Learning molecular symmetry in augmented reality

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Signed:
Abstract

Technologies such as Virtual Reality and Augmented Reality can be used in the education of subjects that are unavailable in the real world for various reasons. In this project, an augmented reality application is developed that allows students to learn molecular symmetry in an augmented reality environment. The results of an experiment where this application is tested show that it helped students to see the spacial arrangement of a molecule and find the symmetry elements that are present in that molecule. This shows that augmented reality has the potential to be a great learning tool for this subject.
# Contents

1 Introduction .......................................................... 7  
1.1 Augmented reality .................................................. 7  
1.2 Related work .......................................................... 8  

2 Background ...................................................................... 9  
2.1 Molecular symmetry ................................................... 9  
2.1.1 Current education method ........................................ 10  

3 Application design and implementation ............................ 13  
3.1 Accessibility ............................................................... 13  
3.1.1 Hardware considerations .......................................... 13  
3.1.2 Software considerations ........................................... 14  
3.2 User interactions ......................................................... 14  
3.3 Extensibility ............................................................... 15  

4 Implementation .................................................................. 17  
4.1 Rendering a molecule .................................................. 17  
4.2 Adding the interaction .................................................. 18  
4.2.1 Inversion center ...................................................... 18  
4.2.2 Rotation axes ......................................................... 18  
4.2.3 Mirror plane ........................................................... 19  

5 Experiment ....................................................................... 21  
5.1 Approach ...................................................................... 21  
5.2 Learning test ............................................................... 21  
5.3 Procedure .................................................................... 21  
5.3.1 Measurements ......................................................... 22  

6 Results ............................................................................ 23  
6.1 Usability ...................................................................... 23  
6.2 Effect on learning behaviour .......................................... 23  
6.3 Comments from the participants ..................................... 24  
6.4 Comments from domain experts ..................................... 24  

7 Conclusion and future research ......................................... 25
The use of digital resources in the current education system to support the learning process has been an important part of education for a long time [1]. Even though consumer electronics and entertainment services have made a lot of progress with the development of innovative technologies such as Augmented Reality and Virtual Reality, the use of these technologies in education is still limited.

In many forms of education, classes are still being taught using basic educational methods such as a blackboard and written handouts. This form of education has not changed much since the 15th century[10]. These learning methods are often being used to teach complex subjects that cannot be properly visualized in a 2D environment. The visualization of these subjects is often an important part for the students to understand the specific subject. Modern technologies like augmented reality could be useful to aid students in the learning process of these complex subjects because it allows them to see and interact with objects as if it were present in front of them. Due to rapid technological advancements, the hardware that is required for augmented reality applications has become widely available and most students are already in possession of hardware powerful enough to run augmented reality applications. For this project, the benefit of learning chemistry in augmented reality will be researched.

1.1 Augmented reality

The main advantage of AR environments for educational purposes is that the student can see an object that is normally unavailable to them and interact with that object in various ways[8]. For instance because the model is too big (e.g. galaxies, planets) or too small (e.g. atoms, molecules). One of many cases where the learning material is hard to visualize is in chemistry. Molecules are too small to see, making it hard to study and interact/experiment with them. An augmented reality environment could help students understand the properties of a molecule by allowing them to see the molecules and interact with them. In this project, an augmented reality application has been developed to examine the possible learning benefits when studying molecular symmetry in an augmented reality environment.

In an augmented reality (AR) environment, computer generated images can be projected in the user’s perspective of the real world. There are various ways to create an augmented reality environment. As long as the hardware that the application is being executed on has some sense of the real world (usually by using a camera) and a graphical display to overlay the computer generated content.

A simple way to add content to the real world is by using image markers that are recognized by the augmented reality application. A marker can range from a QR-code to actual images, but even real world objects can be used as a marker. When a marker is detected by the application, its position, rotation and the distance to the display are calculated and the 3D model will be transformed accordingly and rendered at the correct position and orientation relative to the marker. This gives the user the sense that that virtual object is actually present in the real
world (see figure 1.1).

Figure 1.1: Example of an augmented reality application using a marker

1.2 Related work

Various research to the advantages and challenges of using augmented reality in educational settings has been conducted. Previous research to using augmented reality in educational settings reported some challenges, mainly that it is difficult for students to use.\footnote{http://blogs.solidworks.com/solidworksblog/2013/02/augmented-reality-in-edrawings.html}. The usability of an augmented reality application is an important aspect because the main focus should be the learning experience. Other researchers that developed and evaluated an application for middle-school students to experiment with atoms concluded that augmented reality has a significant supplemental learning effect as a computer-assisted learning tool \footnote{http://blogs.solidworks.com/solidworksblog/2013/02/augmented-reality-in-edrawings.html}.

