

CheMastryVR: Redefining Science Learning with Intelligent Virtual Labs

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Abstract:

Traditional teaching methods, especially in science education, often fail to engage students effectively, leading to widespread struggles in understanding complex concepts. The proposed research aims to develop an immersive virtual reality (VR) game that transforms traditional chemistry learning by enabling students to interact with elements, compounds, and watch molecules form different structures in a dynamic, 3D environment with an AI-powered recommendation system built in-game to assist student learning. Using Agile as its primary methodology, the research project will move iteratively through the development phases, employing constant user feedback to ensure alignment with user needs. The main development platform is the Unity game engine, along with software like Blender for 3D modelling and GitHub for version control. Data used in the research was collected through a survey of 20 high school students in a government school in Muscat, which revealed significant dissatisfaction with the current teaching regime and student enthusiasm for VR-based learning, especially to address challenges related to the periodic table, chemical bonding, and molecular structures. A prototype of the working game was developed and tested, fulfilling the goals and objectives set. Future plan for the game includes customized in-game experiences that follow school curricula and introducing more inclusive and cost-effective ways to play the game such as augmented reality.

Keywords: Artificial Intelligence, Chemistry, Learning experience, Recommendation system, Virtual Reality.

1. Introduction

Chemistry education is the steppingstone for scientific and technological advancements in any country, as it empowers the younger learners to pursue endeavors beyond foundational topics to research breakthroughs. However, the current state of chemistry teaching in schools has managed to scare students away from pursuing such paths, as they may view chemistry a difficult subject to grasp. Research shows students significantly underperforms when tested on fundamental chemistry topics such as molecular structure, chemical bonding, and electron configurations (Al-Balushi et al., 2012). These difficulties are often due to insufficient teaching methods that rely on outdated visualization technique like 2D diagrams and static textbook representations (Chikendu et al., 2021). Over the past decade, new, promising technologies have emerged as solutions to many real-world problems, VR being one of the most notable. Virtual reality has shown significant promise in helping experts in fields such as pharmaceutical research (Norrby et al., 2015), and large database visualization (García-Hernández & Kranzlmüller, 2019). However, very few if any virtual reality applications have been made specifically for school students on fundamental concepts such as periodic tables, element characteristics, and compound structures, which paved the path for this project to be undertaken.

CheMastryVR is a gamified learning experience tailored for students in 9th grade and above, with focus on foundational chemistry concepts to be used by teachers in classrooms as a tool or aid in lessons. It aims to help visualize the periodic table, enable element experimentation and inspection, embed an in-game, AI-driven suggestion system to make the experience smoother for new learners, and to be optimized for use on school-issued hardware.



1.1 Background

Education, particularly in the sciences, forms the foundation for cultivating the nation's future technologists, scientists, doctors, and engineers essential for economic growth and technological advancement. Within this domain, Chemistry holds a distinctive and indispensable role, contributing significantly to societal and industrial development. Consequently, it has been established as a core subject within educational curricula and a prerequisite for numerous science-focused undergraduate programs. However, despite its critical importance and extensive research efforts aimed at improving outcomes, student performance in Chemistry remains notably low (Edomwonyi-otu & Aava, 2011). Addressing these shortcomings requires innovative educational tools that extend beyond traditional teaching methods to engage students more effectively. Given that the chemical properties of molecules are determined by their structural features and fluid interactions, it is central for chemical science students to grasp the concepts of molecular structures and interactions in a life-like, interactive environment. As a result, model kits have been used for students to physically construct and manipulate simply molecular structures since the late 19th century. In the last decade, there had been a noticeable increase in the use of computer-based models to conceptualize chemical concepts. However, most of the tangible and virtual chemical models currently being used in educational settings provide an inadequate demonstration of the essential dynamic aspects of molecules, aspects that include kinetics, diffusion, and reactive collisions. And for this reason, newer, more dynamic and interactive chemical models are needed in their place, allowing for exploratory educational activities during class hours to enhance student independent learning. Virtual reality technology, a technological advancement that has significantly re-shaped the industry, has shown potential to fill this need for chemical education, through its immersion and interactive spaces, VR allows for a deeper, more intuitive understanding of chemical structures and systems. With the recent arrival of easily attainable virtual reality equipment as well as virtual reality software use and development, the technology is beginning to mature into a state where it can be integrated in education, and especially scientific education (Ferrell et al., 2019), paving the path for a future where students feel more confident pursuing careers in chemistry-centric fields.

