann-Whitney p = 0.50, two-tailed).

In the following sections the results from the multiple choice section on the post-test are presented. Next, representative examples of high, medium and low quality diagram responses are presented. This is followed by diagrammatical results presented for each treatment group. Lastly, non-parametric analysis of the number of idea units and proportion of correct idea units will precede the presentation of representative coded idea units (complete coding is available in the supplemental).

Table 2. Mann-Whitney U test results for the multiple choice component between the two groups

	Group	*N*	Median (/6)	Sum of Ranks	*U*	*p*
Pre-test	Sphere	20	4	423	167	0.50
	Spring	19	4	357		
Post-test	Sphere	20	5	429	161	0.40
	Spring	19	4	351		
(Post-test - Pre-test)	Sphere	20	0.5	383.5	173.5	0.63
	Spring	19	1	396.5		

Post-test multiple choice results

The multiple-choice questions were marked for each of the groups and results are summarized in Table 2. A Mann-Whitney test determined no significant difference in student achievement on the pre-test multiple choice section between the groups (Mann-Whitney p = 0.50, two-tailed). Similarly, both groups have similar levels of success on the post-test multiple choice questions (Mann-Whitney p = 0.40, two-tailed). The total collection of participants showed an observed increase in average of 11.1%. To assess if any difference existed between the two groups increased performance, pre-test marks were subtracted from their paired post-test grade and compared. The observed increase in performance were indistinguishable between the two groups at 9.2% and 13.2% for the sphere and spring groups respectively (Mann-Whitney p = 0.63, two-tailed).

Representative Examples of Energy Wells

Students were asked to produce a Jablonski diagram depicting a fluorescence event. Student responses varied greatly in quality. Examples of drawings deemed high, average, and low quality prior to intervention with the analogy are available in Figure 2. Of the 39 participants, 36 students drew versions of the Jablosnki diagram that featured an energy well (1 student left the question blank and two students provided energy lines rather than curves). Fewer than 25 percent of the students (N = 8) were drew well shapes that were deemed high quality. The majority of students produced energy wells that were incorrectly symmetric or featured curly ends in place of vertical asymptotes and horizontal asymptotes (N = 26). Two students produced low quality representations of energy curves. A summary table of the quality of student drawings is provided in Table 3.

Comparison pre-test and post-test responses "spring" analogy

Students in the "spring" analogy group (N = 18) produced Jablonski diagrams that varied in quality, with the majority of students producing diagrams of average quality prior to intervention (N = 10). None of the diagrams drawn by the students showed any modification to the energy well shapes after interacting with the spring system. Several students (N = 5) provided additional details to their Jablonski diagrams in the post-test, namely the inclusion of missing axes (N = 2), and corrections to the axes labels (N = 5). Students also altered their written descriptions after interacting with the analogy systems. The extent of these written modifications is addressed in the 'Coded responses' section. Samples of student drawings before and after intervention with the spring analogy are found in Figure 3.

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Table 3. Summary table of the number of students achieving low to high quality drawings of the Jablonski diagram by groupings.

	Sphere Group				Spring Group			
	Well shape		Overall		Well Shape		Overall	
Quality	Pre-test (n)	Post-test (n)	Pre-test (n)	Post-test (n)	Pre-test (n)	Post-test (n)	Pre-test (n)	Post-test (n)
High	4	5	4	9	4	4	6	6
Medium	13	12	12	6	13	13	10	11
Low	1	1	2	3	1	1	2	1

Comparison pre-test and post-test responses "sphere" analogy

Similar to the spring analogy, the majority of sphere group's (N = 18) drawings from the pre-test evaluated as average in quality (N = 12) and are summarized in Table 3. While several students (N = 3) made very slight modifications to their energy well shape, it is unclear if these changes were intentional or due to normal variation. A single student showed a marked difference in the drawn well-shape post treatment (Figure 4A). In addition to modifications to the illustration, this particular student's written response also improved. As observed with the spring previous analogy, students added missing axes (N = 1) and added/improved axes labels (N = 5).

Coded responses

Students provided a diverse set of explanations for the shape of the energy wells they drew. A single student from each treatment group produced a response that correctly explained the energy well shape prior to interaction with the tool. Most students provided explanations that were incomplete and a surprising amount of students initially left the question blank (N = 11). Student responses were separated into idea units as described in the methods section.

