

## WHEN CHEMICAL BONDING IS PERCEIVED SIMPLE AND INTERESTING: THE DESIGN AND DEVELOPMENT OF A LEARNING OBJECT

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The concept of chemical bonding is abstract and perceived as difficult. While it is a fundamental concept required to comprehend other chemistry topics, the learning outcomes are not always attained. Addressing this issue, our challenge was to create a learning intervention regarding a common, fundamental chemistry concept for students in a variety of undergraduate chemistry courses. We envisioned a learning product that invites students' interest yet is challenging. This design case discusses the process, the literature that informs our design decisions, and strategies incorporated into the design of a learning object entitled Making Molecules: Dot Structures and Ionic Compounds to mitigate the learning issue. Discussion on the context of the project, design and development strategies, evaluation, and project reflection is presented as well.

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<https://doi.org/10.14434/ijdl.v11i3.28801>

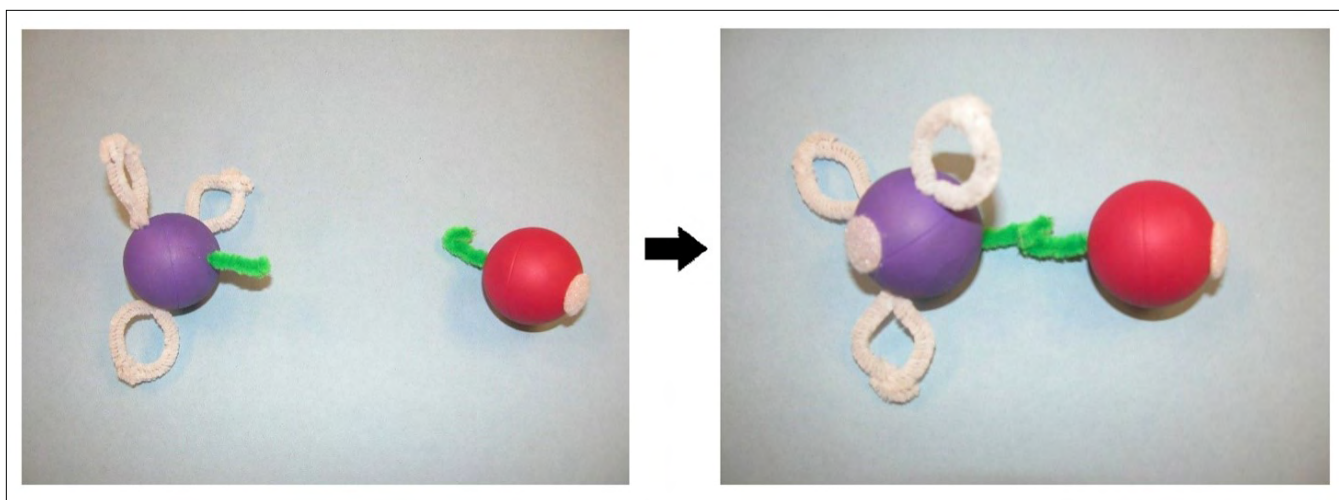
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### INTRODUCTION

The purpose of this project was to design and develop a learning object (LO) in the form of a simulation to promote students' comprehension of chemical bonding through dot structures and ionic compounds. The targeted learners were undergraduate students in a high-enrollment introductory chemistry course called *General Chemistry*, as well as students in a science, technology, engineering, and math (STEM) synthesis general education (GE) course called *Modeling the Fundamentals of Physical Chemistry*. (Synthesis GE courses are required of all students and make explicit connections between two or more STEM subjects.) Students in a chemistry course must master the concept of chemical bonding to understand the properties of molecules. Although the introductory chemistry students were exposed to basic chemistry topics, the learning outcomes related to chemical bonding were not attained. Our challenge was to produce a learning intervention that presented a common, fundamental concept in a way that was simultaneously interesting, engaging, and challenging.



**FIGURE 1.** Image on the left shows physical models of chlorine and sodium atoms which form a chemical bond to yield sodium chloride shown in the image on the right.

This design case describes the process carried out by the eLearning<sup>1</sup> department at California State Polytechnic University, Pomona in collaboration with a faculty member from the Department of Chemistry and Biochemistry. The design team members from the eLearning department consisted of instructional designers, a multimedia developer, and an instructional technologist. The final product is a learning object (LO) entitled Making Molecules: Dot Structures and Ionic Compounds. This design case discusses the project initiation, analysis process, and the relevant literature informing design decisions. The discussion continues with the non-linear design and development description including the constraints encountered, evaluation, and project reflection.

## PROJECT INITIATION

An instructor of General Chemistry and Modeling the Fundamentals of Physical Chemistry initiated the project to respond to the unattained learning outcomes related to chemical bonds by submitting a project request to the eLearning department. (eLearning offers pedagogical and technical support and trainings for faculty to create online, hybrid, and face-to-face courses and design/develop multimedia learning objects.) When reviewing incoming project requests, the eLearning department considers several criteria, including if the corresponding course has been experiencing high DFW rates (DFW courses are those with a high number of students who earn grades D, F, or Withdrew from the course) and/or is a bottleneck course.

<sup>1</sup> When this paper was under revisions, the eLearning department and The Faculty Center for Professional Development merged to one group called Center for the Advancement of Faculty Excellence (CAFE). The eLearning department is now called CAFE.

In the context of this project, the faculty member intended to use it with General Chemistry students and share it with instructors of all General Chemistry course sections. Additionally, the final product would be shared with other upper-division courses to improve or refresh students' understanding. The faculty member further expressed an intention to house the final product in an open repository so that other educators and students from other institutions would be able to use it for free. This project could potentially make an impact on many students.

Considering the project significance, the eLearning department approved the project request, and an instructional designer (ID) was assigned to lead the project. The ID was allowed to form a project team that might include other personnel such as multimedia developer (MMD), instructional technologist (IT), and student assistants as needed.

## ANALYSIS

### Identification of the Problem

The ID and faculty member, who is also the subject matter expert (SME), conducted the first meeting to discuss the student characteristics, learning issues regarding the unattained learning outcomes, and current instructional materials. The discussion also emphasized the importance of addressing the diversity of the students because the targeted students were in various stages of learning progress.

The materials initially used were physical models made from ping-pong balls and pipe cleaners, allowing students to manipulate, form, and design their own molecules (see Figure 1). The SME described how this model was used in a traditional face-to-face class. However, the physical models posed some limitations. Students were not able to practice individually multiple times according to their own learning

pace and were constrained by geographical and temporal limitations. As the physical chemistry course was transformed into a fully asynchronous one, the use of the physical models posed geographical and temporal barriers: online students would not have access to directly manipulate the physical models, and immediate feedback would be absent.