1.2 Problem Definition

Chemistry education faces a major setback due to ineffective or outdated teaching methods, as many instructional approaches present chemistry concepts as isolated and abstract, limiting student's ability to connect the different concepts or apply their knowledge in real-life context. This fragmented and disoriented teaching strategy leaves students struggling with foundational chemistry concepts, which leads to misunderstandings that persist throughout their academic years. In addition to that, the reliance on traditional, lecture-based teaching techniques neglects the dynamic learning needs of chemistry students and fails to create an active learning environment that promotes critical thinking and concept connection and integration. Combined with the complex terminology and difficult chemistry concepts, these shortcomings foster an environments where students may develop anxiety and a negative impression of chemistry, leading to disengagement from the subject and low performance both in-class and on paper (Chikendu et al., 2021). Such practices can lead to shortcomings for the students, for examples, a study conducted among twelfth-grade students in Oman aimed to assess prevalent misconceptions related to fundamental chemistry topics, including atomic structure, compound formation, and chemical bonding. The findings revealed a significant number of shared misconceptions among the participants, highlighting critical concerns regarding the effectiveness of chemistry education in Oman (Al-Balushi et al., 2012). A second study conducted in Omani schools investigated students' attitudes toward science subjects and the school science curriculum, as well as how these factors influence their decisions to pursue science in their post-secondary academic years. The study found that a negative perception of the curriculum was directly linked to students' reluctance to continue studying subjects like chemistry after completing basic education (Al-Wahaibi, 2016). Together, these studies highlight two major consequences of inadequate chemistry education in schools: an unstable foundation in basic chemistry concepts and a reluctance to pursue chemistry in post-secondary education. This hesitancy can ultimately lead to a decline in pharmaceutical research and chemical innovation within the country, impacting scientific advancement and industry growth.

Based on the above studies, a core issue in chemistry education lies in ineffective teaching methods that contribute to declining interest in the subject and a lack of deep conceptual understanding among students. Traditional approaches, such as static model kits and outdated computer-based models, often fail to engage students or

effectively illustrate complex, abstract concepts. In response, virtual reality (VR) technology emerges as a promising, highly interactive solution. VR offers an immersive experience that surpasses conventional visual aids in the classroom by enabling students to explore chemical processes and molecular structures in three-dimensional space, fostering a deeper, more intuitive understanding. This innovative approach has the potential to transform chemistry education, enhancing student engagement, comprehension, and retention by making abstract concepts tangible and captivating (Ferrell et al., 2019).

CheMastryVR is an educational virtual reality game in a dynamic 3D environment where they can explore the periodic table, manipulate elements, and witness molecular structures in real-time. With the help of a VR headset and controllers, students can select, observe, and combine elements to form various compounds, providing a hands-on approach to understanding the composition and behavior of chemical substances powered by AI recommendation system.

2. Literature Review

Medchem VR, developed in March of 2021, is an educational virtual reality game designed to enhance medicinal chemistry education. the game focuses on a specific field of chemistry, which is medicinal chemistry. It allows studying pharmacists to visualise and understand drug molecules, addressing the challenges they often face in grasping complex chemical concepts. Medchem VR uses gamification to improve user engagement, enabling them to construct three-dimensional molecular structures, study structure-activity relationships, and deepen their understanding of pharmacokinetics and pharmacodynamics. Developed as a prototype, Medchem VR was evaluated by pharmacy students, showing significant potential through improving learning outcomes and inspiring future prospects of integrating advanced technologies in pharmaceutical education (Abuhammad et al., 2021).

Similar to Medchem VR, CheMastry VR was developed to address the shortcomings of traditional teaching using gamification, which is defined as the application of game-like elements and concepts in non-game contexts to improve overall audience engagement and motivation (Laguna et al., 2024). However, where CheMastry VR stands out is it's focus on foundational chemistry concepts rather than a smaller sub-set of chemistry. By designing the initial game to support a wider range of learners, it creates an environment that is flexible for future expansions, whereas a game that is designed with a niche user group in mind limits it's opportunities and long-term relevance. CheMastry VR was made not only to assist struggling students in the beginning of their academic journeys, but with enough creative space to incorporate newer modules and include more and more complex ideas overtime.

