

Alchemically:

An Educational Role-Playing Game

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Abstract:

Alchemically is an educational role-playing game that functions as a classroom aid for boosting middle school and high school students' memorization of molecular formulas and molecule's attributes. The game implements several diverse teaching methodologies, including trial and error, practice and feedback, and the presentation of information from audio and visual cues. It also motivates students to continue learning through both intrinsic and extrinsic motivators. Student players craft molecules by choosing and placing atoms into a crafting table, then bonding them together. To help players build molecules, players can reference a journal that includes images, diagrams, and factual information on the molecules included in the game.

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Introduction

The appearance of video games within the field of education is becoming more common. As educators explore new methods of providing students with information and strengthening the learning environment in order to increase learning efficiency and information retention, educational games have become an accepted means of teaching. This is due to their ability to promote a fun and motivating learning environment, thereby keeping the attention of the student while allowing for more flexible ways of communicating the information that may not be possible in normal classroom settings. Video games allow for a large range of learning methods that can be tied together into a single experience. Trial and error challenges allow students to work through problems with a series of failures and successes that reinforce both the material and the methods leading to success, as well as adding a strong intrinsic motivation for the student through the sense of accomplishment when they succeed. Practice and feedback allow students to repeat processes and gain feedback on how they are doing in real time, allowing them not only understand how they can improve and eventually succeed at what they are doing but also discover different results that appear due to their actions. Information presentation can also be an effective educational method by presenting the information directly to the player through an educational figure, or text and audio. Educational games exist in the fields of history, English, math, physics, and even physical education, among many other subjects.

The game Alchemically was made in order to create a learning environment for chemistry education, a subject that can be difficult due to the need for analytical thinking and memorization. It assists students with the memorization of molecular formulas through diverse teaching methods, such as the recreation of molecules, recollection of information, and information presentation through audio and visuals.

Education in Games

Using video games as educational tools has many benefits. In the current public school system, it is common to teach all students at the same pace. Every individual has a unique learning rate in each specific school subject. This can cause some students to fall behind if they are not strong in a certain subject, or others to finish early, and become bored. But educational video games can provide students with a better opportunity to learn at their own pace(3). Games allow students to practice educational material and receive feedback in real time without having to rely or wait on others, allowing them to advance at their own pace. Educational games have been used in schools for years. One of the most popular and memorable games used in schools was *Oregon Trail*, released in 1971, a text-based game set in 1848 that depicts the westward migration of a player-controlled family. An estimated 65 million copies of the game were sold as of 2016, with many school computers having the game preloaded (13). In a talk given by co-creator Don Rawitsch at the 2017 Game Developers Conference, Rawitsch asked the audience how many people have played the game, with a large number of people raising their hands. He then asked how many of those people were introduced to the game in school, and again a large number of people raising their hands, with him stating “that’s typically the pattern.”(2) The game was created when Rawitsch was participating in a teaching program and wanted to find a new way to engage kids in classroom activities. After creating the first iteration of the game, he integrated it into his 8th-grade history class by having kids rotate from doing other activities, such as reading, using maps, etc, to playing the game. He stated that after kids experienced the game they were mesmerized, not realizing that early computers could be used for subjects other than math. Rawitsch used this newfound method as a supporting tool in his teaching to help kids get interested. As the kids played the game, they were experiencing their

own story of traveling the Oregon Trail, fending for their individual family, and experiencing their individual hardships along the way. This allowed students to further understand how diverse the experiences of the Oregon Trail were, with some families making it all the way while undergoing little hardship, while others faced significant problems, possibly not making it to their destination at all. Another one of the educational elements of the game is a hunting minigame. In order for the student players to hunt for food, they would have to type a prompted word, such as “Bang.” Depending on how well the student typed, the results would vary. Incorrect spelling resulted in no food, correct spelling with slow typing resulted in only some food, and correct spelling with quick typing resulted in a large quantity of food, one of the most important resources in the game. This allowed the teaching and practice of another growing skill, computer typing.

With the rise of computers within schools, typing has become a popular skill taught within the world of educational games, leading to the creation of games such as *TypeRacer* and *Typing of the Dead*. *TypeRacer* is a browser-based game that turns typing into a car race. The game pits players against each other by assigning each player to individual car icons. As players type a selected sentence, their cars move down the track. As the sentence is typed, players are placed in accordance with typing speed. The game’s website includes a leaderboard, ranking players according to their words-per-minute (16). This game turns a subject that can be viewed as boring, into a competitive game. Competition adds an intrinsic motivation in the sense of competitive spirit and the accomplishment felt when winning. As a person starts playing these competitive typing games, they may win or lose to other players, but a competitive desire can start to rise, causing these players to want to win more consistently. In order to do that, they have to get better at typing, creating that motivation to continue to practice. *Typing of the Dead* is a game geared towards older players with its mature rating. But even though it is a more graphic and violent game, the educational aspect is still there. The player is a survivor in a zombie apocalypse and must defend themselves in this on-the-rail shooter. But instead of using the mouse to aim and fire, the player must instead type out

phrases in order to kill approaching zombies. While *TypeRacer* was focused on competing against other players, *Typing of the Dead* is instead focused around survival of the player, even allowing for cooperation, as the game can be played with a friend(7). These two games don't even scratch the surface of the number of typing games that students and schools can have access to.

These previously listed games were tools that were mainly used in school, or, at the very least commonly introduced in schools. However, even games that are created without the intention of teaching can informally educate players and can be integrated into an educational setting. The widely popular rocket-building simulator *Kerbal Space Program*, released in 2015, has sold over 2 million copies as of May 2017 and introduces players to the physics-driven world of rocket science (9). Players use Earth-based rocket technologies in order to help small alien creatures called Kerbals enter the reaches of space. As players try out different rockets, they go through a series of trials and errors in order to find a design that will fulfill their mission. The game itself, while generally directed towards the popular simulation game genre of entertainment, has also released a version that is directed towards education and school integration. The developers explain, "The original gameplay is already based on developing design through cycles of trial and error: a probable scenario is that your first few (dozen) rockets won't make it out of the atmosphere. Your rocket didn't go high enough? Maybe add a more powerful thruster. Now you ran out of fuel too soon? Add more fuel tanks. Now it's too heavy?" (4) At its very core, *Kerbal Space Program* teaches students about the process of trial and error, an exceptionally strong learning tool. The game also teaches the fundamental systems of physics, all while maintaining a strong atmosphere of fun, allowing students to make crazy vehicles, and watch them react.