A study at the university of washington compared the use of physical molecular models with the use of an augmented reality representation of that model and showed that while some users still prefer physical models, others prefer augmented reality because they do not have to build the physical model themselves\footnote{http://blogs.solidworks.com/solidworksblog/2013/02/augmented-reality-in-edrawings.html}. Others have shown that chemistry students are often having trouble visualizing the structure of a molecule due to problems with their spacial ability \footnote{http://blogs.solidworks.com/solidworksblog/2013/02/augmented-reality-in-edrawings.html}, a problem that could be solved using augmented reality.
CHAPTER 2

Background

Learning in augmented or virtual reality environments can provide a possible benefit to subjects that are usually unavailable to the student for a number of reasons.

There are education methods that would be too dangerous or too expensive to perform in the real world (for example learning to fly an airplane or learning how to use expensive laboratory equipment). But there are also fields of education where the subject is hard to visualize because it can not be seen in the real world or in some cases is not even a physical object but rather a theory.

One of many cases where the learning material is hard to visualize is in chemistry. Molecules are too small to see, making it hard to study and interact/experiment with them. An augmented reality environment could help students understand the properties of a molecule by allowing them to see the molecules and interact with them. In this project, an augmented reality application has been developed to examine the possible benefits of for studying symmetry in molecules in an AR environment.

2.1 Molecular symmetry

Studying the symmetry of a molecule offers useful insight in many chemical and psychical properties of a molecule. In essence, molecular symmetry means that a molecule can be rotated, mirrored or inverted in such a way that it remains visually unchanged. A molecule can have a number of symmetry operations: operations (e.g. rotations, reflections) that can be carried out on a molecule without changing the appearance of the molecule. There are five symmetry elements that can be present in a molecule, noted by the following group element [3]:

\( \text{E (identity)} \) The identity operation consist of doing nothing and leaves the molecule unchanged. Every molecule has this element.

\( \text{C}_n \) (proper rotation) A molecule can have an n-fold rotation axis. A molecule that has this element will be visually unchanged after a rotation of \( 360/n \) along a certain axis. If more than one of these axes are present, the axis with the highest value for \( n \) is called the principal axis.

\( \sigma \) (symmetry plane) When a reflection in a plane leaves the molecule visually unchanged.

\( i \) (inversion) When every atom in a molecule is inverted through its center and is visually unchanged.

\( S_n \) improper rotation When the molecule is visually unchanged after a rotation along a certain axis followed by a reflection through a plane perpendicular to that axis.

For example, a water molecule (H\(_2\)O) contains 4 symmetry operations that leave the molecule unchanged after they have been carried out. The identity operation, a C2 rotation axis and two vertical symmetry planes (see figure 2.1)).
A group containing multiple symmetry operations is called a point group because it leaves at least one point in the molecule at its place.

2.1.1 Current education method

Knowledge about the structure of a molecule and the possible symmetry elements that can be present in that molecule is an important part of understanding the various properties and behaviours of that molecule.

There are various ways to draw a molecule on a 2D surface such as a screen or on paper but these methods all involve workarounds to represent the geometry of that molecule (see figure 2.2).

To obtain a better understanding of the 3D structure of a molecule, a molecular building kit can be used that allows students to assemble a model of the molecule out of plastic representations of atoms and bonds.

In a survey that was sent out to a small set of students who took a course that involved molecular symmetry, 64% of the students said to experience difficulties with the molecular symmetry part of the course. This was mainly due to having trouble visualizing the molecule as a 3D object.

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1http://chemistry.tutorvista.com/inorganic-chemistry/molecular-symmetry.html
2http://teachbesideme.com/wp-content/uploads/2015/01/618pMnC0gZL.jpg
28.6% said to have used a molecular building kit (see figure 2.3) while an additional 32.1% did not use such a kit but felt the need to use it. 75% of the students reported to feel the need for visual aids such as 3D models or computer visualizations while they were learning molecular symmetry while only 10.6% of those students answered to have actually used those resources.

Some students are experiencing difficulties when trying to determine the symmetry elements of a molecule. This could be due to the fact that students are having trouble visualizing a molecule when it is drawn on a 2D surface.