The Virtual Chemistry Classroom For Chemical Bonding (VC3B) was developed by Hameedur Rahman, Samiya Abdul Wahid, Faizan Ahmad, and Numan Ali. This system, introduced in their paper, was developed to make remote learning more accessible for students in middle school who are studying chemical bonding and formulas. The system uses gamified learning, found through various past studies to enhance student retention and overall engagement. The system is divided into two main games: 'Molecule Construction', where students build molecules by merging together chemicals in the correct order, and 'Chemical Formula', where they challenge themselves by forming compounds based on elements shown to them by the game. The immersion offered by the environment allows students to visualize concepts in chemistry in a more tangible. VC3B's flexibility enables students to access the learning platform at anytime, reinforcing it's effectiveness in supporting chemistry education both remotely and on-campus (Rahman et al., 2024).

While both VC3B and CheMastry VR's approaches target school students and their foundational learning, CheMastry VR distinguishes itself by having a more exploratory approach rather than the guided method VC3B follows. CheMastry VR allows students to venture the space freely, without predefined objectives or time limits. This design embodies the exploratory nature of chemistry as a subject and encourages self-paced learning, creating an environment were students engage with concepts in a way that embodies genuine scientific inquiry.

A study conducted in the Sultanate of Oman aimed to identify common misconceptions among twelfth-grade students in chemistry topics such as atomic structure and chemical bonding using a diagnostic test. The test, which was comprised of 25 questions and incorporated visual and sub-microscopic representations of the topics, was handed out to a total of 786 students. The findings were analysed, and they revealed that a number of final year students struggled with fundamental concepts such as how atoms bond or the nature of atomic particles, these

misconceptions were more severe when visual aids or diagrams were involved, highlighting a desperate need for more effective and engaging teaching methods. The study accentuated how traditional approaches fail to address persistent student misunderstandings, leading to a shaky understanding of foundational chemistry concepts, which is detrimental to student's interest and experience when moving to higher forms of education (Al-Balushi et al., 2012). This is especially relevant for my project, as it reinforces the urgent need for innovative tools in the educational field to simplify complex concepts and make chemistry more accessible to students.

Declining chemistry degree enrolments are a global concern. A study conducted in an English school investigated the underlying reasons for students avoiding chemistry. Survey responses were analyzed, where 506 students were selected to undergo the survey and a smaller group were chosen for individual interviews. The survey comprised of key factors such as interest in the subject, experiences, perceptions of chemistry careers, and doubts on the student's academic ability to excel in the field. Additional influences were also put into account, such as lack of exposure to engaging chemistry experiences. After analyzing student answers, the study managed to highlight how poor educational experiences deter students from pursuing chemistry (Archer et al., 2022). This literature underscores the urgent need for innovative solutions like CheMastryVR to address current challenges and inspire more students to further pursue chemistry after basic education.

Medicinal chemistry is a crucial part of the pharmacy curriculum, but it's complexity, especially in visualizing molecular structures from 2d representations, poses challenges for students. A VR, gamified educational tool was proposed in a study and evaluated on 41 students. The proposed system demonstrated great potential in addressing the issues pharmaceutical students were facing by enabling immersive interaction with 3d molecular models, the tool has assisted student's in understanding, engagement, and retention of complex concepts (Abuhammad et al., 2021). This study highlights how VR can transform traditional teaching methods in chemistry, not just in schools, but in higher education and specialized fields as well. this study has also helped set the project's boundaries, which will stay within the realm of basic chemistry without venturing into more complex concepts. These boundaries will help the project stay on track deadline-wise.

NOMAD2 is the largest open-access materials science database, featuring over 50 million chemical energy calculations, chemical compounds, and chemical data. it includes many components, namely a repository, an archive, an encyclopedia, analytics, and advanced graphics. All supported by NOMAD2's high performance infrastructure. The repository stores raw data, while the archive gives the user a code-independent transformation. Finally, the encyclopedia offers a materials-centric view. NOMAD2 also integrates big-data analysis through many different tools for advanced insights. The study proposed a virtual reality viewer to assist researchers that navigate the NOMAD2 database visualize and interact with their datasets, supporting formats like xyz. And as the platform evolves on user feedback, it pumps out new features, ensuring compatibility with prior builds (García-Hernández & Kranzlmüller, 2019). This model of leveraging open data has inspired the integration of open-source libraries like PubChem in CheMastryVR's suggestion system, allowing dynamic chemical compound suggestions to enhance learning.

