Title
A Molecular Construction Game Based on Principles from Game-Based Learning Sciences

Author
Johnson, Brittany Ann

Publication Date
2023-09-19

UNIVERSITY OF CALIFORNIA, MERCED

A Molecular Construction Game Based on Principles from Game-Based Learning Sciences

A Thesis submitted in partial satisfaction of the requirements for the degree of Master of Science

in

Cognitive and Information Sciences

by

Brittany Ann Johnson

Committee in charge:

Professor Jeffrey Yoshimi, Chair

Professor Zenaida Aguirre-Munoz

Professor Colin Holbrook

The Thesis of Brittany Ann Johnson is approved, and it is acceptable in quality and form for publication on microfilm and electronically:

Zenaida Aguirre-Munoz

Colin Holbrook

Jeffrey Yoshimi, Chair

University of California, Merced
2023

Table of Contents

List of Figures

Acknowledgements

I would like to thank my family for their endless support and sacrifices which allowed me to continue my education. Your constant belief that I would succeed inspired me to always fight through adversity, and for that I am forever grateful.

I would also like to thank my committee members Dr. Zenaida Aguirre-Munoz and Dr. Colin Holbook for their useful insights and guidance throughout my project. I extend my gratitude to my committee chair, Dr. Jeffrey Yoshimi, for believing in me and accepting me as a student. I am fortunate to have received his mentorship throughout both my project and graduate school.

Abstract

A Molecular Construction Game Based on Principles from Game-Based Learning Sciences

by Brittany Ann Johnson for the partial satisfaction of the requirements for the degree of Master of Science in Cognitive and Information Sciences, University of California, Merced, 2023

Dr. Jeffrey Yoshimi, Chair

Education games are becoming increasingly popular with advancements in technology, making educators consider their effects in the classroom. In STEM education, where concepts can be complex, the emergence of new methodologies to teach students the intricacies of science have been examined. This thesis overviews best practices in the design of educational games, drawing on insights from citizen science, gamification, and education research. A prototype game is presented and a set of lessons described, which can be used to teach students about molecular biology, specifically RNA.

Introduction

Video games have been embedded in our society for decades, providing entertainment to game players yearning for competition, enjoyment associated with incrementally solving puzzles, as well as other motivations that keep players engaged (Vorderer et al., 2003; Schoenau-Fog, 2011). There are many genres of video games used for different purposes. Some games tell a story, some have a player solve a mystery, some allow them to compete with friends. In the field of education, ways to use games to change how students learn material have been debated, however supplementing traditional lectures with new, game-based ways of teaching material to students has been associated with increases in student engagement and interest (Barata et al., 2013).

Applying traditional video game methods to educational games, where students are instructed to learn material by playing an assigned game, only partially encapsulates the processes necessary to construct an effective educational game. As educators and game designers collaborate to produce educational games, challenges have arisen. Designers aim to create games that engage students and improve retention over traditional lectures. Combining methods from multiple fields, such as education, video game design, the psychology of motivation, and other areas can produce better educational games by identifying appropriate methods for specific educational contexts (Ahmad et al., 2019).

In this thesis I review the impact of integrating citizen science practices with gamification principles and consider how this merger can be used to design educational games. I propose a game based on a prototype simulation that I helped develop, which can be used to teach concepts in molecular biology. Section 1 provides an overview of the methods of gamifying a scientific process and highlights attributes that can be applied to an educational game. Section 2 reviews games in the realm of education, describing considerations and mechanisms that have been shown to be effective for game design in education. Mechanisms include fully guided instruction, effective gamification, and aligning learning goals with the structure of a game. Section 3—the core of the thesis—develops a prototype for a new molecular biology game that applies the concepts outlined in the first part of the thesis in an extended and realized example. It is a web-based game that is widely accessible and can be used by students to learn the basics of molecular biology. Four lessons, or levels, are proposed to aid in learning RNA and its functions. The first lesson uses definition-matching to help students focus on essential terms to learn the basics of RNA. Lesson 2 transitions into learning the primary structures of RNA, such as its nitrogenous bases, so students can learn how bases interact to form different bonds. Lesson 3 demonstrates the nature of RNA bonds and how they can attract towards each other or repulse away from each other, showing the different properties within the structure. In lesson 4 students enter a free play level to build structures and explain how the interactions work in the RNA strand they created, encouraging discussion in the classroom. The section concludes with future directions for the game, including more complex physics lessons, which can then be translated into a gamified version to aid in students learning challenging and rigorous scientific concepts.