Educational games can also not only teach those who are playing the games but can also help the field of science itself, essentially making the players the students as well as the teachers. *Foldit* is a perfect example of this, being a game that teaches players about protein-

folding, how proteins restructure themselves to serve different purposes within cells. The problem with protein folding is that predicting it is incredibly hard, with the developers explaining one of the main problems behind the research of protein folding, “the number of different ways even a small protein can fold is astronomical because there are so many degrees of freedom. Figuring out which of the many, many possible structures is the best one is regarded as one of the hardest problems in biology today and current methods take a lot of money and time, even for computers.” (11) In order to assist with this problem, Foldit was created. The game uses players as a way to further research within the field of protein folding. As humans, we possess strong puzzle-solving intuition, able to work through problems quickly and efficiently. Players across the world can play Foldit, finding the most efficient protein fold in order to solve a problem, scoring more points for the most efficient protein. As such, players are placed in a competitive scene, competing against each other in order to make more efficient proteins. But while this is happening, not only are players learning about this important field of science, but they are also helping scientists better understand the field, and help in the fight against deadly diseases and disorders such as HIV, Cancer, and Alzheimer's.

Designing Games for Learning

The implementation of formal educational subjects in video games has been a concept that has been around for a long time, but recently, the market has been growing, with larger amounts of capital being invested in the field (5). Teachers are exploring these games in search of new tools to help aid the learning process in their classrooms. As stated in an article by Ronald A. Smaldone, a Professor in Organic and Materials Chemistry at the University of Texas at Dallas, “there are many advantages to providing educational content in a computerized game format, one of which is that it permits learners to move at their own pace. A horizontal learning approach allows students who understand the material quickly to move on to more challenging material, whereas those that need extra time can take it, making it truly

personalized.” (10) In many current school systems, education is treated in a linear fashion at a set pace. All the students in a class are taught the same things on the same days, with tests assigned. This can be difficult for some students, as not everyone learns at the same pace. That is why video games can be so beneficial to creating a strong basis of trial and error within a learning environment.

Video games allow for multiple challenges that can have a trial and error aspect, allowing for this method to become more readily available when compared to normal classroom lessons, which can require a lot more day to day planning. As students try to learn new pieces of information, they form bonds connecting this information. As they try different methods, some of these bonds do not work, which results in the elimination of those methods. Students continue this process until they find a method that explains the information for which they are looking (15). Yet when taking tests or doing homework, students cannot experiment as much, as there is generally only one chance to test out a solution, and if their solution fails, it can have a negative impact on their grades. This situation is common in real life, as many opportunities do not allow multiple tries, but for the sake of school education, trial and error can be a valuable tool. Educational games allow this, even encourage it to some capacity. Many games allow players to play with the system, solving puzzles through multiple attempts, in a relatively consequence-free setting. The largest consequences a player may have is having to retry, lose some points, or lose a small amount of progress. Failure within these games creates for a powerful learning experience, and can even be seen as good game design (10).

Another set of motivations that good educational games create are intrinsic and extrinsic motivational elements. Intrinsic motivation is created through the mental states that players create as they are playing a game. This can include accomplishment felt after completing a difficult challenge, curiosity created through an interesting world, and wanting to explore the world(6). When creating a challenge, it becomes a balance of difficulty in order to keep the player motivated. If a challenge is too easy, the player will lose motivation as they are not facing

a difficult challenge that they must overcome. But if the obstacle is too difficult, they will lose the motivation due to losing hope at beating the challenge. In order for a player to keep motivation, they must be able to feel a strong sense of accomplishment when they have completed the challenge, knowing that they jumped a hurdle that required effort, but not so much that it was impossible. Good game design involves building up these challenges over time, teaching players how to accomplish tasks, then giving them challenges to allow them to show what they have learned. This is how school works; students learn the fundamentals of a subject and use those fundamentals in order to learn more challenging subjects. A good game also keeps the motivation going by creating a sense of curiosity within the player. If a person is curious about a subject in school, they are more likely to learn about the subject, asking questions, and seeking out information. If a game presents its material in a way that stimulates the player's curiosity, the player will become more invested in the game, allowing for a larger sense of motivation, and potential strengthening of the educational goals of the game.

While internal motivations can drive players, external rewards can also be strong motivators. These are called extrinsic motivators and are based on an external stimulus. As players play through a game, they are granted rewards, ranging from points, coins, gear, items, or more. These items help a player understand how well they are doing, able to compare point scores with other players or use the gear to strengthen their own characters. The desire to collect these items can be a strong motivator for players. If educational games have some sort of motivator from rewards, they can increase their learning effectiveness by keeping players in the game. A strong example of this is collectibles. By having a player collect a variety of items, and telling them which ones they do and do not have, it can create a strong sense of accomplishment and pleasure when the player does collect these items. This ties back into the intrinsic motivator of accomplishment when facing challenges, as these extrinsic motivators can help fuel the player to complete the challenge.

As players are facing these challenges, or playing in a trial and error environment, they are practicing some skill. This is one of the reasons that video games can be so beneficial in education, as they allow for repeated practice within an easy-to-access environment. Video games allow for this repeated practice and provide real-time feedback to the player. This can be either a success or fail message, or a more complex explanation. But if the feedback is in real time, it can allow players to learn. Even if the explanation is simple, generally players can use this feedback in order to understand the problem, and where they may have gone wrong. In many platform games, where the player must jump across gaps, avoiding obstacles, spikes are used as deadly traps. If a player falls into these, they will likely not receive a message saying “you have fallen into spikes, jump over them next time,” but just due to the act of them falling in and seeing a game over screen, they can infer that they were supposed to jump, jump earlier, or maybe go an entirely different route. Even without a game giving you specific feedback, games can still give enough information that players can understand that their solution does not work, and can find a new way to achieve their goal. Games have many different ways of motivating players, and that is why they can be so helpful in creating a fun learning environment because they can create new ways of motivating students that may be difficult or impractical to have in a standard classroom setting.