Another study details the development of a Virtual Reality (VR) game for teaching organic chemistry. It emphasizes the analysis of existing games on the current market, the goals of VR in education, and the importance of having object manipulation available within the VR environment. The game utilized the Leap Motion Sensor of the HTC Vive headset to enable users to interact with atoms, structures, and molecules. The development process consisted of three iterations, each followed by general evaluations of the contents, and a final assessment by high school students. The findings confirmed the viability of VR for teaching Organic Chemistry (Rodriquez & Prada, n.d.). This literature is highly relevant to the project, as it offers a structured approach to iterative development and inner game mechanics. Overall, it has helped plan the development process of the game and set realistic timelines for each stage of development.

Collectively, past work and literature highlights a growing consensus that Virtual Reality, when tailored to the needs of the community, can bridge the gap between complex chemistry theories and student comprehension. These studies justify the need for a game like CheMastryVR, a project that merges the latest interactive technology, gamification, and Artificial Intelligence to make foundational chemistry more accessible for students and easier to

teach for teachers. These insights form a solid foundation for the project's scope and help define its objectives and goals, ensuring it addresses the educational challenge.

3. Methodology

The data collection method used for this project was a survey. The main goal of the survey was to collect data from students that will aid in the development of CheMastryVR. The survey was distributed to 20 students ranging from 9th grade to 12th grade. The survey comprised of 4 multiple choice questions and 2 open-ended questions on varying topics within the scope of the project. The survey was distributed to a select number of students in a government school in Muscat with the presence of teachers and faculty. The survey mainly focused on assessing student dissatisfaction with current chemistry teaching methods and gauging their responses to the idea of an educational, chemistry-centric VR game.

The survey results reveal that the majority of students find chemistry challenging, with 70% believing current teaching methods are inadequate. Key areas of difficulty include the periodic table, chemical bonding, molecular structure, and electron configuration. Despite having no prior exposure to VR in education, all respondents expressed enthusiasm for the potential of VR to improve their learning experience. They viewed it as a novel, engaging, and innovative tool that could make complex chemistry concepts more understandable and fun. These findings highlight a strong demand for interactive, immersive solutions like CheMastryVR, which could address these challenges and enhance students' understanding of chemistry.

As part of the data collection strategy, a short school tour was conducted where teachers were invited to participate in a test run of the game and provide feedback. Several teachers mentioned how the game encouraged curiosity in students, promoting learning through exploration rather than memorization. They were also thoroughly impressed by how the game captures concepts like electron configuration and compound formation in three-dimensional form, allowing students to fully grasp topics that were once considered difficult to convey through traditional mediums like images and videos. When it comes to future iterations of the game, teachers suggested the addition of a virtual mascot that guides the player using voice instructions to help them navigate the environment more easily and make the game environment more lively. Teachers also suggested having the option to start some in-game activities or some short quizzes to challenge and test the students on in-game. All in all, teachers saw potential in CheMastry VR to help bridge the gap between theoretical and practical chemistry, enhancing student engagement both in the classroom and outside of it.

As far as the software methodology is concerned, for CheMastry VR, The Agile Methodology is the most ideal. Given the dynamic and evolving nature of an educational VR game like Chemistry VR, Agile will give room for continuous enhancements to the finished product throughout the development process. This iterative approach is critical, as it enables quick and easy incorporation of user feedback. Additionally, agile breaks down large, complex tasks into smaller, more bite-sized tasks. This feature will allow the game to be brought together with fast-paced, functional, and working pieces of the final product in short sprints, which is ideal for testing. As the project progresses, Agile's adaptability to changes can be extremely helpful, as with time many features and changes may be done to the project based on user feedback and recommendations.

The main platform used to develop the game is the Unity game engine. This game engine operates fully on C# and has a scene manager to shift between different scenes such as the main menu and main game environment, an inspector to set the ID for different objects, manage texture and attach scripts to game objects. The game objects were modeled using the open-source software Blender. The final prototype will be uploaded on Itch.io for distribution.

4. Results and Discussion

Figure 1 shows the main lab environment for the game, which holds all in-game actions and interactables.



Figure 1 Lab Environment

Figure 2 shows the first part of the laboratory table. The periodic table was represented through a periodic keyboard, where each element is a key within the keyboard.