Total Idea Units

The total number of idea units before and after intervention was compared within groups and globally for all participants (Table 4). When the idea units were pooled for both groups, the entire population of students showed a significant increase in the number of idea units produced after intervention (Wilcoxon Signed-Rank p = 0.0015). When calculated within groups, it was found that the number of new idea units for the spring analogy was significantly higher when compared to earlier responses (Wilcoxon Signed-Rank p = 0.0058). However, the sphere groups increase in number cannot be distinguished from random variability (Wilcoxon Signed-Rank p = 0.10).

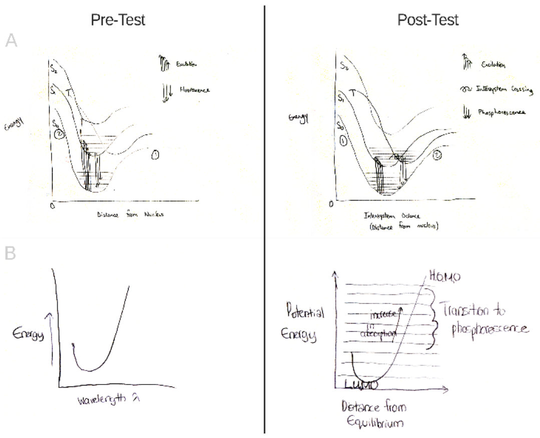

Figure 3. Two examples of student responses for diagram illustration and description pre- and –post spring analogy intervention. (A) Example one highlights the consistent well shape drawing before and after treatment as seen in all student examples (B) Example two has corrected labels for the axes.

Correct Idea Units

Next, we examined the number of correct idea units prior and post intervention (Table 4). Both groups were examined individually before and after intervention and each was analysed using the Wilcoxon Signed-rank test. The sphere group's total number of correct idea units after intervention was significantly higher than pre-intervention (Wilcoxon Signed-Rank p = 0.011). In contrast, the proportion of correct idea units after intervention in the "spring" analogy treatment was indistinguishable from ordinary variability (Wilcoxon Signed-Rank p = 0.11).

Idea Unit Categorization

When comparing the categorization of the idea units as either descriptive or explanatory the two inter-raters had 74% proportionate agreement (ie. proportion of matched responses) and a Cohen's kappa coefficient of 0.47. The results from the spring analogy were consistent between the two inter-raters, with the majority of responses being descriptive in nature both before and after intervention. For the sphere analogy, approximately equal proportions of explanatory and descriptive idea units were recorded prior to

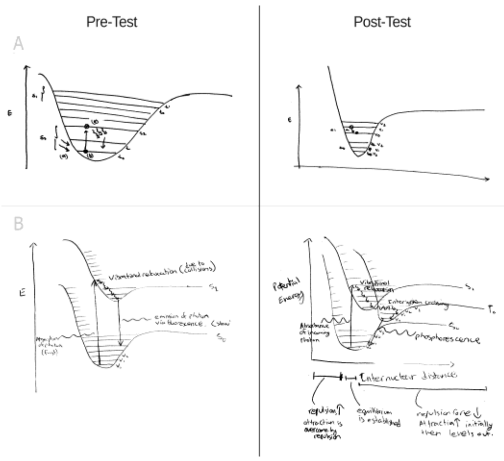

Figure 4. Two examples of student responses for diagram illustration and description pre- and –post sphere analogy intervention. (A) An example of a student correcting the well shape after intervention (B) The student added a dependant axis, and included labels for the forces experienced between atoms.

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Table 4. Wilcoxon Signed-Rank test results for the idea units generated by students

Number of idea units produced

Grouping	*N*	*N* unequal	Mean	z-score	*T*	*T-crit*	*p*
All participants	29	23	Pre = 1.8 Post = 3.0	-3.16	35	73.6	0.0016
Sphere	13	9	Pre = 2.1 Post = 2.9	-1.62	9	5.7	0.10
Spring	16	14	Pre = 1.5 Post = 3.1	-2.75	9	21	0.0058

Percentage of correct idea units produced

Grouping	*N*	*N* unequal	Mean	z-score	*T*	*T-crit*	*p*
All participants	29	20	Pre = 41.1% Post = 72.64%	-2.96	27	52.8	0.0031
Sphere	13	9	Pre = 41.7% Post = 82.7%	-2.53	1.5	5.7	0.011
Spring	16		Pre = 40.6% Post = 64.5%	-1.58	15.5	10.7	0.11

intervention. However, inter-raters varied greatly in their assessment of the sphere group's post-intervention response, with the inter-raters ascribing opposing ratios of descriptive/explanatory ideas. This contradiction makes it difficult to provide any definitive assertions about the affect the analogy had based on the categorization of the idea units.