Chemistry in Games

Chemistry can be one of the more difficult subjects to learn in grade school due to its requirement of analytical thinking and memorization. However, it is also a subject that can be effectively implemented into video games due to its structured set of rules, such as the number of bonds each element can have, and the effects created from each molecules due to its structure. A team of researchers at the University of Texas at Dallas, including Ronald A. Smaldone, created their own system of teaching chemistry through a modification of the game Minecraft, a game focused around player freedom and creativity. This mod, named Polycraft

World, is a project focused around the integration and teaching of chemical processes, using the Minecraft world. The Polycraft World expansion is a free mod that works with any valid Minecraft license and builds off of Minecraft's crafting system in order to allow for new items, and more importantly, walks players through the process of creating those items. Players are able to create items such as pogo sticks, by going through the full process of collecting the base ingredients, crafting polymers, and using refinement processes in order to come to the end goal of getting new said item. Polycraft World uses these processes and items to keep players interested, giving them goals to work towards while having difficult challenges that they must overcome in order to achieve them, and teach them about these chemistry concepts. Smaldone explains that "by coupling practical concepts such as distillation, extrusion, and chemical processing to attaining highly desired items in the game such as enhanced tools, jetpacks and flamethrowers, we hope to strike a balance between being engaging and deeply educational."

(10) This concept is a very important one when it comes to educational video games. In order to be effective, educational video games need to have goals in order to keep students interested and motivated, whether this is the sense of accomplishment from completing a task, or materialistic rewards. Polycraft keeps players motivated through the difficulty of the processes to create the items, as well as the payout that the items provide. The creators are providing items to players that enhance the already established gameplay, making their characters slightly stronger, giving them new means of transportation, or just providing a tool that is purely meant to be fun.

Having choices within video games can help strengthen the learning environment that they provide by giving players a variety of goals to pursue. In a Stanford article, the research of Constance Steinkuehler is talked about, stating how she did a study on grade school boys, some of which were reading below their expected level, yet several grades above if the text was from an online game. Upon further research and testing, it turns out that if the boys were given a choice of what they wanted to read, their reading level improved dramatically as compared to

not being given the choice. This is why their reading level was so much higher when the text was from online games because they chose to play those games, they chose that reading material. She concluded that choice was a quintessential element in learning. (18) This is a large benefit of video games being used for education. They allow for more choices for the player. The player can choose which challenges to complete, or how to go about completing them, and through that choice, their minds become more open to the information that is presented through the gaming format, allowing for more efficient learning. This is the basis behind Alchemically. While traditional teaching of chemistry within schools is done through textbooks, homework, and tests, by creating an experience for students that not only teaches the same concepts but does so in a way that makes students want to continue playing and therefore learning, the amount of information about chemistry retained by students can be vastly improved.

Teaching Chemistry with Alchemically

Alchemically is a game focused around the teaching of chemistry students utilizing the Role-Playing Game (RPG) genre. RPGs are games where the player is put into the role of someone living in a fictional setting. They are then tasked with interacting with that world, completing quests, talking to people within the world, and following a story. While not all RPGs have the feature, some feature the idea of having free will, limiting the restrictions put on the player, allowing them to play and do as they wish instead of following a linear gameplay path.

Alchemically is built with this idea in mind, creating a linear quest line, but adding side quests that players can choose to follow, and letting the player freely explore and interact with characters. The reason Alchemically is based on an RPG, is due to the unique experiences that RPGs offer. Many RPGs include crafting systems, offering players the ability to create useful items by combining components they find during their travels. This system fits chemistry really well as molecular formulas can be broken down into simpler elements, atoms. RPGs also

provide multiple ways of keeping the player motivated, which is very important in educational games, as having players decide they want to learn something rather than being forced to learn it, increases the efficiency of learning. These motivational elements that both the RPG genre and Alchemically include is a story-driven world, free exploration, and character progression. Role-Playing Games offer a unique ability to present unique and stimulating challenges and opportunities while keeping gameplay dynamic, all while being able to connect everything through a story-driven world. This is because the point of an RPG is to create an interesting world with which the player can interact. This allows Alchemically to have different methods of teaching, such as random Non-Player Characters (NPC), who might give you advice, or quiz the player on molecular formula recollection, or present situations with rewards that can further education, all while still maintaining a common narrative, and allowing the player to learn at their own pace, and through their own methods.

Alchemically takes the common concept of crafting in RPGs, and makes it the main focus of the game, allowing players to craft molecules using the periodic table of elements. In many fantasy games, the player usually fights with a weapon, such as a sword, and has skills that reflect that, or uses magic, and can, therefore, cast spells that shape the world around them. In many of these RPGs, players have the ability to craft items like potions or other concoctions, but the games are generally vague on the process behind the creation of these items, making it basically the same as magic. A player will get two or more components that vaguely resemble the end item, and put them together, magically creating this final item. For example, in order to craft a health potion, the player may only need a glass bottle and a flower. This situation ignores details such as how the flower actually heals organic matter, and any processes behind turning that flower into a potion. For the most part, these sorts of games do not teach a specific subject and are instead used for entertainment purposes. The goal of Alchemically is to change that, bringing learning into the standard video game formula, providing an experience that is both fun and educational, while keeping both aspects blended. From the