Augmented reality could be used as an educational aid for this subject. An augmented reality learning method could lend itself well to this subject because it contains multiple difficulties that can be remedied by aiding the student to visualize and experiment with the subject. For this project, an augmented reality application was developed that allows students to experiment with molecular symmetry. The goal of this project is to evaluate the added benefit of learning in an augmented reality environment compared to the traditional learning method.
To maximize the learning experience and usability of the application, the requirements and essential features were considered before starting the development of the application.

1. The application needs to be designed and implemented in a way that it is accessible to a lot of students without the need for special hardware or expensive equipment.
2. The application should provide intuitive interactions to support the learning process.
3. The application should be extensible so that any molecule can be experimented with.

### 3.1 Accessibility

#### 3.1.1 Hardware considerations

Augmented reality applications can be developed for many platforms. They can be designed for expensive head-mounted displays or video see-through devices, but can nowadays also be developed for 'regular' smartphones since most of them contain a high-resolution camera, a powerful processor and a high-resolution display.

In order for this application to be accessible to the maximum number of students, the necessary hardware should be easily available and affordable. Also, the number of required devices and extra input peripherals should be kept to a minimum.

There is various hardware available that could be used as a target for an augmented reality application and each of these has its advantages and disadvantages (see table 3.1). Several of these platforms where compared to find the most suitable solution:

- **Microsoft Hololens** a pair of mixed reality smartglasses developed and manufactured by Microsoft.
- **Google cardboard** A simple VR viewer originally designed by google.
- **Handheld AR** By using the camera and a display on a smartphone or tablet.

<table>
<thead>
<tr>
<th></th>
<th>Microsoft Hololens</th>
<th>Google Cardboard</th>
<th>Handheld display</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cost</strong></td>
<td>$3000,00 (development kit)</td>
<td>around $10,00</td>
<td>From around $100,00</td>
</tr>
<tr>
<td><strong>Extra hardware required</strong></td>
<td>none</td>
<td>Smartphone</td>
<td>none</td>
</tr>
<tr>
<td><strong>Navigation</strong></td>
<td>Gesture interaction</td>
<td>Only visual</td>
<td>Visual and touch</td>
</tr>
</tbody>
</table>

Table 3.1: Comparison of augmented reality platforms.

The hololens is not an option for this project because it is too expensive and therefore limits the amount of students that are able to use the application. Google Cardboard is accessible
due to its low price but limits the interaction possibilities since it is a head-mounted solution and therefore touch input is not accessible. The best option is to develop the application for a smartphone because it is the cheapest option (Google Cardboard will need a smartphone as well), and allows the most freedom when designing the interaction methods.

Developing the application for smartphones will increase its accessibility, since most students these days are in possession of a modern smartphone powerful enough to run AR applications. The application should be compatible with any recent smartphone running either iOS or Android. Android and iOS are responsible for a combined market-share of 98.9%[7] so supporting these platforms ensures that most students in possession of a smartphone are able to run the application.

3.1.2 Software considerations

To develop the application for multiple mobile operating systems, the Unity game engine is used. Unity is available for both Windows and Mac OS Operating systems and offers most features for free and provides almost everything that is needed to develop this application. Unity is able to compile applications for various platforms, including all major mobile operating systems.

For augmented reality support, the Vuforia framework can be added to the Unity project. Vuforia allows for an application to use specific predefined markers to use as an anchor to display virtual content relative to those markers. Vuforia offers support for the tracking of up to 5 different markers at once, so multiple markers can be used to provide different functionality in the application.

By adding the framework the application is able to render an 'AR Camera view' that shows the camera and looks for markers. Objects can then be placed in 3D space relative to the marker. Vuforia’s online developer portal allows images to be uploaded which can then be processed and converted to a marker database that is compatible with the Unity engine. Various markers will be used in this application, with the most important one being the marker where the molecule is projected on.

3.2 User interactions

The main screen that the user will see after opening the application is a camera view and a basic instruction text on how to start using the application. The first instruction is to point the camera at a marker. Whenever a marker is detected, a molecule is projected on top of that marker and a toolbox will appear. The student can then select a tool from that toolbox to perform several spacial operations on the molecule.

Because this application is designed for mobile touch devices, the possible interaction methods are different than those on a desktop computer. There is less screen space on average sized smartphones compared to a desktop monitor and no mouse or keyboard input. Therefore the number of buttons and selectable items is kept to a minimum and interactions are mostly based on touch gestures and moving the markers. To provide the student with a basic understanding of the application and how to use it, a number of user interface elements are provided. These are placed on top of the camera view and consist of various buttons and text elements.
interface elements provide a basic way for the user to navigate through the various options and available tools. While the application is in use, a help button is always present on top of the screen that when pushed/clicked will display a scrollable textbox with instructions on how to use the application and the tools.