### Description of Students

The targeted students would be 18 years old or older. They were undergraduate chemistry students enrolled in General Chemistry or Modeling the Fundamentals of Physical Chemistry, a synthesis GE course, which was delivered online asynchronously. The physical chemistry students had already completed courses covering fundamental chemistry topics, and most were in their third year. Many may have had a pre-conception that chemical bonding was abstract and difficult, and therefore, might not have adequate motivation to be persistent in learning this content. Since the faculty member intended to use the final product with General Chemistry and other chemistry upper-division courses, the SME and ID would have to consider a wide range of student backgrounds, pre-knowledge, and prior experiences.

Because the final product would be housed in an open repository, the ID and SME additionally considered other potential users. High-school teachers would be able to use it for free to teach the concept to their students. In this context, the student users would be younger than 18 years old and they might have different prior knowledge than those enrolled in a university-level course.

### Task Analysis

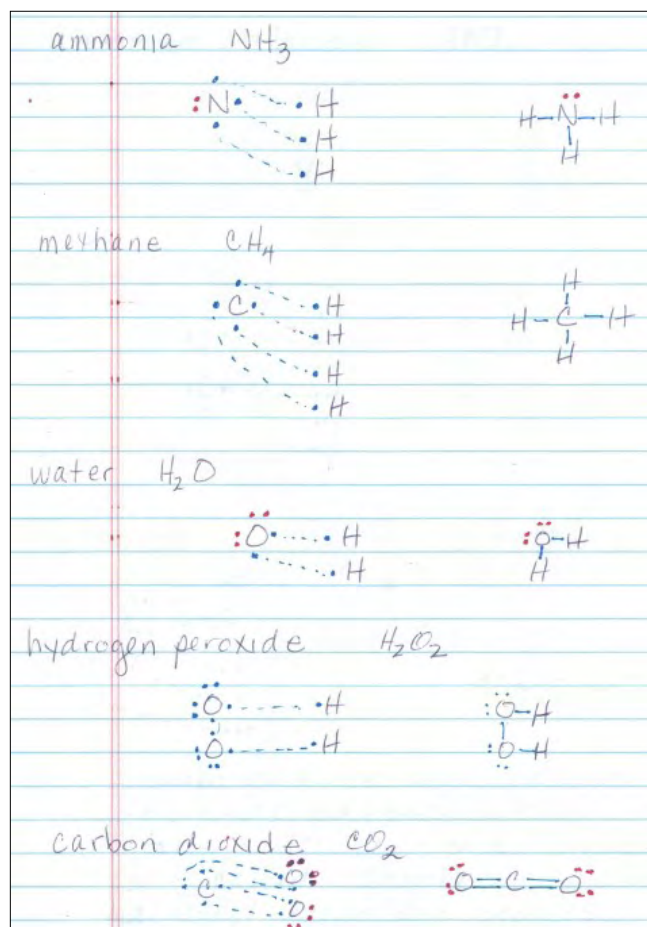
After conducting the first meeting, the ID followed up with the SME, requesting and analyzing the current syllabus and relevant resources (e.g., the hand-made physical models from ping-pong balls and pipe cleaners). Next, the ID conducted a task analysis by collecting further information from the SME. During this time, the ID attempted to understand the required steps for students to design stable molecules from atoms and ions. Both SME and ID discussed such steps through emails. Conducting a task analysis of a concept without possessing background knowledge is challenging. Therefore, the SME assisted the ID with the task analysis by providing handwritten explanations of how atoms and ions bond to form molecules.

Figure 2 shows the handwritten illustration by the SME for explaining how lone electrons connect to form chemical bonds. In this figure, one blue dot represents a lone electron that is available to be connected with another lone electron. The two red dots mean that these electrons are already paired, and therefore, they are not available to form chemical bonds. Figure 3 displays the handwritten explanation of how ions bond to form ionic bonds. Cations (ions with a positive

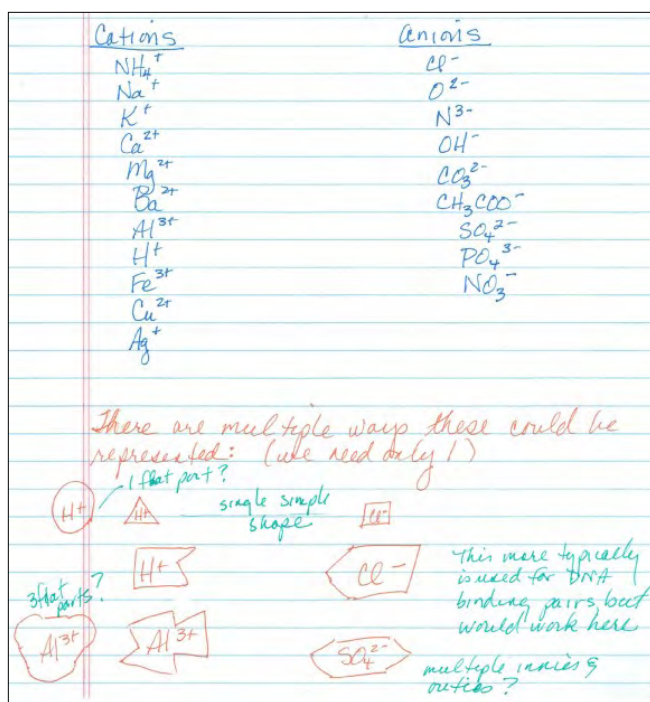
charge) are connectable with anions (ions with a negative charge). Each ion may have up to three charges which are available to pair with an ion of the opposite charge.

The steps described in the handwritten illustrations were summarized and transformed by the ID into enabling learning outcomes. The SME assisted the ID with the formulation of these enabling learning outcomes until they were accurate. The finalized enabling learning outcomes were defined as follows—students are able to:

1. design molecules from atoms by connecting lone electrons between atoms to form chemical bonds;
2. decide whether an isomer's structure matches the two-dimensional diagram presented in the feedback;
3. infer that chemically stable molecules have no unpaired electrons;
4. predict the number of valence electrons (unpaired and total) from the element's position on the periodic table;
5. discover that ionic compounds require equal numbers of positive and negative charges to be stable; and
6. discover that ions bond, or combine, with ions of the opposite charge.



**FIGURE 2.** The handwritten illustration by the SME for explaining how lone electrons connect to form chemical bonds. In this figure, each blue dot represents a lone electron.



**FIGURE 3.** The SME's handwritten explanation of how ions bond to form ionic bonds. Cations (ions with a positive charge) can only be paired to anions (ions with a negative charge).

### Exploration of Existing Interventions

Because chemical bonding is a fundamental topic, the ID explored open learning object repositories (e.g., MERLOT at <https://www.merlot.org>) to seek any relevant instructional materials that could address the specified learning outcomes. Another criterion considered was the accessibility of the materials. Accessibility refers to the efforts to follow Section 508, in which educational institutions provide all students with equal access to campus information technologies (Wakimoto & Soules, 2011). This is to ensure that all students, regardless of (dis)ability, can succeed academically.