1. Gamifying Citizen Science Methods and Science Education

This section first introduces citizen science, which involves everyday citizens participating in scientific tasks. Simulations are sometimes used that show how scientific concepts can be embedded in game-like environments. I then discuss gamification, describing key frameworks and methods. Gamification can be used to motivate game players and students. The next subsection focuses on student motivations and suggests ways to maintain player engagement. Lastly, I consider how methods from these areas can be helpful when building an educational game.

1.1: Citizen Science

Citizen science can be defined as scientists recruiting volunteers to participate in science (Vohland et al., 2021). Traditional scientific practices typically occur in lab settings. Citizen science projects break down the barrier between science and the public and allow volunteers to participate in science outside of the lab. Collaboration between scientists and volunteers can facilitate scientific advances.

An example of citizen science is Foldit, a computer game released in 2008 with a main goal: advance prediction of protein structure and user-built predictions to extend player's understanding of uniquely generated protein functions. In biochemistry, it is difficult to understand the information the protein's function provides, because protein structures exist as macromolecules, which are microscopic and undetectable to the human eye. Foldit's developers recognized this issue and gamified the process of protein folding to contribute to understanding these mechanisms in new and refined ways. By building this software, developers have also enhanced the learning of this content by generating opportunities for students to learn biochemistry at a more accessible level.

Foldit developers used gamified methods to create their protein folding game, demonstrating tools that can be translated into an education game. Color-coded areas on the protein simulation mask the complexities of the structure while keeping the system's integrity intact, which can be used in the classroom to teach students the basics of protein folding in a visually intuitive way. As you pull the sheets and helices of the protein around some actions produce a higher score and others produce a lower score, which gives a sense of what functional proteins are folded like.

Foldit has yielded positive results for students from different classrooms and universities. In a study of university students interacting with Foldit in their biochemistry course, 100% of surveyed students reported an increased understanding of protein folding due to playing the game (Farley, 2012). Another class incorporated Foldit into lab sessions, where 100% of students surveyed also reported Foldit to be helpful in the understanding of protein folding and class material (Achterman, 2019). Integrating Foldit into the lesson plan can aid students in learning complex structures of protein folding.

Potential benefits of Foldit include providing different learning experiences and opportunities for students. Traditional learning of biochemistry and protein folding do not incorporate visuals like Foldit that the user can manipulate. This interactive interface allows students to further enhance and preserve information learned in the classroom by alternately interacting with the material. Another benefit is the increase in student attitudes on the subject. In a study measuring the interactions and understandings of protein folding using Foldit, students described how working on real-world problems while learning class material increased motivation to play and enjoyment, overall increasing engagement in the material (Franco, 2012).

1.2: Gamification

In its most basic form, gamification adds game elements to something that did not have game elements before. Game elements are characteristics of games such as points, badges, and leaderboards (or "PBL"). These items incentivize game players to get maximum points, play to earn badges based on specific acquired skills, or see how they match up to friends or other players on a leaderboard (Huang & Hew, 2015). Other elements can also be incorporated into games to keep players engaged, such as theoretical structures that promote continuous gameplay, such as "progression stairs." Progression stairs onboard players with introductory levels, then create opportunities to build upon skills in preparation for harder levels, and sometimes culminate in a hardest "boss" level. In this way players can incrementally develop skills as they move from one challenging level to the next (Werbach et al., 2012). This keeps players balanced between easy and challenging activities. If players believe a level is too easy or difficult over multiple sessions of play, there is a higher likelihood they will disengage and lose interest. Keeping games balanced, with a mix of easy, hard, and moderately difficult levels, sustains player engagement at a higher frequency than favoring one difficulty (Andrade et al., 2006).

A fundamental component of gamification is an interactive interface. Some games allow a player to navigate a world freely and explore. Others allow the game player to learn about a system by manipulating items in a virtual world. An interface can include a virtual avatar, which helps players navigate the game and gain an understanding of what actions are expected of them. The avatar can help direct an individual through a game and give hints when needed (Malone, 2018). This additional assistance is essential for elevated human-game interaction on a computer as it helps the human navigate the system and supports them when they feel stuck. Assistance from a virtual avatar can present itself as feedback on a game given from a talking-head, as shown in Figure 1.