Comparisons of some representative idea units from each of the analogy groups are found in Table 5. The idea units presented are from the post-test and feature explanatory idea units. The idea units are separated based on the part of the energy curve being described.

A commonly observed addition to participants' idea units, post-interaction with the spring analogy, was the inclusion of concepts like "potential energy" and "kinetic energy". Additionally, mention of spring-like behaviour or oscillatory motion, particularly bond stretching and compression, was observed after treatment with the spring model. Alternatively, student responses following treatment with the sphere analogy primarily mention attractive and repulsive forces. This group also had fewer mention of the oscillatory nature of the system or bond stretching and compression, favouring instead distances between atoms and the forces that dominate at these distances.

Discussion

Multiple choice results

The multiple choice section of both the pre-test and post-test asks students about material that was not featured in either of the interactive analogies. While the questions were based on molecular excitation and related topics, the questions were primarily used as a means to establish equality between the two groups. Additionally, the questions were chosen to orient students to the topic without priming their focus on the concept of energy wells. The Mann-Whitney test showed that student performance on both the pre-test and post-test multiple choice questions were indistinguishable between the two groups. As well, the increase in performance after intervention with the analogy was the same for both groups. The observed performance boost may be attributed to the post-test multiple choice questions being less difficult rather than the any influence by the analogy system. Thus, the performance observed on the multiple choice questions established equivalency between the two treatment groups.

Interpretation of the energy wells featured in the Jablonski diagram

With the exception of a single student, participants failed to correct the well shape of the Jablonski diagram after interacting with the instructional analogies. We propose several potential explanations for participants' inability to improve drawings of energy wells. Firstly, participants could be failing to connect the energy well presented in the analogy to the energy wells found within the Jablonski diagram. Transferring the well shape from the analogy to the Jablonski diagram may have been too great a leap, even when accounting for students' familiarity with the topic. This could be due to poor understanding of the Jablonski diagram and a failure to recognize that energy wells are featured in the diagram (Cook, 2006). Interestingly, the changes featured in many student's written descriptions suggested that they were at the very minimum connecting the interactive analogies with the Jablonski diagram. However, the student responses that featured updated descriptions taken from the interactive analogy may not be an indicator of increased conceptualization but rather a rote memorization of text-based descriptions. The ability of individuals to recall recently observed facts may be factoring into student's written responses. Unfortunately, students were not assessed at an interval to test for long-term acquisition of the information presented. Thus, it is quite possible that students failed to understand what was presented in

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Table 5: Representative examples of idea units from both the spring and sphere analogy after intervention.

	Spring Analogy	Sphere Analogy
Vertical asymptote	"It cannot come too close to the nucleus"	"As distance between the two decreases the repulsion forces acting on the system increase drastically"
	"The highest potential occurs when they are close due to nuclei repulsion (like bond compression)."	"When the atoms are too close, they repel each other (electronic repulsion)"
Absolute Minimum	"the bottom of the E well indicates when the electron is at an equilibrium between its potential and kinetic energy"	"At the bottom where the atoms are distance away from each other so that the attractive and repulsive forces cancel out, it will be in equilibrium and energy is low (stable)."
	"The lowest energy point of the well is the point where there is equal repulsion and attraction"	"Shape of energy well is due to the distance between adjacent nuclei"
Horizontal asymptote	"As the distance increases, this breaks as the atoms are too far away to be attractive to each other"	"It plateaus eventually as the two atoms /species no longer interact in space therefore no change in energy"
	"If it stretches too far away from the nucleus, it flies off (like a spring breaking)"	"If molecules move very far from each other at one point the energy will flatten since bond will break"
General Well Shape	"The electronic state is in a shape of a "U" because of the simple harmonic motion of the electron"	"You see a very steep energy slope initially, that rises again (smaller slope) then plateau's"
	"the bottom of the E well indicates when the electron is at an equilibrium between its potential and kinetic energy"	"The energy well is the simple harmonic oscillation between 2 atoms due to competing attraction and repulsive forces"

the analogy and the failure to correct the well-shape was an indication of this superficial understanding.