The ID found a few materials after exploring the existing learning object repositories. However, after consulting with the SME, none of these materials would be suitable for our context. For example, other learning products found at that time would not allow students to manipulate, form, and design their own molecules. Several other products did not properly represent the atoms' size. Other products either did not display the bonds nor use high-quality graphics. Additionally, the accessibility of these materials was questionable. Based on this rationale, the ID and SME agreed that a custom-built, section 508-compliant LO could be developed, precisely aligned with the particular learning outcomes. The ID progressed the project by formulating the design and development goals for the project.

### Design and Development Goals

Two types of goals were formulated: goals for the front-end (user interface) and goals for back-end, such as the interactivity level.

The user interface goals were to:

- design and develop a web-based learning object interface that was easy to use and was visually appealing;
- use appropriate representations of atoms, electrons, molecules, and ions; and
- integrate accessibility features that were compatible with assistive technologies such as screen readers.

The back-end goals were to:

- design the geometries of each atom, electron, molecule, and ion;
- ensure that the interactions were compatible with assistive technologies such as screen readers;
- create learning activities that would allow students to manipulate each piece that can form molecules; and
- develop a web-based portal to host all graphical pieces and interactivity of the LO.

The SME and ID formulated the goals to specifically define the aim and scope of the project while ensuring alignment with the learning outcomes. Once the goals were established, the ID formed the project team.

### The Project Team

The initial team was comprised of the ID, SME, and MMD. The ID was the project coordinator. Using eight years of experience in eLearning, she managed the project tasks, tracked the progress and timeline, coordinated meetings amongst the team members, and acquired resources needed for moving the project forward. The SME is a full professor and has been teaching chemistry courses for more than 30 years. The MMD would develop and assemble the pieces needed for the LO. The MMD had been with eLearning for a few months when he joined the project. This was the MMD's first major development project with the eLearning department.

A challenge arose when the team experienced a change in ID before the project was completed. The newly assigned ID had similar work experience and background (nine years of working experience in the instructional design field) as the previous ID. She had to both jump into an ongoing project and quickly gain a sufficient understanding of the content. To overcome this challenge, she learned the topic from the project materials provided by the SME and previous ID; reviewing the handmade physical models and the handwritten explanation were helpful in gaining a fundamental understanding of chemical bonding. When needed, she requested the previous ID and SME to give her an overview

of chemical bonding through a meeting until she gained a proper understanding of the topic and project progress. Upon a sufficient understanding of the topics and project status, the ID felt the need to expand the team by recruiting an IT who could assist in testing the developmental versions and progressing the development. This IT had also been with eLearning for a few months when he joined the project. To move to the next step, the ID then searched the relevant literature to obtain ideas regarding the design strategies.

### **Relevant Strategies Informed by the Literature**

The SME and ID also thought about the importance of consulting with relevant literature so that the learning intervention would not allow students to unmeaningfully click on the pieces in order to merely move on to the next activities. The SME forwarded the literature related to chemical education and difficulty in learning chemical-bonding topics to the ID. The ID searched for the literature related to design strategies that match how people learn, particularly on learning quantitative subjects that are considered difficult, uninteresting, and complex. Then the ID synthesized the key points from the literature.

#### *Quantitative topics perceived as complicated*

STEM domains, including chemistry, are perceived as abstract, difficult, boring, and uninteresting (Bayir, 2014; Caglar et al., 2018). It is not a surprise that the number of students pursuing STEM fields is too low to meet the demand (Caglar et al., 2018). However, there are some recommended strategies to make the learning of science content accessible to a broader group of students. Some of these strategies are presented below.

#### *Using multiple representations*

Students, as novices, are unable to envision how atoms bond without a representation and object manipulation (Eastwood, 2013). For example, students fail to comprehend the physical attributes of molecules in three dimensions because most textbooks provide two-dimensional representations. Therefore, the use of multiple representations (macroscopic, sub-microscopic, and symbolic) in chemical education assists students to synthesize information from different representations into accurate mental descriptions (Johnstone, 1982, 1991; Talanquer, 2011; Treagust et al., 2003).

#### *Directing attention to relevant information*

Comprehending chemical-bonding concepts requires higher-order (abstract) thinking. Higher-order (abstract) thinking demands the construction of appropriate schema (Merrill, 2002). The targeted students of this project are considered learning novices who may not have developed suitable schema, thereby resulting in working memory overload. The strategy to help students construct their schema into a

proper one should be carefully selected. Directing students' "attention to processes that are relevant to learning or to the construction of schemas" can address this issue (Sweller et al., 1998, p. 265). Clear instructions and expectations of how to complete the activities are additionally crucial for mitigating the issue (McGuire & McGuire, 2015; Alessi & Trollip, 2001).

#### *Incorporating guidance fading effect*

Another strategy is to scaffold students' comprehension by using the guidance fading effect (Sweller, 2008, 2010). While explicit guidance is provided initially, the guidance can fade away gradually as the students gain mastery and form proper schema. This provides a reminder to carefully sequence the content, learning activities, and difficulty level.

#### *Ensuring accessibility*

Students have different backgrounds, (dis)abilities, and demographics (Lewis & Sullivan, 2018). The percentage of people requiring accessibility in the U.S. has increased from 11.9% in 2010 to 12.8% in 2016 (Kraus et al., 2018). Educational institutions are strongly encouraged to provide all students with equal access to campus information technology (Wakimoto & Soules, 2011) and equal opportunity to utilize communications technology (Lewis & Sullivan, 2018). Therefore, it is important to design instructional materials with accessibility in mind so that all students, regardless of disabilities, can succeed academically.

#### *Using learning object as a suitable intervention*

The use of an LO can assist learners with visualizing abstract concepts (Bayir, 2014; Geselbracht & Reisner, 2010) and provide multiple perspectives or representations of the content (Wiley, 2002). Defined as "any digital resource that can be reused to support learning" (Wiley, 2002, p. 6), an LO can address a learning outcome. It is also flexible, shareable, and reusable; this resonates with the SME's intent of sharing the final product with multiple courses. It is small enough to update the content directly on the database without developing a new version of LO (Ritzhaupt, 2010). In case there is a need to address future technical issues, such as compatibility with a new version of browsers, the team can relatively be quick to update the LO.

Incorporating literature heuristics, an LO can be strategically designed and developed. Therefore, the final product or LO can effectively reduce students' excessive efforts on utilizing working memory (Gustafson et al., 2011) and assist with schema reformation. SME and ID agreed that creating LO would be appropriate.

## DESIGN

### Content Sequence

During a meeting discussing the layout and content sequence, the team thought of placing the free experiment activities first to attract students' interests and trigger students' curiosity to explore further. All team members agreed and decided that this was strategic for sequencing the content and activities. A mockup to show this layout was then developed using Photoshop (see Figure 4).