beginning of the game, the player will have access to the molecule crafting table (Fig. 1). This grid of hexagons, used due to hexagons being the common method of depiction in chemistry as well as their natural ability to fit together in an offset pattern, contains 36 slots, with 13 elements that can be used for crafting. The table is limited in size in order to limit the size of molecules so that the player does not have to spend long periods of time making molecules consisting of 40+ elements. The 13 elements were selected due to their common usage in basic and useful molecules that are simple enough to be created by a novice of the game, but also able to be used in the challenges that the game offers. The crafting system not only takes into account the elements that are present within the formula but also how the elements are bonded together. When elements react with each other, they share electrons, creating bonds between them, thereby forging a molecule (1). Some of these bonds share two electrons, creating a single bond, but others share four electrons, creating a double bond. More electrons can be shared, creating higher order bonds, but for this game, only single and double bonds will be focused on. Players start by clicking and dragging the atoms into the hex-grid, dropping them within slotted spaces in the grid. After the player adds the appropriate elements to the crafting table, they can turn on a series of buttons that appear in the top corners of each slot. These buttons represent the bonds that can be made between atoms. Lines can then be drawn between these buttons, indicating the bonds that occur between different elements and how they share their electrons. Players start off with only the knowledge they have in their head, and by progressing through the game, they will acquire more molecular formulas that will be recorded in a journal built into the game. This journal provides images and information on different aspects of the molecules, such as the name, molecular formula, molecular structure, bonding structure, uses of the molecule in the game, as well as other secondary information, such as molar mass, melting point, and boiling point (Fig. 2). By having this journal, players can look back on the information they have collected, as well as use the information as a reference for when they are crafting molecules. This journal system allows players to collect information over time, introducing the

education of chemistry at a steady rate. But even with this system, students are not limited to the molecules that the game introduces to them. If the player has previous knowledge of chemistry, they are able to explore using the crafting table. If the player knows the molecular formula of a chemical already, such as water, which is two Hydrogen atoms, and one Oxygen atom, with two single bonds, one between each Hydrogen atom and the Oxygen atom, they are able to craft it even if it has not been unlocked within the journal yet. If they do so, it will thereby be unlocked within the journal, allowing users to know if they discovered a valid molecule, as well as providing the information needed in order to learn about the molecule and recreate it at any time. This allows for a sense of exploration and experimentation, as students can try out different combinations, and have the ability to learn about new molecules through experimentation. Just as players are free to explore the environment that the game takes place in, finding new areas and new quests to undertake, they are free to explore the technical side of the game, trying out different combinations of atoms and bonds in order to see what does and does not work. This freedom of exploration helps strengthen the fun educational environment by creating a playground that the player can do as they wish with, creating the choice of what and how to learn.

In many RPGs, the player is put into the role of a person living in the world. As they progress through missions, they will level up, get stronger, and be able to complete more challenging tasks. This can create a motivation for players to continue playing so that they may become stronger, rising to the top. However, in these traditional RPGs, this task of leveling up involves making the character stronger by spending points into making the character stronger, quicker, smarter, or luckier. Alchemically takes a different approach, tying the power of your character into the collection aspect of the game and the knowledge of the player. As the player goes through the world and collects the different sections of molecular information to fill out the journal, they are becoming more powerful by increasing the number of tools that they can use. Alchemically focuses around strengthening the player by adding to the players own knowledge

rather than the knowledge of the character that the player controls. It is only by learning that the player can get stronger and climb their way to the top. As players collect these formulas, they are learning them, allowing them to craft them faster and more efficiently, making their characters stronger. This strengthening of the player is tied to the world that the player's character lives in. As the player progresses through the story, they will encounter many different NPCs that are in need of assistance, some early on, and others much later. These quests usually involve the player crafting some sort of molecule in order to help the citizen. The player may not have the power to help the citizen when first met. This creates the motivation for the player to progress through the story and find a means to complete the quest. This further defines the free exploration aspect of the game as players can approach these NPCs and embark on their quests whenever they please, and can acquire the knowledge in order to complete them however they want, whether it be by following the game's storyline and gathering the information, or experimenting until the player finds the information on their own.

The game places the player in control of an Alchemist-in-training who encounters difficult situations as they learn to harness the elements in order to create concoctions used to change their surroundings. The player starts off on an island, not knowing what is going on in order to help set up the story, encouraging the player to talk to the nearby person, Lajos. Lajos has an exclamation mark floating above his head, a common trope in RPG games, indicating that he has something to say to you, or more specifically, a quest, a task for the player to do with a possible reward. Players are presented with a few choices here. They can either click on the man in order to talk to him or continue along the road, having no restrictions in doing so. By continuing along, they do not get two of the formulas that they would get by talking to Lajos, making learning the system, as well as the following challenge, more difficult. However, that is the only effect, and the player can continue along just as well, allowing for a larger sense of player freedom. If the player does decide to talk to Lajos, he tells you that he will teach you the practical application of Alchemy. When the player speaks to him again, a video is triggered

which goes through the steps of using the journal to look at a molecule's information, and the entire crafting method, explaining each step. Once the video is over, the player gains control of their character again. At this point, from observing previous testers, players will follow the video's example, and craft a vial of water. If they walk towards the campfire, another video will trigger, explaining how to use the inventory and action bar in order to use your crafted molecule. The video directs the player into putting out the fire through this system explanation. A consistent response from players has been to replicate the video, thereby putting out the fire and finishing the quest.

The reason that videos were used in order to teach the mechanics of the game is due to trial and error of educational structures. In the early stages of Alchemically, when players would speak to Lajos, a large text box would come up, explaining the situation and how to craft water. However, through observation and feedback, players quickly got bored or overwhelmed by the amount of text. A video was implemented in order to create a more engaging way of learning. Players responded much better to a video format of teaching rather than text, likely because the combination of visuals and audio created a more interesting experience, as well as having a walkthrough of the process made it easier to remember. This introduction was also split up into two sections in order to allow players a break. Once players watch a tutorial video, it was likely that they would reenact the video's example. By presenting all of the information at once, it can overwhelm players, causing them to forget certain key aspects. This way, players will watch the video about how to craft, practice crafting to solidify the knowledge, then watch the video on how to utilize the molecules, again practicing afterward.