A critical skill for students to have when studying chemistry is representational competence, which is the ability to navigate the multiple external representations found within chemistry (ex. graphs, reaction mechanisms, equations) (Gilbert & Treagust, 2009; Johnstone, 2009; Nersessian & Chandrasekharan, 2009; Pande & Chandrasekharan, 2014). Students interacted with the analogy and witnessed the drawing of an energy well, but they may have failed to link the graphic to other relevant representations. In support of this idea is the observation that students often have trouble interpreting the real-world meaning of graphs well into university (Berg & Phillips, 1994). It is possible that students were unable to conceptualize the well shape and thus unable to reproduce it within the Jablonski diagram. Alternatively, students might have failed to see the significance in the well shape and dismissed it as an unnecessary detail, again suggesting a fundamental misunderstanding of graphical representations (Schorr, 2003).

Lastly, there is potential whenever visual representations or analogies are used for cognitive load to factor into students' ability to retain information (Sweller, 1994). Cognitive load theory posits that there are limitations in working memory when processing several channels of information at once that can prevent the conversion of short term into long term memory. In particular, there are three major loads: one that is germane to the subject matter, another that is intrinsic to the learn experience and one that is extrinsic to the learning experience. Students faced with complex visual stimuli may be unable to retain key information because of the extraneous burden often found in visual stimuli. While the interactive analogies attempted to reduce cognitive load by including multiple representations (ie. 3D model and 2D graph), aspects of the visual analogy may have detracted from recognition of the well shape, in particular the spring or spheres in motion could have obscured the energy curves from notice (Simola, Kuisma, Oörni, Uusitalo, & Hyönä, 2011). It has been shown that motion is a highly salient feature and can detract from other features in an animation (Franconeri & Simons, 2003; R. K. Lowe, 2003). Furthermore, the graph was linked to the motion of the spring/sphere by a tracer dot; thus, the tracer dot may have been a point of fixation for students rather than the important, yet static well shape. Hence, students were likely unable to retain all details present in the interactive analogy including the well shape because of distracting salient features.

In summary, student's inability to rectify drawings of energy wells suggests that students may have overlooked the graphs presented in the analogy, failed to understand the significance of these graphs, or were unable to recall the graph due to the visual treatment provided.

Evaluating the success of the analogies through written student responses.

Student explanations contained increased numbers of idea units following intervention with both analogies. Globally, there was an increase in the number of ideas presented post-intervention, suggesting that students were supplementing their responses with information they acquired by

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interacting with the analogy systems. It is interesting that when the groups were examined in isolation, only the spring group showed a definitive increase in idea units. While trending close to signficance (p-value = 0.10), the increase observed in the sphere group could not be distinguished from normal variance.

An indicator that the two analogies differed in performance is the proportion of idea units that were evaluated to be correct. While the number of idea units didn't necessarily increase for the sphere group, the proportion of correct idea units generated post-intervention did increase. The opposite was observed for the spring analogy, which increased in the number of idea units but failed to improve upon the quality of responses after treatment. The source for this difference may lie in the information presented in the analogies themselves. The spring analogy relies on the description of oscillatory motion, potential energy, and a restorative force when the spring is pulled/compressed from equilibrium. While these underlying forces are correct for the spring system, they are not the same forces present between two atoms in a bond. Hence, students describing the energy curve using this restorative force would be incorrect. Also, students seemed inclined to include concepts such as kinetic energy even though these weren't relevant to the energy of the molecular system (seemingly because of the motion featured within the animation). Interestingly, students related the spring breaking to the bond breaking at large internuclear distances; however, most students failed to indicate that the atoms are sufficiently far away to prevent electrostatic and orbital interaction. Results suggest that the spring analogy promoted the transfer of ideas about bonding that were not always consistent with the phenomena described and thus did not contribute to improved performance post-treatment.