However, while further discussing this layout in another meeting, the team thought again whether this sequence was suitable according to the literature. In the updated sequence, the guided activities are provided initially before allowing students to freely experiment on their own. The team, then, decided to include the following tabs in the LO:

1. Introduction page
2. Molecular builder, consisting of two sub-tabs:
  - 2.1. Pre-programmed, guided molecule-building activities
  - 2.2. Free-experimental molecule-building activities
3. Ionic compounds
  - 3.1. Free-experimental ionic-bonding activities

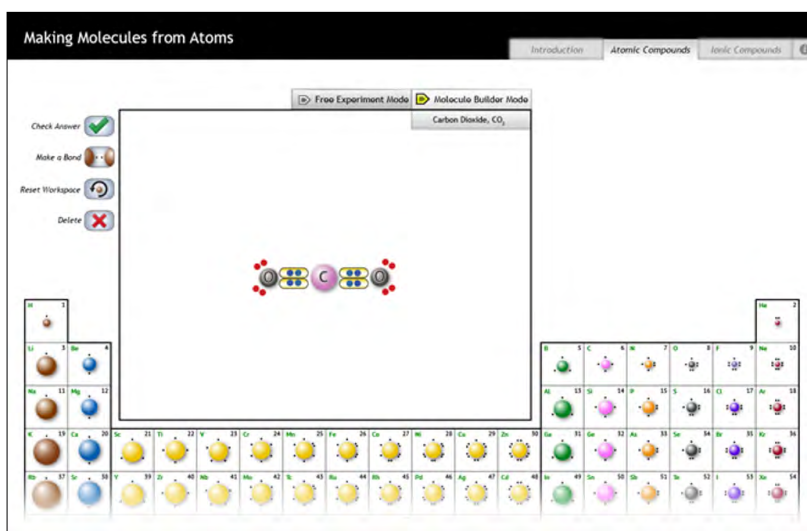
Table 1 (next page) displays the alignment between the problems related to learning chemical bonds, strategies (or design principles) learned from the literature, design decisions regarding the tabs and features included in the LO, and the rationales.

#### Tab 1: Introduction Page

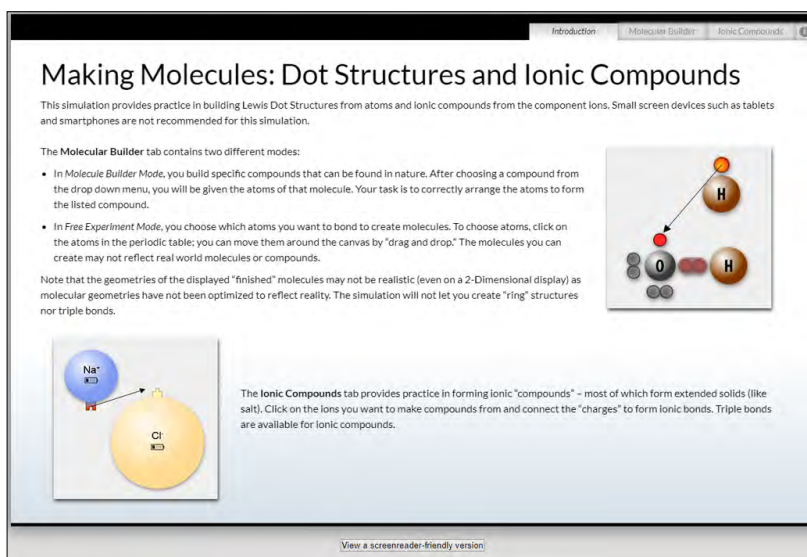
The first tab of the LO is the Introduction page. It includes technical recommendations for successful navigation. Instructions regarding the activities in each tab are provided so that students can anticipate the required learning tasks. The Introduction page also displays a preview of the LO content. For example, two images are displayed to reinforce the instructions (see Figure 5).

#### Tab 2: Molecule Builder

The content was deliberately sequenced to allow students to practice problems, based on the learning complexity (easy



**FIGURE 4.** An early mockup displaying an initial sequence. The free experiment mode was presented before the guided activities within the molecule-building topic.



**FIGURE 5.** The Introduction page welcomes the students to the LO. Title, brief description, instructions, and expectations are presented. Two sample images are included in the introduction page to reinforce the instructions. The free experiment mode in the second section of MB tab was designed to allow students to control their own learning. The activities designed in this section encourage students to freely experiment with electron bonding, as depicted in Figure 8. The guidance has slowly faded as students gain more expertise.

tasks are presented first). At least two of the three chemistry representations were included when designing:

- sub-microscopic representations allow students to manipulate the entities that are typically unseen by the naked eye
- symbolic representations display a comparison between the molecules designed by the students with a typical chemical structure diagram.

PROBLEMS	STRATEGIES LEARNED FROM LITERATURE	FEATURES INCLUDED IN LEARNING OBJECT	RATIONALES
<p>Students are unable to comprehend how atoms bond without representations and object manipulation.</p> <p>Chemical-bonding concepts are perceived as abstract.</p>	Using multiple representations	<p>At least two types of representation are used:</p> <ul style="list-style-type: none"> <li>sub-microscopic representations to allow students to manipulate the chemistry entities that are too small to be seen by the naked eye</li> <li>symbolic representation to allow students to make comparison with the chemical structure diagram and images in texts</li> </ul>	The use of multiple representations (macroscopic, sub-microscopic, and symbolic) in chemical education assists students in synthesizing information from different representations into accurate descriptions (Johnstone, 1982, 1991; Talanquer, 2011; Treagust et al., 2003).
<p>Chemical-bonding concepts are perceived as difficult and uninteresting.</p> <p>Students can easily overload their working memory even at the beginning of learning.</p>	Directing students' attention to relevant information and providing clear instructions	<p>Introduction tab is provided with clear instructions and transparent expectations of how to complete the activities. It additionally includes two appealing images.</p> <p>All activities in the LO focus on straightforward, fundamental processes.</p> <ul style="list-style-type: none"> <li>Only a lone electron can be connected with another lone electron on another atom to form chemical bonds.</li> <li>An ion can only be paired up with another ion of the opposite charge (i.e., ions with a positive charge are connectable with ions with a negative charge).</li> </ul>	Directing students' attention to relevant information and processes can assist them in constructing appropriate schema (Sweller et al., 1998) because they do not have to maximize their working memory during the learning process (Gustafson et al., 2015).
<p>STEM-related problem solving is complex. Students tend to maximize their working memory while attempting to solve the problems.</p>	Incorporating guidance fading effect	<p>Two types of activities are incorporated:</p> <ul style="list-style-type: none"> <li>guided activities in the first section of Tab 2 Molecule Builder, where students are presented with pre-programmed, guided molecule-building activities;</li> <li>free experimental activities in the second section of Tab 2 Molecule Builder, where students are presented with free-experimental molecule-building activities after gaining an expertise from the earlier activities; and</li> <li>free experimental activities in Tab 3 Ionic Compounds where students are presented with free-experimental ionic-bonding activities.</li> </ul>	<p>Students may need to be scaffolded so that they can comprehend STEM-related complex problems (Caglar et al., 2018).</p> <p>Providing apparent guidance in the early activities can set a strong foundation on the students' understanding of the topic and would form an appropriate schema to conduct the next, more complex activities (Sweller, 2008, 2010; Sweller, et al., 1998).</p>
<p>The LO contains interactive pieces requiring the use of mouse. However, students with a physical dexterity or visual impairment may not be able to rely on the mouse to use the LO.</p>	Ensuring Accessibility	<p>The interactivity of each piece, such as atoms, electrons, ions, and molecules, is designed to be compatible with assistive technology such as screen reader.</p> <p>The screen reader friendly version is provided as an alternative version which also contains equal content.</p>	Students are diverse in their backgrounds, (dis)abilities, and demographics; therefore, they should be provided with equal access to information and communication technologies (Lewis & Sullivan, 2018; Wakimoto & Soules, 2011).