After putting out the fire, players can return to the man, as indicated by the exclamation mark over his head. He will explain to the player that it would be a good idea to seek out the town and see if the residents need any help. He also explains that a bog in between the current location, and town, has turned acidic, and gives you a formula that can help get past this obstacle. This new molecule is Hydroxide, a molecule with a simple formula, that acts as a base

for some cleaning agents, such as Lye and Potassium Hydroxide. The reason this molecule is given to the player is due to its basicity on the pH scale. As such, due to the acidic nature of the bog, the interaction of the hydroxide with acid would create a neutral substance, water (19). The reason that this interaction is so important in the game, is because it creates a whole new set of questions that kids can be curious about without having it forced upon them, and can allow for new scenarios to be taught about, such as acid rain, or the inclusion of acidic mine drainage from the local mine. While not all players will seek out further information, it still presents the concept of an important chemical reaction, allowing for further explanation. As players head along the available path, they reach the bog, which is portrayed by water with large green clouds emitting from it, a common game depiction of something that is acidic or poisonous. As the player approaches the bog, a final video will play, showing the player run into the water, and taking damage. This is to show that the player is still vulnerable, and misuse of the world or tools can result in damage and failure, but that these obstacles can be overcome. This video shows that there is another aspect to the game, giving the players the idea that these chemicals can be dangerous. Based on this video as well as the information presented to the player earlier, the player is given enough information to learn that by using the Hydroxide molecule, the bog will be safe to pass through. This starting sequence is an efficient way to get the player familiar with the basic mechanics of the world.

With the open space that the island offers, players can understand how to perform basic game operations like moving and interacting with objects. The player is presented with the opportunity to learn the crafting system through the use of tutorial videos, but they are not forced into this. A large part of education is the idea that students learn at different paces and have different methods of learning. For some, these videos will be the most efficient way to learn, even being able to rewatch some of the videos if needed. But for other students, watching a video, even only a 40-second one is not something they enjoy doing and would rather figure out the system through experimentation.

Upon safe passage of the bog, the player has access to a more open area, with multiple quests available to the player. The road splits in two after the bog, the first path leading to town. While traveling to town, the player will encounter a book that provides the information for the Hydrochloric Acid molecule. In town, the player will encounter two quests, one of which entails a man looking for some TNT in order to help with his mining company, the other being a law enforcement agent telling the player of some out of control robots, saying that the player should talk to the scientist Rira in order to deal with the situation. Down the second road, the player will come across a fallen tree and a man trying to chop it down so he can make a delivery on time. The player can use the Hydrochloric Acid to corrode the tree, earning the mans thanks who provides the formula for Nitric Acid. Continuing along, the player comes across Rira, a scientist and inventor residing on the island. She informs the player that her creations have experienced a glitch and are running around, and requests help in catching them. She then guides the player through the steps of making Rubber Cement, requiring the player to craft Isoprene that Rira can refine into Rubber, then having the player craft Toluene, so that it can be combined with the Rubber to create the Rubber Cement. This chain of quests introduces an important concept, that molecules can be used to build off of each other. These molecules all are based around a carbon ring, allowing players to get a sense of how these molecules build off of each other, and how to break them down to assist with memorization of large structures. She tells the player that they must first break the armor of the robots, giving the formula of Iron Oxide, also known as Rust, and then use the Rubber Cement to immobilize them. Just by the beach are the four robots who run away from the player as the player approaches. This quest introduces a combat-like challenge, creating the need for quick thinking in a dynamic challenge.

Upon ensnaring of all four robots, Rira tells the player that she is looking to get off the island, but needs some help doing so, and tells the player to meet her across the river behind the town. The player can find her again by following her or finding her later by going through the passageway behind the town. Along the way, the player will experience two other quests, one

asking for fertilizer for the island's crops, and another asking for medicine to help an injured man. Ammonia, an important chemical in fertilizer, can be crafted to finish the former quest, but in order to create Aspirin in order to help the injured man, the player must talk to Rira again, who offers to craft it through the use of Acetic Acid and Salicylic Acid, gathered from willow tree bark. This information introduces the knowledge of how some of these molecules can be acquired in real life through alternative processes. Rira also can help the player learn to craft TNT through the use of Toluene and Nitric Acid, presenting another example of molecular deconstruction, as a structure made up of a Nitrogen atom and two Oxygen atoms can be found in Nitric Acid, as well as TNT, allowing players to better understand the construction of the large molecules, and showing how players can use this knowledge to help with memorization by breaking the molecule into pieces. Rira is looking to get off the island through the use of a blimp-like vehicle, requiring the player to craft Rubber once again in order to finish repair on the balloon. The player must also create Helium gas, showing that elements by themselves have uses. With these requirements fulfilled, the player and Rira can leave the island, ending the demo. This narrative journey gives the player something to work towards, giving them goals instead of letting them loose in an empty playground. In order to achieve goals in games, there generally needs to be some sort of difficulty or conflict. While the mission to capture the robots does as a sense of conflict due to them running away from the player, the rest of these missions do not create much conflict. Instead, Alchemically creates this difficulty through the mechanics of the game itself. The difficulty comes from remembering how to craft certain molecules, which helps the player become more invested, and learn along the way.

The whole system is built around the idea that players can learn at their own pace, without the idea that they should be learning, becoming an overbearing burden on them. The students should still have fun learning chemistry through the game, integrating the educational aspect through a means that further improves the gameplay instead of hindering it. The crafting system is focused around exploration, allowing the player to craft any formula at any time, as

long as they know the molecular formula, either through previous knowledge or through discovering the formula through in-game quests.