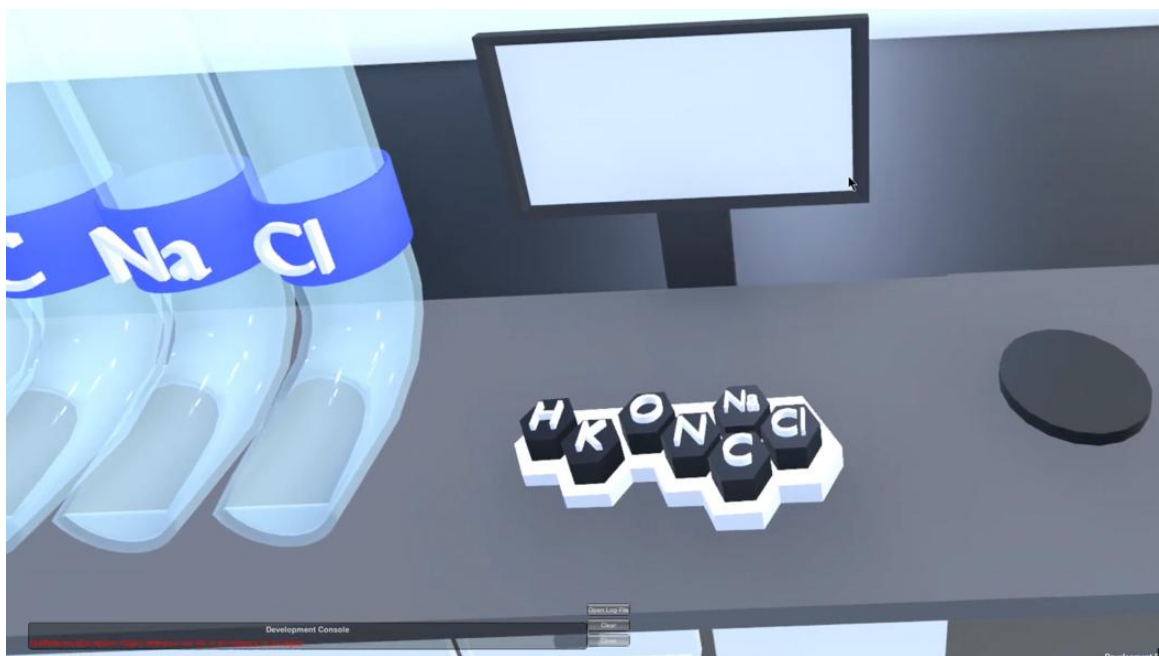


Figure 2 Periodic Keyboard, User Selection Screen And Element Inspection Podium

In Figure 3, the user presses an element key on the keyboard, the user selection screen is updated based on each generated element, and the elements are then dispensed through their dedicated dispensers.