Figure 1. Talking head instructing players how to navigate a game.

In the game shown in figure 1, the virtual avatar is a cartoon woman, helping the player understand the space and the consequences in the specific environment, which in this case is tax rates and budget items for taxpayers in a simulation of the United States (iCivics, 2022). This educational game is made to teach students different aspects of what the government is responsible for in the United States, which can become increasingly complex as students navigate different budgets.

1.3: Motivation

In order to maintain player engagement, game elements can be modified to increase the likelihood that players will play the game again. Thus it is important in game design to focus on motivation. One theory that can be used to understand levels of motivation is Self Determination Theory (Deci & Ryan, 2012). There are two main types of motivation: intrinsic and extrinsic. Intrinsic motivation stems from personal interest, while extrinsic motivation requires an external motivator, such as a reward or incentive. Extrinsic motivation is difficult to maintain due to requiring an external motivator, which is less consistent in one's environment. Intrinsic motivation, rooted in one's personal interest to fulfill a specific action, is more likely to sustain ongoing motivation compared to extrinsic.

In the context of a science game, intrinsic motivation can promote a strong connection between the player and their efforts in a game. With a genuine interest in the game and its purpose, an individual may want to continue playing and complete harder tasks as the game progresses. It may also influence the degree which students want to learn material. In a study of undergraduate students in Southern California, students were given number puzzles—cards that had multiple equations on them to solve—to complete and were asked to choose which puzzle they would want to do (Inoue, 2007). The study indicated students with higher individual interest in the number puzzles chose more complex puzzles, while students with lower individual interest did not. Interest in the game and the subject lead students to choose cards that were harder to complete due to wanting a challenge and enjoying problem-solving tasks. Results from this study show the impact of personal interest on students' motivation to learn and solve problems in the classroom.

Adjusting the difficulty of concepts is also important when designing a game. If scientific concepts in a game are too difficult to understand, it can discourage someone from playing it. One way to solve this issue is to conceal the science with a more straightforward interface that does the same functions but with more appealing aesthetics and less intimidating concepts. For example, Borderlands Science, shown in Figure 2 (right) took the game Phylo (left) and added more gamified elements, disguising the science in a Tetris-like game.

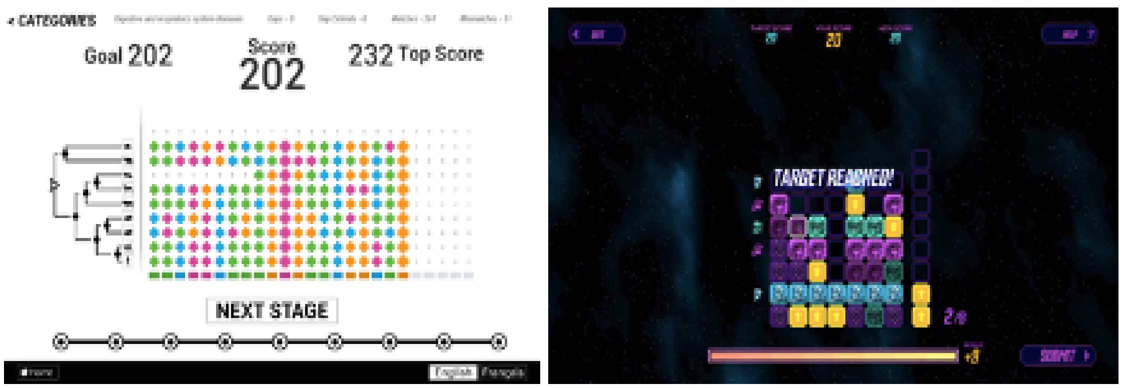

Figure 2. Citizen science game Phylo's (left) purpose is to solve the Multiple Sequence Alignment problem by interpreting DNA and identifying new genes. Borderlands Science (right), a mini game within Borderlands 3, attempts to solve the same problem with more engaging and gamified aesthetics.

By disguising the science elements, players can feel more comfortable interacting with the interface. It also includes more engaging aesthetics, incentivizing a player to continue playing. Pairing theories of motivation with gamified methods creates an environment that can strengthen player engagement and interest.