A video game provides a set of goals for the player to accomplish and gives them the means to complete them. In Alchemically, the player's first challenge, if they chose to undertake it, is to craft a vial of water using the molecular crafting system. The quest-giver displays a video for the player, walking them through the full process of looking at the information on water within the journal, crafting the water molecule in the crafting table, and using it to extinguish the fire. Water is one of the first molecules taught to kids, so many people know the molecular makeup of water is two Hydrogen atoms, and one Oxygen atom, but actually putting that knowledge to use, selecting the correct elements, and drawing the correct bonds between each element, can be a different and challenging experience. While students likely won't have much difficulty crafting water due to the tutorial and the simplicity of the molecule itself, as the game progresses, more complicated molecules become available. These molecules can contain many different elements and many different bonds, which can be hard to memorize. But the goal of this game is that through the repetition of creating these molecules, players will learn to see patterns and groups within these molecules, breaking them down, allowing for better memorization as well as a more fundamental understanding of molecular makeup. An example of this is Trinitrotoluene, commonly known by the abbreviation TNT. TNT is a common tool found in many video games, such as Minecraft, due to it being commonly known, as well as being a relatively safe explosive device, requiring a much more deliberate trigger to set it off. The player is first introduced to TNT in Alchemically by crafting it through a chain of crafting smaller molecules that can be combined to create TNT, which unlocks the information on the molecule within the journal. The player can also craft the molecule to unlock the information if they already know the molecular makeup. In the town, a man presents a quest to the player, asking for some TNT in order to assist with some mining that he is doing, as his drill broke. When players first take a look at this molecule, it can be quite overwhelming. During observation

when kids from different age groups playtested the game during the Virginia Tech Science Festival, those who found the tome and looked at the molecule, generally had a surprised look on their face. However, of those who discovered it, a majority tried making the molecule (albeit with some assistance from the project's attendants). The assistance that we provided the kids, was talking them through the breaking down of the molecule into simpler parts, something that Alchemically was later developed to do more independently. The reason that this molecule was included within Alchemically, besides the earlier explanation of it being a common tool in video games, is because of the organized structure. The molecule is built out in a relatively symmetrical way, allowing for easier memorization, and also has very distinct components that can be broken down into multiple groups, allowing for multiple, clearly-defined steps in the creation of the molecule (Fig. 3). A ring of six carbon atoms makes up the inner skeleton of the molecule, connected by alternating single and double bonds. Attached to this ring are 4 branches, as well as two hydrogen atoms. The first branch is one made up of a single carbon atom and three hydrogen atoms, with only single bonds. The other three branches are Nitro groups, made up of one Nitrogen atom and two Oxygen atoms. Since these are all the same, it means that almost half of the molecule can be memorized through the knowledge of a single, simpler group or branch. The use of this molecule, providing a fun tool to play with within the context of the game, also allows for the teaching of how large molecules can be broken up into smaller, easier to remember, sections. With the current standing of Alchemically, the size of molecules is restricted, but as the project develops, the creation of larger molecules, such as sucrose, a sugar, the molecular formula of which is $C_{12}H_{22}O_{11}$, will be explored through the use of these smaller groups acting as building blocks. A system where students would start out with smaller molecules, such as Hydroxide (HO), or nitro groups, and through mastery of those, can then use them as fundamental building blocks, just as they would with single atoms. This would allow for quicker creation of large molecules such as sugar, which uses multiple hydroxyl groups, while still keeping the same level of education, potentially improving memorization.

Ethical Issues in Education

Alchemically has changed a lot over the development of the game, but one of the largest changes has been to the combat system within the game. Alchemically is a game heavily inspired by Dungeons and Dragons, a game with is focused around exploration, diplomacy, and combat. Players face all manners of threats, ranging from goblins, dragons, slimes, and bandits. As such, a combat system was initially introduced within Alchemically to give it that fantasy combat feeling, saving yourself and others from those that wish harm upon you. Players could use the molecules within the game to subdue enemies, as well as solve problems around the world. However, this brings up the question of ethics in schools. As Alchemically is a game that's purpose is to be used in schools, it must follow a policy that is fit for schools. When combat is present within the game, the question arises of "Should students be taught how to use chemicals in order to harm living beings?" Overall, the answer to this question, in the context of a game meant to be used in schools, is "No". Schools should be teaching students how to use chemistry in order to help the world. The next question that this can create, however, is "To what capacity is a being ethically okay to harm or subdue?" This question is what brings Alchemically towards its current state. There are many aspects that are taken into account when trying to determine if something will create empathy when it has been brought harm, but two large aspects are if it is humanoid in shape and if it has a face. The Boy Scouts of America is an organization that is meant to train kids in character development, responsibility, and self-reliance. In doing so, they teach kids different skills, some of which include safe use of firearms and other ranged weapons. However, while they are within the organization, they are only allowed to shoot at targets that are neither living nor human representations. This includes any events that involve any sort of ranged weapon, real or fake, including laser tag and paintball. Historical reenactments can be allowed but only in the case of the weapons being aimed over the head of the reenactment participants (8). With these ideas in mind, the combat system

within Alchemically was not removed but instead changed to create nondestructive challenges. In Alchemically, one of the quests that the player must do is to help the scientist Rira capture her robots that went out of control. In order to do this, the player is tasked with breaking their armor using molecules such as rust and then stopping them from moving using rubber cement. By using this method, it addresses the two main issues. First, the robots are not humanoid, and are more akin to floating boxes, allowing for the players to distance themselves from the characters. Second, and most importantly, the means of completing the quest are through non destructive means. While the player does have to get rid of the armor of the robot, this is purely for the gameplay mechanic side, and the character is not supposed to actually harm the robot. Rira states to the player that she wants them all to be unharmed, as she can fix them up as they have been subdued. The player is shown how to create Rubber Cement because it acts as a strong non destructive adhesive which can be used to stop the robots. If the player decides that they instead want to destroy the robots, they are able to do this, but the quest will not be able to be completed. This solution works for the goals of Alchemically, allowing for the challenge of a combat-like situation, but not encouraging the use of chemistry for destructive means.