**TABLE 1.** The problems related to learning chemical bonds, strategies (design principles) learned from the literature, our design decisions regarding features included in the LO and the rationales of design decisions.

### Guided activities

The first section of Molecule Builder (MB) tab initiates the guided activities, presenting 13 chemical compounds listed in order of difficulty (Figure 6). When students select a compound, they are presented with its unconnected constituent atoms, and are then guided to pair all lone electrons between different atoms until they form a molecule. Students create chemical bonds by clicking and dragging from one lone electron to another lone electron. An arrow indicates which electrons will be connected, and a change in the electrons' appearance indicates that they are able to form a bond: Upon connecting two lone electrons, the associated atoms move so that the two electrons are near each other. The two electrons are then highlighted to appear as a single unit, and from that point on their atoms move as a single unit when manipulated. Once all lone electrons have been paired, students are given a chemical structure diagram to compare with the molecule they have made. This allows students to check the accuracy of their answer (see Figure 7).

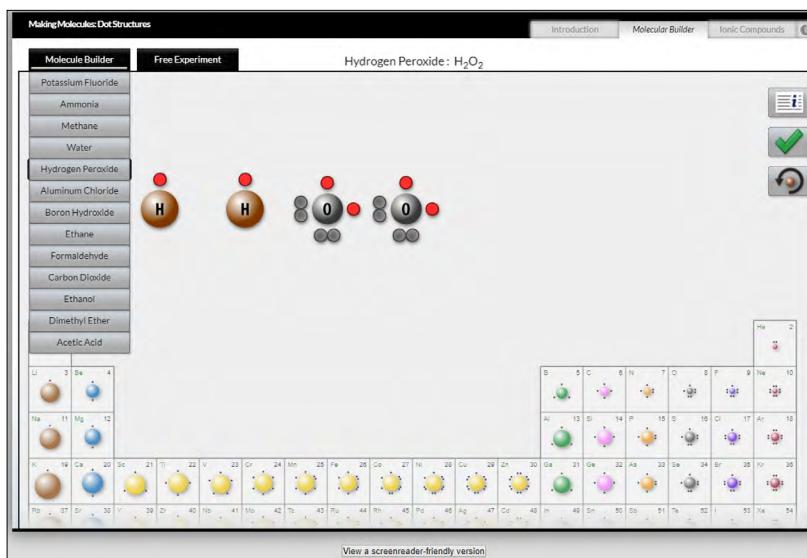
### Free experiment mode

The free experiment mode in the second section of MB tab was designed to allow students to control their own learning. The activities designed in this section encourage students to freely experiment with electron bonding, as depicted in Figure 8. The guidance has slowly faded as students gain more expertise.

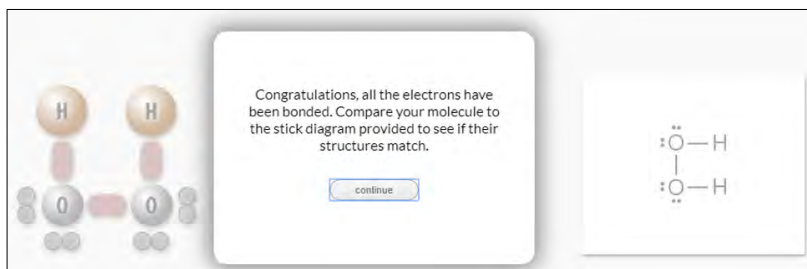
Here, students can choose various atoms from the periodic table to build their own molecule. They can then bond the lone electrons in the same manner as the guided activities. When completed, students can request feedback which determines if all the available electrons have been bonded. Students also have the option to clear the workspace, freeing up space to build additional molecules, and to remove individual atoms and molecules (see Figure 9).

### Tab 3: Ionic Compounds

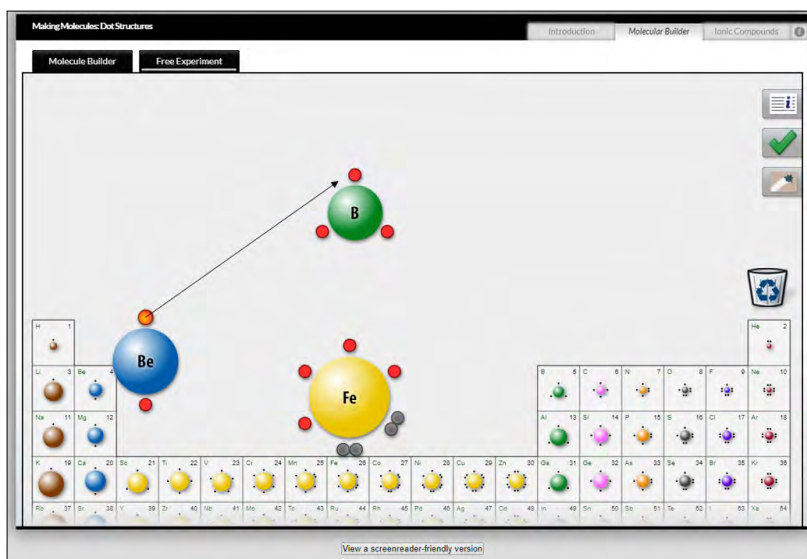
The Ionic Compounds (IC) tab offers only free experiment mode because students should already have gained the necessary expertise before reaching this level. This section is similar to the MB Free Experiment Mode; only instead of choosing atoms to bond, students are