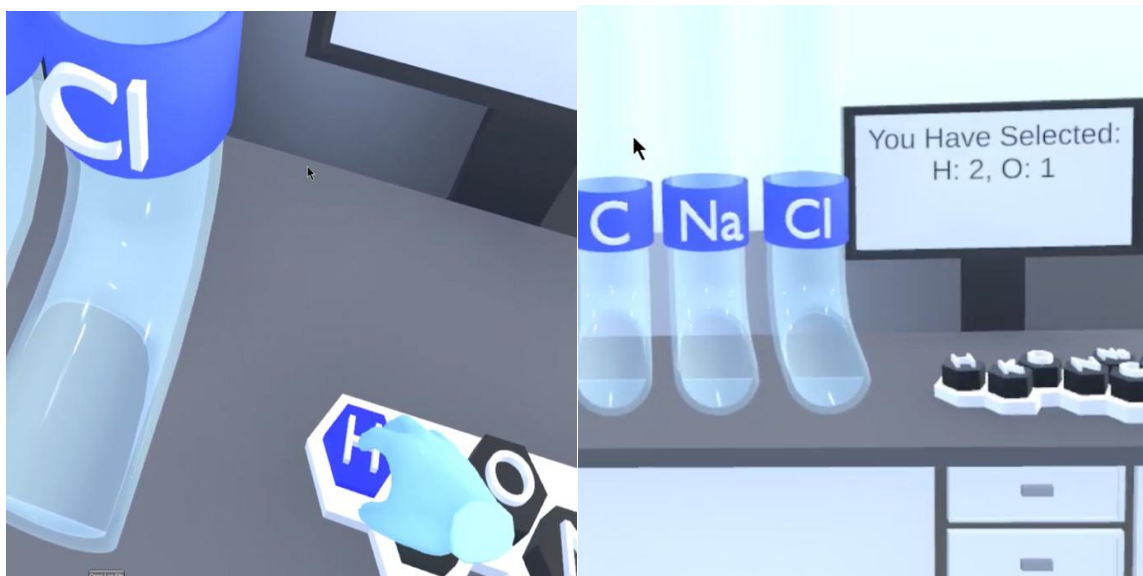


Figure 3 Selected 2 Hydrogen Atoms And One Oxygen Atom

Elements in game are pickable and can be inspected freely. When a specific combination of elements are generated, the intelligent recommendation system will suggest a compound that can be made using the current selection of elements. the compound structure generated by the suggestion system will appear empty, as shown in Figure 4, prompting users to fill in the blanks with the elements in their designated, logical places.



Figure 4 System Suggestion and Element 3D Spheres

In Figure 5, the player is picking up their generated elements and placing each sphere in it's dedicated place within the empty structure. Upon completion, a red button will appear below the completed compound, when pressed, that compound's game object will be generated.



Figure 5 Compound Forming

In Figure 6 the water game object has been generated, the user then picks up the watering can interact with the pot, once the water particles collide with the pot, the seed grows to a sapling.

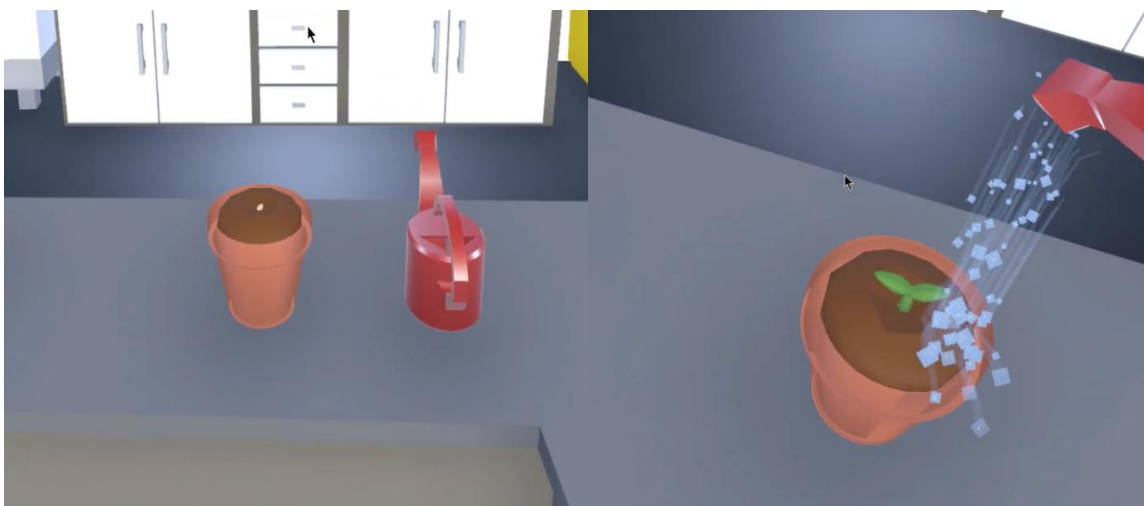


Figure 6 Game Object Of H₂O And Playing Animation

Following the same steps, Figure 7 shows the user completing the compound structure of KNO₃ (Fertilizer). After the compound is built and the button is clicked, the fertilizer game object will be generated in scene.