If players are allowed to use molecules in whatever way they want, this can create some interesting situations. As players acquire the knowledge for more destructive molecules, such as Hydrochloric Acid, some of them may want to use these molecules on NPCs around the world. As Alchemically stands, this action is allowed. Players can use these molecules on the characters of the world, and the molecule's effects will occur. However, this has consequences. Each character has two types of status bars, an armor bar, and a health bar. If a player uses a molecule to damage the NPC, the armor bar will be affected first, not hurting the character, acting as more of an annoyance or inconvenience. This will cause the NPC to talk to the player, telling them to be more careful, as these molecules can be dangerous, but otherwise acting normally around the player. However, if the player continues this action and manages to inflict damage upon the NPC that drains the health bar, the NPC will talk to the player, demanding

that the player leaves them alone. If the player tries to talk to the character anymore, the message will be repeated, and any quests that the NPC had will be locked off. This can have some heavy consequences for the player, as it can halt progress and cut off rewards, deterring such action. This system was created in order to allow for the feeling of free-will. Players can explore and use these molecules in order to learn what they can do. But they are also taught how to use these molecules for beneficial purposes by employing consequences similar to real life, as hurting someone will likely cause them to not talk to you. Alchemically approaches this ability to explore in a way that allows freedom, but uses it to teach proper ways to utilize chemistry.

Future of Alchemically

Alchemically is already a working and entertaining educational game, but it has a lot of potential behind it. Other beneficial features can be implemented in order to further improve the learning experience. As it is, the crafting table is a set size, allowing for the creation of complex molecules, but also limiting the player so that they do not have to spend large amounts of time constructing a single molecule. However, by limiting this, you are also cutting off some incredibly important substances, such as sugar ($C_{12}H_{22}O_{11}$). While making the crafting table an “endless” map, allowing for plenty of space for countless atoms, this only fixes half of the problem. In order to drag 45 elements onto the crafting table, then create bonds for each, a large amount of time would have to be taken, drawing the player away from the game, and causing them to become irritated or bored. A better method would be to allow players to build with structures alongside single atoms. Sugar is a complex molecule, but it is in fact made up of two simpler molecules, glucose and fructose (14). By allowing a player to build out these simpler molecules, and save them to a template, allowing them to place them again as a single structure instead of needing them to rebuild, it offers multiple benefits. Firstly, players do not have to spend enormous amounts of time creating the large molecule multiple times. Secondly,

it allows for the exploration of much larger molecules. Thirdly, and potentially most importantly, it teaches students about multiple molecules, and how these molecules interact and can build off of each other. Because larger molecules are generally made up of smaller molecules that bonded or interacted in some capacity with each other, students need to learn this. It not only helps students better understand the world of chemistry and molecular interaction but also help with memorization once they learn the smaller parts, such as TNT being made up of a carbon ring as well as three nitro groups.

A way for the players to learn these molecules, memorizing them, but while keeping a good balance of learning and play, would be to add a progression system for each molecule. As a player crafts a molecule, the progress on that molecule will fill. Once the progress bar is filled, the player will be able to craft that molecule without having to remake it. This would allow for another goal that players can work towards. A question that is created in this scenario would be if this sort of method would cause players to learn the molecular formula, but only temporary, forgetting the information once they are allowed to automatically craft the molecule. A way to fix this potential problem could be an ammo-based system. The progress bar works the same, but once it is filled, it only allows ten or so automatic crafts before it resets, needing the player to fill the bar again, but in a shorter amount after each consecutive refill. This way, players would have a goal to work towards, but would need to refresh their knowledge after long periods of time.

The world is also an important part of Alchemically. In order for players to better understand what these molecules can do, a more dynamic world is needed in order to have more interactions. If players can understand what these molecules can do just by using the world as an open sandbox, it can be very beneficial to the learning process.

Conclusion

Chemistry can be a difficult subject to learn due to its need for analytical thinking and memorization. But by creating a fun learning environment, even this difficult subject can be learned. Alchemically is a game that helps create this fun learning environment by creating an engaging game that has players craft molecules. By having players craft molecules repeatedly, the game can help with the memorization of molecular formulas, and by having players utilize these molecules to overcome obstacles, players can better understand what these molecules do, and how they can be used. While the primary educational goals of Alchemically are the memorization of molecular formulas and learning about their structures, and the understanding of these molecules uses, there are also secondary educational goals, such as being aware of molecular attributes like molar mass, melting point, and boiling point, or understanding how larger molecules can be deconstructed into smaller components. These secondary educational goals are not needed in order to progress through the game, unlike the primary information, but are still available for those who want to learn more. Alchemically utilizes many different teaching methods, each having their own strengths, to help students learn, such as trial and error, practice and feedback, and lecture, allowing for a variety of methods to help kids learn the subject. Intrinsic and extrinsic motivations are used to keep players engaged, such as the feeling of accomplishment and the ability to complete a collection respectively. Having a story combined with the ability to freely explore also keeps players engaged in Alchemically. Overall, Alchemically has shown itself to be a fun and engaging learning tool, helping people of all ages learn chemistry and memorize molecular formulas.

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Figures



Fig.1. Crafting Table

Water

Chemical Formula:

H_2O

z

Molar Mass:

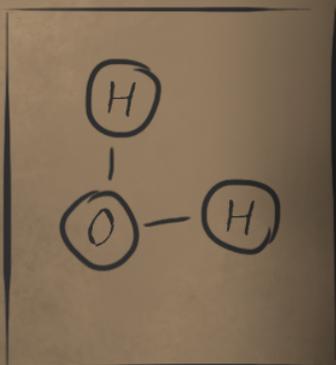
18.01528(33) g/mol

Melting Point:

0.00 °C (32.00 °F; 273.15 K)

Boiling Point:

99.98 °C (211.96 °F; 373.15 K)