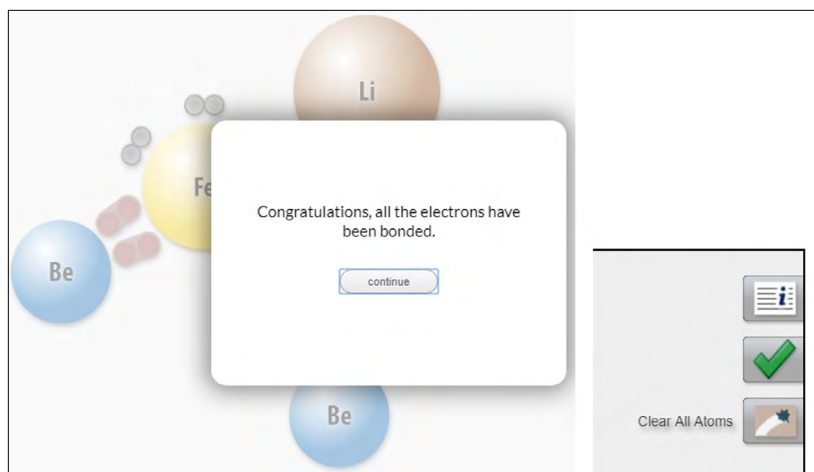
**FIGURE 6.** Guided activities are the initial exercise given to students via a drop-down menu of pre-programmed chemical compounds. In this figure, hydrogen peroxide has been selected.



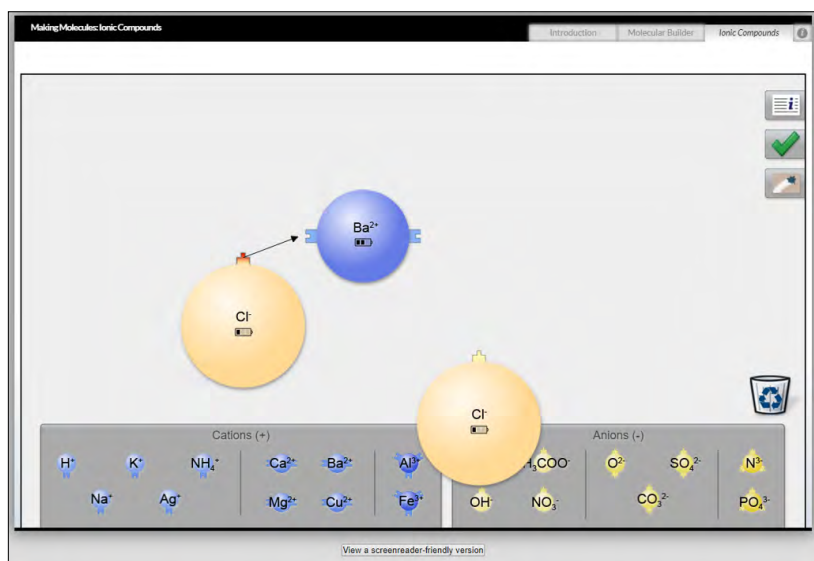
**FIGURE 7.** Immediate feedback and a graphic figure are provided when students check the accuracy of their answer. Students can check the accuracy of their answer by comparing it.



**FIGURE 8.** The Free Experiment mode in the Molecular Builder tab. Students can drag an element from the periodic table and drop it into the "workspace" to build their own molecule.



**FIGURE 9.** On the right are the Check Answer, Clear All Atoms, and Trash (for disposing of unneeded atoms) buttons included to additionally provide learner control. After creating a molecule, students can check the accuracy of their answer by clicking the Check Mark button. The screen can be reset by clicking the Clear All Atoms button in order to be able to build another molecule.



**FIGURE 10.** The IC tab has also been designed to allow free experiments. Students should already have gained the necessary expertise before reaching this level. Students can select ions from the palette, drag and drop them to the “workspace,” and create their own ionic compounds.

provided with an assortment of ions to choose from (Figure 10). Ions are represented as circles with “charge arms” sticking out that indicate the relative charge of the ion. Positive and negative ions are differentiated by color and the shape of their charge arms. Each ion also has a small battery icon to indicate its relative charge. As with the MB tab, students form bonds between ions by clicking and dragging from one charge arm to another. Upon bonding, the two ions move near each other so that their charge arms link together, and the two ions then behave as a single unit. Just as in the Free Experiment mode of MB, this IC screen has buttons to

Review Instructions, Check Answer, Clear All ions, and Trash (to remove an ion).

### Accessibility Feature

During the early design phase, the team decided that the interactivity of each piece, such as atoms, electrons, ions, and molecules, would be designed to be compatible with assistive technology. Hence, this LO would be designed and developed with accessibility in mind to avoid two separate design processes.

### DEVELOPMENT

The MMD created the graphical elements and interactivity of the learning object using a combination of HTML5 canvas and the CreateJS JavaScript library. This technology was selected on the advice of the Senior Multimedia Developer for its similarity to other programs the MMD was familiar with, as well as for its compatibility with multiple platforms and web browsers. (eLearning department’s previous multimedia projects had been built using Adobe Flash, which had compatibility issues and was beginning to fall out of favor with multimedia developers.) Initially, the MMD sought to also integrate the Box2dWeb physics engine into the CreateJS-based development. The purpose of using this physics engine was to control the geometries of the atoms and molecules as they were bonded in various configurations.

After seven months of assembling the pieces and building the interactivity through the physics engine, the MMD faced a constraint. The MMD had not previously worked with a physics engine and had difficulty in getting the application to behave as desired. Figure 11 illustrates the earlier development using a physics engine. After consulting with other members of the eLearning department, the MMD decided to restart the development using only CreateJS and HTML5 canvas. Without the aid of a physics engine, the approximated geometries between bonded atoms had to be calculated and set using pure JavaScript. Consequently, the ease of implementation and compatibility with multiple platforms and browsers used by the students could be achieved.

The simplified calculations to set geometries, however, also created a new issue where certain configurations of bonded atoms would cause some atoms to overlap in the 2D representation. After discussing the issue with the SME, ID,

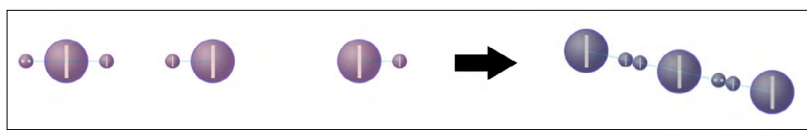
and IT, the decision was made to reduce the opacity of overlapping atoms so they could both be seen. Also, an extra mouse interaction was added so that the back atom could be seen more clearly when clicked.

The MMD used Adobe Photoshop and Adobe Illustrator to create various graphic elements such as the individual atoms, ions, and other pieces, by following the multiple-representation concept. Incorporating multiple representations was challenging, especially for representing the ion charges. The MMD initially created the ionic representation to illustrate the charges by embedding the positive and negative shapes in the ions. However, when he began to develop the interaction feature to allow students to connect the charges for forming ionic compounds, the positive and negative shapes of the ions did not fit one another. Upon another discussion with the team, he decided to discard the initial images and redesign the ion graphics as well as the charges. The simplified design of the ions allowed them to be created directly from code.