For this application to have achieve the desired learning benefits, students should be able to interact with the molecules in the app and in that way discover symmetry elements.

To allow the student to experiment with the molecule that is rendered, a number of interaction methods are needed. Since there are various symmetry operations the application is required to have multiple interaction methods to allow the user to discover these symmetry operations. In this application, three distinct forms of interaction with the molecule are possible: inversion, rotation and mirroring the molecule through a plane. To allow the user to focus on one symmetry operation rather than all of them at once, a 'toolbox' is present in the application. This allows the user to select a tool to find a specific symmetry operation in the molecule and experiment with it.

**Inversion Center** With this type of interaction, a point is rendered between each pair of atoms. The user can select one of these points to project a copy of every atom and bond within the molecule through that point.

**Rotation axes** With this tool, a single atom or bond can be selected within the projected molecule. The application generates a set of rotation axes passing that atom or bond for the user to choose from. When one of those axes is selected, a copy of the molecule is rendered that can be rotated around the selected axis. When the copy of the molecule matches the original molecule after a specific rotation, the symmetry is discovered.

**Mirror plane** This tool is not one that needs to be specifically selected in the tool menu, but can actually be used at all times. To discover mirror planes, a second marker needs to be placed in the view of the camera. When detected, this marker acts as a mirror that reflects the projected molecule.

By using these tools, various symmetry elements can be discovered.

### 3.3 Extensibility

To allow a varied learning experience, the application should work for any molecule. Therefore the application should be able to generate molecules based on a data format representing that molecule. Therefore the application is able to parse and render .xyz file formats. The advantage of using this data format to render the molecule is that is an open standard and these files can be converted from most other molecule file formats using open source software.

The .xyz file format is a simple format that represents a 3D molecule object. The first line of an .xyz file states the number of atoms in a file. The second line holds a description for the file, and every other line in the file represents an atom.

Each of these lines states the kind of atom, followed by their x, y and z coordinates. Based on every atom's covalent radius and the distance between two atoms, the bonds between atoms can be calculated.

The advantage of using this file format is that any molecule can be imported and used to experiment with in this application. An example of an xyz file that represents benzene (see figure 3.2) is shown in listing 3.1.

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1http://openbabel.org/
Listing 3.1: xyz file that represents a benzene molecule.

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0.0000</td>
<td>1.40272</td>
<td>0.0000</td>
</tr>
<tr>
<td>H</td>
<td>0.0000</td>
<td>2.49029</td>
<td>0.0000</td>
</tr>
<tr>
<td>C</td>
<td>-1.21479</td>
<td>0.70136</td>
<td>0.0000</td>
</tr>
<tr>
<td>H</td>
<td>-2.15666</td>
<td>1.24515</td>
<td>0.0000</td>
</tr>
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</tr>
<tr>
<td>H</td>
<td>2.15666</td>
<td>1.24515</td>
<td>0.0000</td>
</tr>
</tbody>
</table>

Figure 3.2: 3D model of a benzene molecule.
CHAPTER 4

Implementation

The entire application is developed in the Unity game engine. The development of this application started by rendering a simple molecule based on a file that represented that molecule, followed by adding 'behaviours' to this digital molecule that allows various kinds of symmetry interactions with this molecule. Behaviours can be added to 3D objects in Unity by adding scripts to them. These scripts can be written in both C# and Javascript. All scripts that are used for this application are written in C#.

4.1 Rendering a molecule

To render a molecule based on an xyz file, every line of the file is parsed to get the location and type of every atom. The name of the atom is used to determine its size and color and the x, y and z coordinates are then used to render every atom at its correct position. They are then rendered as a sphere with a radius and color based on the properties of that atom. When all molecules are rendered, the distance between each individual atom is compared with all other atoms that are rendered and when that distance is smaller than the sum of their covalent radius, a bond is rendered between them (see figure 4.1). Every bond and atom is stored in a list that is managed by the molecule object. This functionality is written in a C# script that can be attached to any Unity gameobject to render a molecule relative to that object.

Figure 4.1: Ethane molecule rendered on a marker.
4.2 Adding the interaction

4.2.1 Inversion center

To implement the inversion center functionality, a script is used to determine the midpoint between all atoms that belong to a molecule. This point is calculated by adding the position vectors of both atoms and dividing the resulting sum by 2.