Students from the sphere analogy group were introduced to attractive and repulsive forces between the spheres as the source of the anharmonic oscillatory motion present in the Morse potential. Many students modified their responses after using the sphere analogy to incorporate these forces as the underlying cause of their drawn energy well. Mention of the repulsion between nuclei at small distances was common in student responses. Students also mentioned an attractive force between atoms at certain distances, and the lack of attractive/repulsive forces at large distances to account for bond breaking. Interestingly, while the electrostatic spheres showed some oscillatory motion, many student answers failed to mention the vibrational properties of molecular bonds. Some misconceptions did occur, for example, a student suggested that an attractive force exists between the nuclei, which is fundamentally incorrect. However, the majority of students were able to successfully integrate the repulsive and attractive forces into their description of the energy wells. The success of students following intervention with the sphere analogy suggests the constructed system served participants well as an analogy for molecular bonds.

Both analogies were capable of influencing student's thoughts about energy wells. The spring analogy fostered ideas about the oscillatory behaviour of atoms in a bond and provided the concept of restorative forces for the bonds energy. The sphere analogy promoted the concept of repulsive and attractive forces between atoms, and how these forces change with respect to distance. This highlights how analogies may alter student comprehension, and that different analogies can emphasize certain concepts more than others. These results are expected given structure-mapping theory, which states that familiar systems map the higher-order rules that govern its behaviour to the new target system(Gentner & Holyoak, 1997; Gentner, 1983). Explicitly, structure-mapping predicts that students would attribute the restorative force present in the spring analogy to a molecular bond and the concepts of attraction and repulsion would be obtained from the sphere analogy. The two analogies afforded students different interpretations of the energy well, with the sphere system, which better mirrors molecular bonds, functioning better than the spring analogy.

A single student showed a decrease in answer quality following treatment with the analogy. After interacting with the sphere analogy the student sacrificed accurate details and relationships in favour of a simplified explanation. For example, details about the "electronic repulsion from the inner molecular orbitals" of two atoms were replaced in favour of the generic statement, "when atoms are too close, they repel each other". This suggests that analogies may be best employed when introducing new concepts at a basic level to novice learners but may cause confusion for the intermediate student who is trying to consolidate prior knowledge using the analogy (Spiro et al., 1989). An alternative explanation may be that the student after viewing the analogy modified their response to reflect what they perceived to be the most acceptable response to the instructor rather than reflecting their understanding of the phenomenon (Crisp, Sweiry, Ahmed, & Pollitt, 2008).

Impact of interactivity on the analogy system

Both analogy systems were presented in an interactive interface that featured two external representations. It was anticipated that the interactive system would lend well to supporting the analogy of the electrostatic spheres by giving the students an opportunity to manipulate the system and observe the consequences of this change in real time. Similarly, the interactive spring analogy allowed manipulation of the system, with the inclusion of the spring breaking at long distances. While a comparison with static versions of the analogies are not available, the ability of the sphere analogy to transfer the concepts of repulsion and attraction and the spring to convey the oscillatory nature of the molecular bond indicate that these systems were moderately successful. However, as mentioned, students inability to draw correct energy diagrams after using the analogical system might be an indicator of cognitive overload, where details on the graph shapes were overlooked for more salient or more visually presented information. Another reminder that care must be taken when employing technology for interactive visualizations that the most thematically relevant information is attended to by the viewer.

Conclusions

The findings of this study suggest that students are able to incorporate aspects of an interactive analogy to their explanations of a related concept. Not all of the information in the presented analogies transferred successfully, however, as was observed with the energy well shape. Information that was transferred successfully corresponded with the structure-mapping theory of analogies, explicitly, the higher order-relations rather than superficial similarities are transferred from the analogy to the novel concept. Educators must further refine concepts that are transferred from an analogy to ensure the new conceptualizations best describe the phenomona.

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Exploration into the construction of an analogy for the instruction of the Morse potential led to the creation of the electrostatic spheres model. The electrostatic spheres analogy leveraged technology to make it interactive, animated and feature multiple levels of representation. The analogy was capable of transferring concepts like the attractive and repulsive forces found between the atoms in a molecular bond, and students were observed using these concepts to explain features of the Morse potential. Whether the inclusion of the interactivity of the sphere analogy aided student understanding was not explicitly tested, however, the analogy did successfully transfer understanding to the system within this framework. The failure of the interactive analogy to update energy well visualizations might be attributed to the high visual salience of the spring/spheres motion, which detracted attention from other important features (for example, the static well shapes). Consequently, the authors suggest that instructors and developers carefully consider the integration of animated graphics when presenting multiple levels of representation to explain complex chemical phenomena.

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