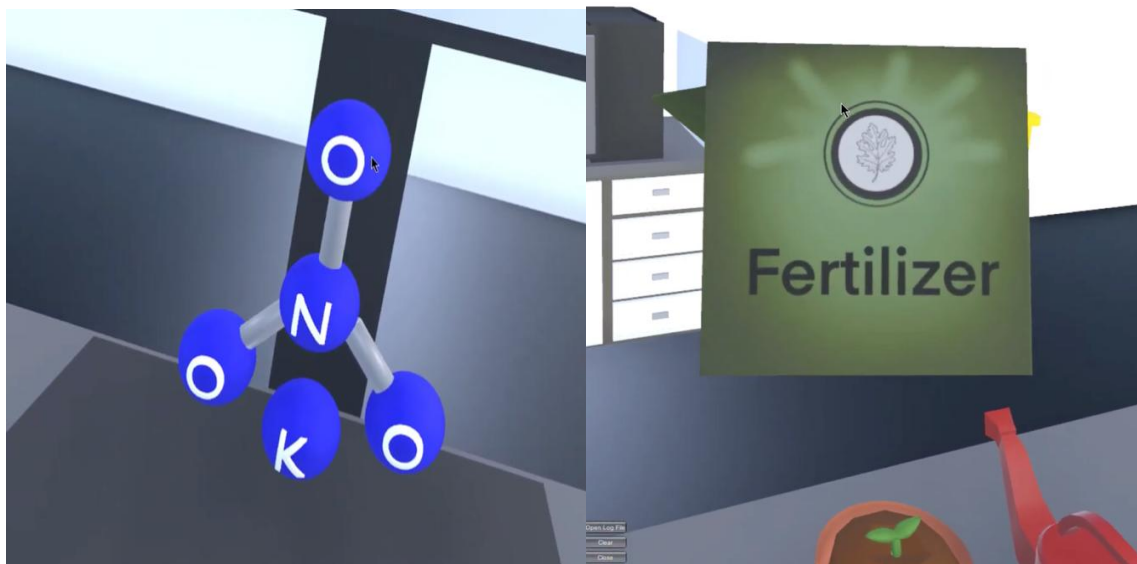


Figure 7 KNO₃ Compound Forming and Game Object Fertilizer

The fertilizer game object is used by the player in Figure 8, growing the sapling into a flower.



Figure 8 KNO₃ Game Object And Animation

The same elements that are used to build in game compounds can also be inspected on the Inspection podium. Here, each element's electronic configuration is displayed in 3d space, allowing students to visualize the concept more vividly. This is shown in Figure 9.

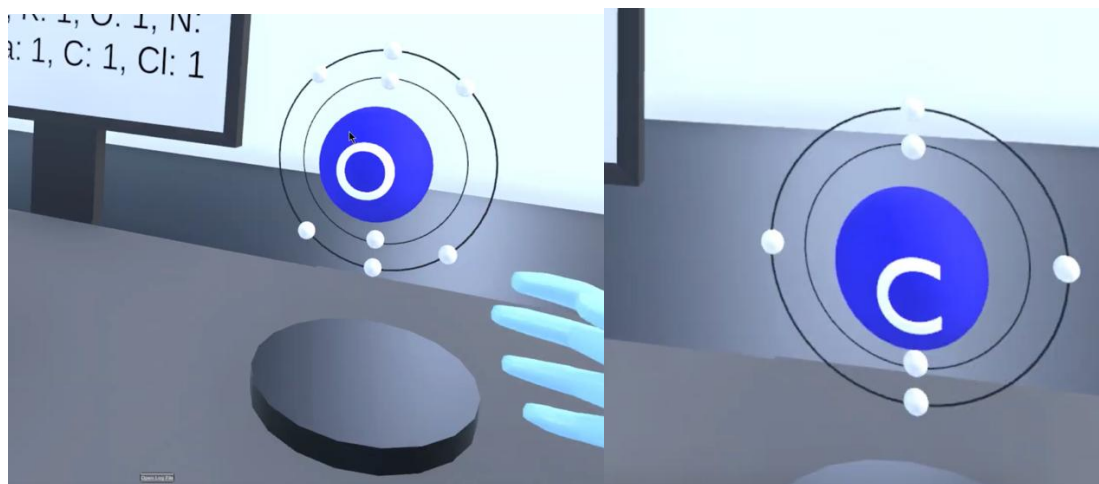


Figure 9 Element Inspection And Electron Configuration

The in-game recommendation system was created in script using a point-based system. The compounds were all listed in a dictionary called Compound map which held the elements that make up each compound along with their frequency. Each element generated in-scene was recorded in the user selection list with its frequency, these selections were used to form the suggestions. Using the point system, if the user selection contained an element that was present in the compound but not with the same frequency, that compound will be given a single point for each matching element, however, if the user selection matches the element and frequency in a compound in the compound map, that compound is given two points. The system then suggests the compound with the highest number of points or the closest match to the user selection and displays it on the suggestion screen. This system helps make gameplay smoother for students and guides them throughout their session.