When the user selects one of these generated points, a copy of the molecule is rendered as a wireframe and an animation script is added to all molecules and bonds in that copy. This script can be added to any gameobject and moves that object back and forth between a given start and end position. To calculate the end position, the position vector of the selected point is multiplied by 2, subtracted by the position vector of the atom or bond that need to be animated.

![Image of molecule being inverted through its center.](figure4.2)

Figure 4.2: The molecule while it is being inverted through its center.

4.2.2 Rotation axes

Possible rotation axes are rendered when an atom or a bond is selected. When an atom is selected, multiple rotation axes are rendered in the same direction as all bonds that are connected to that atom. When a bond is selected, a rotation axis perpendicular to that bond is rendered.

![Image of molecule with generated rotation axes.](figure4.3)

Figure 4.3: The molecule with its generated rotation axes.

When a visible rotation axis is selected, a copy of the molecule is rendered as a wireframe and a rotation script is added to that copy. This script tracks the touches on the screen and when a drag gesture is recognized, the copy of the molecule is rotated around the selected axis. The angle between the original molecule and the rotated copy is stored and displayed on the screen.
4.2.3 Mirror plane

A virtual mirror can be used to detect symmetry planes in the molecule. This is implemented by adding a plane gameobject that is rendered in a 'reflective material'. This material is added to the plane so that all objects in front of the plane will be reflected in that plane. This plane is then attached to a new marker that can be used together with the molecule marker. The material that is being used in this application is installed from the Unity Asset store \[1\].

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\[1\]https://www.assetstore.unity3d.com/en/#!/content/34824
5.1 Approach

Various students are asked to perform a series of assignments with and without the application, followed by a survey in which they are asked about their overall experience using the application.

5.2 Learning test

The experiment asks the users to determine the symmetry elements in 10 different molecules, within two conditions.

**Condition A** Assignment where the symmetry elements need to be answered using the traditional pen and paper method.

**Condition B** Assignment where the symmetry elements need to be answered using the augmented reality application.

This research will consist of a within-subject design, where every test subject will participate in both conditions. To make sure both conditions have an equal level of difficulty, two molecules in condition A are identical to two molecules from condition B. The remaining 3 molecules in condition A will be matched to the other molecules in condition B based on structure and the complexity of the symmetry elements in that molecule.

To eliminate the possibility that the order of the conditions will affect the result, the participants will be randomly selected to either start with condition A or condition B.

Besides the two conditions, the participants will be divided in two groups:

**Group 1:** Students with knowledge about the subject. This group contains chemistry students who took the quantum chemistry course in their second year.

**Group 2:** Students without any knowledge about the subject.

5.3 Procedure

Each person completed the test in the same environment to eliminate any external factors. Every participant was reminded that the test is fully anonymous.

Before starting the test, every participant was handed a short introduction and explanation about the subject as well as the basic theory of molecular symmetry. This way both students with background knowledge as well as the students that are completely new to the subject can participate in the test. Before starting the experiment with the application, each participant got to experiment with an example molecule (H$_2$O) so they could get familiar with the application.

After this short introduction, the assignments were made.

For every molecule, 4 questions were asked:
1. Does this molecule contain a rotation axis?
2. Is that axis the principle axis?
3. Does this molecule contain a symmetry plane?
4. Does this molecule contain an inversion center.

For each of these questions, the student had to answer whether the symmetry element is present and if so, where it is located. When using the augmented reality application, the provided tools can be used to find the symmetry elements.

5.3.1 Measurements

The result of the test is measured by two parameters for each condition: speed and accuracy. The speed is measured by the average amount of seconds it took a student to complete all 5 assignments in either condition A or condition B. The accuracy was measured by the number of correct answers, which will lead to a score from 0 (no correct answers) to 5 (all answers correct) for every student.

At the end of each test, the participant was asked to answer a few questions about their experience using the application. These questions include:

1. The overall usability of the application.
2. The extent at which the augmented reality application has added extra understanding of the subject.
3. The extent at which the augmented reality application has contributed to their answers to the assignments.
4. If they would use this application rather than a molecular building kit.
5. If they would use this application in a course that includes molecular symmetry.
CHAPTER 6

Results

For the initial experiment, 10 chemistry students participated in the test. The full experiment took about 30 to 40 minutes per participant. More symmetry elements were found in the augmented reality environment than in the 2D environment. While some students took longer overall than others, more time was spent with the AR application than when answering the questions on paper.