Effects

Extinguishes fires

Fig. 2. Journal Entry

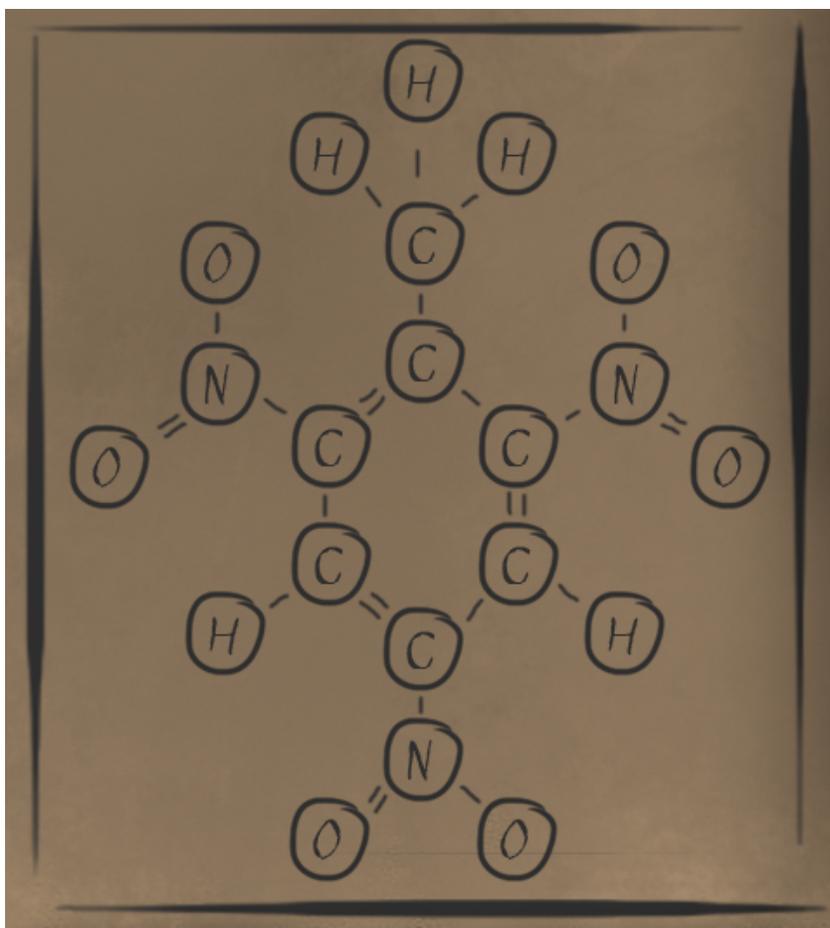


Fig. 3. TNT Molecular Structure

Bibliography

1. 9.1: Types of Molecular Bonds. (2016, November 1). Retrieved September 23, 2018, from [https://phys.libretexts.org/TextBooks_and_TextMaps/University_Physics/Book%3A_University_Physics_\(OpenStax\)/Map%3A_University_Physics_III_-_Optics_and_Modern_Physics_\(OpenStax\)/9%3A_Condensed_Matter_Physics/9.1%3A_Types_of_Molecular_Bonds](https://phys.libretexts.org/TextBooks_and_TextMaps/University_Physics/Book%3A_University_Physics_(OpenStax)/Map%3A_University_Physics_III_-_Optics_and_Modern_Physics_(OpenStax)/9%3A_Condensed_Matter_Physics/9.1%3A_Types_of_Molecular_Bonds)
2. GDC. (n.d.). *Classic Game Postmortem: Oregon Trail*. Retrieved from https://www.youtube.com/watch?time_continue=25&v=vdGNFhKhoKY
3. Gee, J. P. *What Video Games Have to Teach us About Learning and Literacy* (Palgrave MacMillan, 2003).
4. KerbalEdu - Teaching. (n.d.). Retrieved November 10, 2018, from <https://kerbaledu.com/teaching>
5. Metaari: Game-based learning market will reach \$17 billion by 2023. (n.d.). Retrieved November 30, 2018, from <https://www.gamesindustry.biz/articles/2018-08-08-metaari-game-based-learning-market-will-reach-usd17-billion-by-2023>
6. Mozelius, Peter. (2014). *Game Based Learning – a Way to Stimulate Intrinsic Motivation*. Proceedings of the International Conference on e-Learning, ICEL.
7. Rikki. (2015, March 24). *Typing of the Dead Overkill* [Text]. Retrieved November 4, 2018, from <https://www.sega.com/games/typing-dead-overkill-0>
8. Shooting Sports. (n.d.). Retrieved November 13, 2018, from <https://www.scouting.org/outdoor-programs/shooting-sports/>
9. Sirani, J. (2017, May 31). *GTA Publisher Acquires Space Sim Kerbal Space Program*. Retrieved December 8, 2018, from <https://www.ign.com/articles/2017/05/31/gta-publisher-acquires-space-sim-kerbal-space-program>

10. Smaldone, R. A., Thompson, C. M., Evans, M., & Voit, W. (2017). Teaching science through video games. *Nature Chemistry*, 9(2), 97–102.
11. Solve Puzzles for Science | Foldit. (n.d.). Retrieved November 10, 2018, from <https://fold.it/portal/>
12. Tekinbaş, K. S., & Zimmerman, E. (2003). Rules of play: Game design fundamentals. Cambridge, Mass: MIT Press.
13. The Oregon Trail Game's Minnesota Roots. (n.d.). Retrieved November 4, 2018, from <http://www.wbur.org/hereandnow/2016/05/17/oregon-trail-roots>
14. The Sucrose Molecule. (n.d.). Retrieved November 11, 2018, from <https://www.worldofmolecules.com/foods/sucrose.htm>
15. Trial and Error Theory: Experiments and Limitations | Learning. (2016, November 5). Retrieved November 8, 2018, from <http://www.psychologydiscussion.net/learning/learning-theory/trial-and-error-theory-experiments-and-limitations-learning/2499>
16. TypeRacer - the global typing competition. (n.d.). Retrieved November 4, 2018, from <http://play.typeracer.com>
17. University of Texas at Dallas. (2017, February 15). Learning chemistry within Minecraft video game. *ScienceDaily*. Retrieved August 19, 2018 from www.sciencedaily.com/releases/2017/02/170215084111.htm
18. University, S. (2013, March 1). Using games as an educational tool provides opportunities for deeper learning, panelists at Stanford event say. Retrieved November 10, 2018, from <https://news.stanford.edu/2013/03/01/games-education-tool-030113/>
19. pH and alkalinity. (n.d.). Retrieved November 8, 2018, from <https://www.lenntech.com/ph-and-alkalinity.htm>