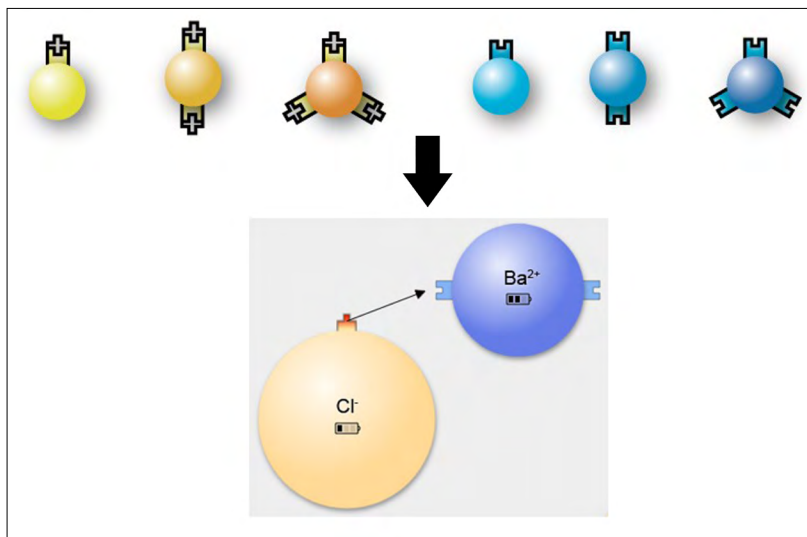
While recreating the ion's graphics, the MMD came up with the idea of using a simple battery icon to include within the ions and presented it to the team in a meeting. He described his proposed idea that the battery icon could be drawn to be similar in appearance to the power indicators often used in cellphones and other electronic devices so that it would be immediately familiar to students. The battery could contain anywhere from zero to three bars, indicating the "charge" of the ion. Each time the ion is bonded, the battery would lose a bar and the color would fade; this reinforced the meaning that the new bond has reduced the relative charge of the ion and the hue of the sphere. After considering this proposed idea, the team thought that the battery representation would promote students' mental image and encourage schema formation. Therefore, the team agreed to proceed with this idea. See Figure 12 to see the initially designed ions and the final version of ions.

## GOING BACK TO DESIGN AND DEVELOPMENT

Throughout the entire development phase, the MMD also attempted to integrate the accessibility features. Much time was lost due to the difficulty in development and the need to start over with the use of different development tools. Integrating the accessibility features in the interactive version would require another layer of complexity by manipulating the existing coding that already worked well with the



**FIGURE 11.** The earlier development using a physics engine. The initial purpose of using this physics engine was to control the geometries of the atoms and molecules as they were bonded into various configurations. However, the atoms and molecules did not behave as planned.



**FIGURE 12.** The initial ion charges would not fit one to form a compound (upper image). The redesigned ions use symbolic battery icon (lower image). When the ions are bonded, the battery will lose a bar, depicting that the new bond has reduced the relative charge of the ion.

geometries and interactivity. Therefore, the MMD presented a plan to design and create a parallel version of the learning object that was accessible to screen readers and navigable solely by keyboard. A View a screenreader-friendly version button could be added to the Introduction page. Clicking this button would direct screen-reader users to another page containing a lower level of interactivity that would still allow students to gain an equal understanding and experience about chemical bonding. The screen-reader version would display high contrast colors and be navigable through a keyboard. Therefore, students with a physical dexterity impairment would not have to rely on the mouse to navigate and to connect the electrons and ions. The MMD also assured the team that developing this screen-reader version would not be time-consuming. The team members were convinced and voted to proceed with this proposed idea.

In the screenreader-friendly version, the molecules, atoms, electrons, and bonds are represented via a series of text-based lists. The content sequence is still the same as the interactive version, which consists of: (1) Introduction tab; (2) Molecular Builder tab which is comprised of Molecule Builder (guided activities) and free Experiment; and (3) Ionic Compounds tab (free experiment activities only).

## Making Molecules: Dot Structures

### Molecular Builder: Free Experiment

[Molecular Builder](#) [Molecule Builder](#) [Ionic Compounds](#) [Return to Introduction](#)

**Instructions:** Start with the "Select Atoms" list. Atoms are listed by their column in the periodic table (up to the 4th row). Use the up and down arrow keys to choose atoms to work with, then press Return to add an atom to the "Work Area"; focus will automatically jump to the Work Area. Once you have multiple atoms in the Work Area select an atom and press Return to jump to a list of that atom's electron valence positions. If an electron position is listed as an "Unpaired Electron" select it and press Return to jump to a list of "Atoms Able to Bond with" that atom and electron. Select an atom and press Return to create a bond with that atom. Once a bond is made focus will jump back to the Work Area and the two atoms will be replaced in the Work Area by a "Molecule". Select the Molecule and press Return to jump to a list of its constituent atoms. Select atoms from either the Work Area or the Molecule's list to continue making bonds. Use the "Check Answer" button to check if all the electrons have been paired. The "Clear Work Area" button will remove all atoms and molecules from the work area. When in the Work Area list you may also remove a single atom or molecule by selecting it and pressing Backspace or Delete.

**FIGURE 13.** The alternative version is screen-reader friendly and was tested using assistive technologies. This version is provided to comply with Section 508. Therefore, students who are unable to drag and drop items on the screen can attain an equal learning experience. This version also provides students with specific instructions on how to move the atoms and connect the electrons.

JavaScript was used to change the contents of the various lists as the user selected individual atoms. Students can then examine the electrons of that atom to see what other atoms they are bonded to. Upon successfully bonding all available electrons, students are given a detailed verbal description of the structure of an element. For example, hydrogen peroxide ( $\text{H}_2\text{O}_2$ ) is described as follows—each oxygen has a single bond to hydrogen and a single bond to the other oxygen. Figure 13 provides an illustration of the screen-reader friendly version where screen-reader students can conduct equivalent free experiments to design their own molecules.

## IMPLEMENTATION

The completed LO is housed in an open repository. The instructor of the Modeling the Fundamentals of Physical Chemistry course provided the URL link to the students in a Blackboard Learning Management System module as part of a lesson unit in this course. Students were prompted to complete the 13 preprogrammed chemical compounds (see the Guided Activities section above) and six additional free-experimental molecules (see the Free Experiment Mode section above). Individually, they were asked to take screenshots of their additional molecules and submit the images to the campus learning management system, Blackboard. While the LO provided immediate feedback regarding the answer accuracy, the instructor provided meaningful and motivating feedback, along with a grade. Other instructors or educators interested in using this LO may also simply obtain the URL

link, assign their students to carry out the learning activities in the LO, and administer an appropriate assessment.