The average time the participants took to answer all questions on paper was 9.7 minutes, while the average time they took using the app was 16.5 minutes.

6.1 Usability

All participants were able to finish the test and use the application without any major issues, although some interaction methods and user interface elements can be improved. Some users had trouble reading the instructions that were displayed on the screen and needed multiple attempts to correctly perform the desired interaction.

The option to invert a molecule through the inversion center was immediately clear for all students but some experienced difficulties when trying to select the inversion center in larger molecules or molecules where there were other atoms in front of the inversion center.

Some students experienced issues while trying to find symmetry planes with the virtual mirror, mostly because they wanted to turn the molecule or the marker that was used for the mirror in such a way that the camera lost track of one of those markers.

The participants rated the usability of the application with an average of 7.5 on a scale of 1 to 10 in the survey after the experiment. 9 of the 10 students said to be using this application rather than a molecular building kit and every participant answered they would use the application in a class where molecular symmetry is being taught if it was available.

6.2 Effect on learning behaviour

More questions were answered correctly when using the augmented reality application (see table 6.1), especially when the assignment was to locate rotation axes or symmetry planes.

Each condition had one molecule where the symmetry elements were relatively easy to find. In condition B, all participants found the symmetry elements in this molecule, compared to 7 of the 10 students in condition A. The students who already took a course where molecular symmetry is taught had less trouble finding the symmetry elements on paper, but still made less mistakes when trying to find them in the AR application.

The participants rated the amount of which this application would help them find the symmetry elements in a molecule with an average 8.0 on a scale of 1 to 10 in the survey after the experiment, this included the students who already took the course as well as the students without background knowledge about the subject.
<table>
<thead>
<tr>
<th>Symmetry Element</th>
<th>Condition A</th>
<th>Condition B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotation axis</td>
<td>64%</td>
<td>96%</td>
</tr>
<tr>
<td>Mirror plane</td>
<td>74%</td>
<td>92%</td>
</tr>
<tr>
<td>Inversion centre</td>
<td>86%</td>
<td>100%</td>
</tr>
<tr>
<td>All symmetry elements found</td>
<td>48%</td>
<td>88%</td>
</tr>
</tbody>
</table>

Table 6.1: Average percentage of correctly answered questions.

The students who had no prior experience with the subject answered in the survey that experimenting with the molecules in the AR application helped them understand the concept of molecular symmetry, while the students that already had experience with molecular symmetry said that their understanding has not changed but it still helps them locate the symmetry elements in a molecule.

6.3 Comments from the participants

Most participants were initially amazed that they could see and interact with a molecule on the table where the marker was placed. One student said to have a lot of fun playing with the molecule while taking the test. Other students mentioned that the ability to either rotate the molecule in 3D or select an axis in the molecule and rotate a copy of that molecule around that axis helped a lot to find specific symmetry element.

6 students specifically commented in the survey that viewing a molecule in AR helped them with their understanding of the spatial arrangement of that molecule.

6.4 Comments from domain experts

The application was presented to a university professor that teaches molecular symmetry to students in a quantum chemistry course. She acknowledged that students are having problems visualizing 3D structures when they are represented in 2D and that that might be a reason why students are having trouble identifying the symmetry elements in a molecule.

While still preferring a molecular building kit to visualize the molecule, she mentioned every form of visual aids are desired when learning subjects like these, with the benefit of getting the actual sense of the 3D representation when viewing a molecule built with a molecular building kit or in this AR application due to the molecule being presented in the real world.
CHAPTER 7

Conclusion and future research

The goal for this project was to research the effect of studying molecular symmetry in AR. This has been achieved by implementing an AR application that allows students to interact with molecules in various ways. This application has been compared with the traditional learning method by conducting an experiment in which various students were asked to find the symmetry elements in a molecule when drawn on a piece of paper and by using the AR application.

The results of the experiment show that augmented reality has potential in education when subjects can not be visually represented in the real world. Representing molecules in augmented reality can help students with the understanding of the 3D structure of a molecule and locating symmetry elements in that molecule.

While some users experienced some issues with the usability of the application, it helped all of them to determine the symmetry elements in the molecules.

To improve the usability of this application and the research regarding the learning benefits of using the application, the application requires several improvements and extra features to be developed for the app. Based on the user feedback that was collected in the survey and during the experiment, some interaction methods need minor improvements.

To research the learning effect of studying molecular symmetry in AR, the application should include the feature to collect and analyze data about the usage of the application. Also, a new experiment with a larger group of test subjects should be conducted.