The game was also made using lower graphic settings and less complex in-game environment objects, where the lab environment was merged in the 3d editing software Blender to appear as a single game object. This makes rendering the game environment easier when running the game, making it less likely to overload the CPU and an optimized game experience overall. The game is also playable on the laptop with Meta Airlink, making it easy for teachers to play the game on the headset and project it using built-in projectors.

5. Conclusion

This project attempted to address the shortcomings of modern-day chemistry education and the declining student interest and understanding in the subject by introducing virtual reality technology. By revolutionizing the way topics are conveyed within the classroom, CheMasteryVR aimed to improve student's experiences of chemistry as a way to reignite the passion of learning within the youth and help encourage more to seek out science-centric studies post-secondary education.

Some limitations that can obstruct implementation of the game within educational settings are high costs, as VR hardware can be quite costly and difficult to acquire in large enough quantities to cover all classrooms, resulting in a reluctance to accept the game as a solution or tool by both government-owned and privately-owned institutes. Another limitation can be accessibility issues, as not all school students feel comfortable wearing a VR headset, some can have underlying medical conditions that can cause motion sickness, while others with visual impairments and other physical disabilities will take no benefit from playing the game. This can alienate some students and negatively affect their educational experience.

One way that can help mitigate the limitations in future iterations of the game is the implementation of augmented reality alongside virtual reality. Augmented reality is a mix of real-life and digital media, overlaying 3d objects, images, sounds, or information onto a real-life environment (Hayes, 2025). Augmented reality will keep the game's initial aim of three-dimensional and interactive learning, but implement it onto more accessible hardware such as smartphones and tablets, where the game can be downloaded as a mobile or web application and played

using the device's camera. This will help eliminate the need for costly hardware, encouraging more schools to incorporate CheMasteryVR into their existing curriculums and contribute to the broader initiatives of rekindling learners' intellectual curiosity in chemistry, cultivating their confidence and drive to pursue the discipline at a university level, thereby bolstering the restoration of the nation's biomedical and scientific research and development efforts.

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CheMasteryVR: إعادة تعريف تعلم العلوم من خلال المختبرات الافتراضية الذكية

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المخلص:

تُعاني أساليب التدريس التقليدية، خصوصًا في تعليم العلوم، من ضعف في جذب انتباه الطلاب وتحفيزهم، مما يؤدي إلى صعوبات واسعة النطاق في فهم المفاهيم العلمية المعقدة. يهدف البحث المقترح إلى تطوير لعبة واقع افتراضي (VR) غامرة تعيد تشكيل عملية تعلم الكيمياء التقليدية، من خلال تمكين الطلاب من التفاعل مع العناصر والمركبات ومشاهدة تكوين الجزيئات في بيئة ثلاثية الأبعاد ديناميكية، مزودة بنظام توصية مدعوم بالذكاء الاصطناعي مدمج داخل اللعبة لدعم تعلم الطلاب. يعتمد المشروع البحثي على منهجية Agile كأساس لتنفيذه، حيث يتم تطوير النظام على مراحل متكررة مع الاستفادة المستمرة من ملاحظات المستخدمين لضمان توافق المنتج مع احتياجاتهم. تعتمد عملية التطوير على محرك الألعاب Unity، إضافة إلى برنامج Blender للنمذجة ثلاثية الأبعاد و GitHub لإدارة الإصدارات. تم جمع البيانات من خلال استبيان شمل ٢٠ طالبًا من المرحلة الثانوية في إحدى المدارس الحكومية في مسقط، وأظهرت النتائج وجود عدم رضا عام عن أساليب التدريس الحالية، مقابل حماس كبير لتبني التعلم القائم على الواقع الافتراضي، خاصة في معالجة التحديات المرتبطة بالجدول الدوري، والروابط الكيميائية، والبنية الجزيئية. تم تطوير نموذج أولي للعبة واختباره، وحقق الأهداف المحددة في البحث. وتشمل الخطة المستقبلية تطوير تجارب تعليمية مخصصة تتماشى مع المناهج الدراسية، إلى جانب توفير طرق أكثر شمولًا واقتصادية لتشغيل اللعبة مثل استخدام تقنيات الواقع المعزز.

الكلمات المفتاحية: الذكاء الاصطناعي، الكيمياء، تجربة التعلم، نظام التوصية، الواقع الافتراضي.