## EVALUATION

### Informal Formative Evaluation

Throughout the design and development phases, the team conducted continuous informal formative evaluations. Each time there was a developmental update, the MMD involved ID and IT in assisting with testing and debugging. Additionally, meetings among ID, MMD, and IT occurred without the SME to discuss updates, testing/debugging results, and whether the learning outcomes and SME's previous feedback were addressed. If the update did not sufficiently address the learning outcomes and SME's previous feedback, a modification, usually minor changes, was performed. When the update was ready to show to the SME, the entire team including SME met to discuss and carefully review each update. SME provided feedback regarding content accuracy (e.g., relative atom size and appropriate representations) and suitability to the learning outcomes and context. To

follow up, SME provided additional references that helped the project progress. During the development phase, the MMD also simultaneously conducted informal evaluations. Therefore, he discovered a failure through the abnormal geometries and interactivity of the atoms and molecules, decided to discard the early development, and explored an alternative tactic.

### Evaluation of the Design

The SME and ID collaboratively designed a short survey, which was administered to 47 students of the Modeling the Fundamentals of Physical Chemistry course; the current plan is to further explore the impact of this LO and develop an empirical paper in the near future. Some students reported that using the LO gave a new perspective toward existing understanding and promoted critical thinking. Students additionally affirmed that it provided clear scientific models representing atoms, ions, and molecules as well as the molecule formation. They also provided recommendations how the LO could be enhanced by accommodating more complex molecules and accurate geometries. This may indicate that students were motivated to receive challenges by solving more advanced problems. This notion suggests the important value of the literature-informed strategies manifested in the LO. Table 2 provides a few of the highlighted themes, examples and representative comments from the students' open-ended responses.

THEME	EXAMPLE	REPRESENTATIVE QUOTE
Visualization of the concept	How atoms bond or connect	"I can now visualize on how a molecule is built, in which I did not have the strongest ability beforehand."
	Characteristics of ionic and covalent compounds	"[I realize] atoms could connect to one another through lone electrons or different in charge."
	Representation of the size and ratio	"[I like] how the bonds were visually represented and how it showed the size of the atom."
	Extended visualization to macroscopic properties	"Knowing the composition of molecules is really important to determine and predict a variety of compounds with same molecular formula and how it can indicate the bonding arrangement of atoms in molecules."
Promotion of concept comprehension	Helpful learning tool	"A visual representation of how atoms are bonded is a helpful way to review the basics learned in general chemistry."
	New perspective about the concept	"Bonds can be easily thought of as a sharing of electrons between atoms rather than some other construct."
	Promotion of critical thinking	"... without angles in bond structures, there would be so many limitations on what we could do with molecules."
Promotion of the desire to learn more	Desire to take more classes	"... later I may take more [Chemistry] classes."
	Enjoyment during learning	"Chemistry is more fun that I thought."
	Desire for obtaining more information about the compounds	"[I wish] it might tell us more about each molecule we made and its properties."
Suggestions for an improvement	Requests for more activities for complex molecules	"I only wish that the size of the potential molecules that I could build was bigger... most molecules and compounds in our bodies are... larger"
	Requests for enhancing the representation	"I only wish that the molecules were more realistic and that the electron geometries were reflected more accurately."
	Requests for enhancing the LO performance	"[I wish] the program was a bit more responsive it runs a little slow from my tastes."

**TABLE 2.** A few of the highlighted themes, examples, and representative comments from students' open-ended responses.

## PROJECT REFLECTION

This project provides examples of challenges that can be faced by a design team while attempting to produce a learning product with a high level of interactivity. The team carefully consulted the existing literature so the final product would be both interactive and meaningful for increasing students' interest and understanding of chemical bonding. Because the design and development of the LO were aligned with the literature, it added another layer of complexity due to the additional time for reflecting on the literature and selecting the suitable strategies for the project context. However, the team is confident that this effort is worthwhile because the interactive LO prevents students from merely clicking on the content without gaining a meaningful learning experience.

As the MMD was new in the department, this project was his first complex project. Although he had some familiarity with the physics engine, it was his first time utilizing it. Numerous weeks were spent exploring the tools and the development moved along for a few months; however, it was discovered that the geometries and interactivity of the atoms and molecules could not be controlled as planned. In this case, seeking help from others revealed alternative ways. Therefore, the MMD was able to solve the development issue by using different tools. This also implies the importance of collaborative efforts within the team. The ID could have requested an expansion of the project team by recruiting another MMD who had produced LOs with a high level of interactivity. Alternatively, the MMD could have sought suggestions from a more experienced MMD or shared his initial plan on using the Box2dWeb physics engine with another MMD as early as possible. If early suggestions had

been sought from the senior MMD, this could have saved several months of development phase that was discarded. However, the overall belief is that all team members gained a meaningful design experience through both failure and success. This project has garnered an award from AECT Division of Distance Learning in 2019.

The experience designing this LO also confirms that design process is not linear. This resonates with Tracey and Boling (2014) that the design process is rarely smooth, systematic, or linear. The design team members used their knowledge, skills, experience, and pedagogical beliefs to make judgments and consider contextual factors (Tessmer & Richey, 1997). Additionally, other constraints, such as technological and time limitations, affected the design progress. For instance, the integration of accessibility features within the interactive version had been intended in the initial design plan. At that time, the team had not anticipated having two versions with different interactivity levels. However, the integration did not occur as planned due to the difficulty with the physics engine used to control the interactivity and due to the timeline issue. Therefore, the team went back to the design phase for developing the screen-reader friendly version.

One limitation is that the team did not conduct a formative evaluation with the target audience. The prototypes and each developmental update were tested by the team members themselves. The team might have missed insights from the real users that could have been used to inform subsequent design decisions. However, it is worth noting that the team members, except SME, did not have the content background. In a meeting to close the project, there was a discussion that the team members had gained an understanding about the content from working on this project.

According to Gibbons (2014), “the lone designer who could do it all is an extinct species” (p. 34). The design and development of this LO could not have been completed without a joint effort among the SME, ID, MMD, and IT. Without a direct involvement of SME, the team would not have learned about the necessity of multiple representations used in chemical education.

## CONCLUSION

The ultimate goal of this project was to promote student interest, engagement, motivation, and mastery of a STEM topic that has been perceived as difficult and uninteresting. According to literature, the number of STEM students is low. This project sheds light on innovative ways, grounded in the existing literature, to mitigate the issue. Each of the team members brought expertise into this project to expand the practice associated with instructional design for increasing students' interest to learn STEM-related topics. Through the collaborative efforts, the team was able to produce this

free-to-use LO—available at <https://elearning.cpp.edu/learning-objects/making-molecules>—that is currently listed in an open repository. The possibility to impact a vast number of STEM students through this LO is endless.

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