Concepts in gamified citizen science, addressed above, can be integrated into the development and design of an education game. Games allow students to learn about a system not just by passively reading about it or viewing it, but by manipulating it in a virtual world. Progression stairs can be utilized to create a balance between easy and challenging levels to construct valuable skills and to stay engaged. Masking difficult concepts with a game interface that replaces scientific images with game aesthetics can make learning concepts more appealing. The open nature of some games can allow students to participate in creative thinking processes without being intimidated by the system's complexity. Ideally a game captures students' intrinsic motivations, creating an experience that they want to engage in for its own sake, rather than just for a grade.

2. Game Design with Education in Mind

This section discusses how games can be incorporated into education. Fully guided instruction and gamified motivation can encourage students to interact with the material with increasing success. The context of a game and how it is presented to students is analyzed. The section concludes with suggestions on how to align learning goals with games in ways that promote learning and engagement.

It has been shown that students can retain information at an increased rate when information is presented in a game format compared to standardized lectures (Farley, 2013. Introducing games into educational settings can increase student involvement when topics get complex (Barata et al., 2013). Effective educational games intrinsically motivate students, increase participation, and enhance learning (Paras & Bizzocchi, 2005; Small, 1997). Video games are popular for people of all ages, especially adolescents. However, key steps must be taken to develop a game that successfully educates and engages students. Given a game's planned educational context, it is suggested that developers adopt specific motivators, structured information, and presentation to attempt to improve the educational experience for students.

If a game is too education focused students can lose drive and motivation to play (Nicholson, 2013). However, a game designed to be more entertaining and less educational will be less effective in completing educational goals, such as retaining information. The challenge for the game designer is to find a balance between design features targeting learning goals and promoting a fun and open environment.

2.1: Adopt Fully Guided Instruction

According to pedagogical research, adopting fully guided instruction, where an instructor explicitly directs students through material to create foundational knowledge, enriches a student's ability to learn and understand new material (Clark, 2012). When students are learning novel concepts, employing explicit instruction such as clear objectives, guided practice, and informative feedback can limit the potential for ambiguity. Instructors using fully guided instructional methods can incorporate games into their lesson plan to solidify the understanding of new concepts.

Integrating games has shown positive benefits to student's experiences with new material and how they retain presented information in STEM education (Gutierrez, 2014; Jones et al., 2019). It is recommended that educators do not depend on games to deliver in-depth lessons to their students but instead are advised to use them to supplement learning. When there is an opportunity to have a game supplement learning, it ought to reinforce ideas that the student is learning or will be learning in more detail. Relying solely on the game's information without an integrated lesson plan will result in the student's education transitioning from fully guided instruction to partially guided instruction, where the instructor is less active in teaching the lesson, requiring students to use prior knowledge to solve a problem (Clark et al., 2012). This type of instruction is most appropriate for learners who have foundational knowledge of the concepts and/or skills targeted by the game, not students learning new material.

2.2: Consider Effective Gamification Methods

Using gamified motivation tactics can either motivate students or have adverse effects depending on what methods are applied (Whitton, 2007). Depending on what is being taught, select gamified motivation strategies could benefit or harm a student's participation and learning experience. For example, the most popular motivation tactic in games is a PBL (Points, Badges, Leaderboards) approach, which can motivate players by competing with others to get the most points and to be first on the leaderboard. A traditional PBL approach may be a drawback in an educational setting, as it can demotivate students due to the game's competitive nature (Domínguez et al., 2012). Learning can be challenging and uncomfortable, especially when concepts are not fully understood, so adding competition where students can see how they compare to their classmates can cause dissatisfaction with themselves, lack of motivation, and decreased likelihood to continue play. A way to navigate this is to keep some elements while abandoning others to refine the learning environment. If using the game to supplement an in-class assessment and a learning experience, points and badges can be of value to show students' progress in the game without making it overly competitive. Generating a receptive and supportive environment for students will enable them to finish the game without negative pressures regarding how they compare to other students, leading to motivated play and active participation.

2.3: Align Goals with Game Elements

It is recommended that learning goals are aligned with the intended use of a game to increase the likelihood of success in game-based learning. It is valuable to brainstorm ways in which students can gain positive benefits from the game, given the learning approach an educator takes. Instructors can adopt a scaffolded learning approach, where the instructor participates in collaborative efforts with students to build their understanding of a given concept (Wood et al., 1976). Utilizing a student's learned knowledge can enhance a student's understanding of a topic and influence reflection of learned concepts, allowing teachers to transition from hands-on learning to "transferring responsibility" to the student to build on basic concepts (van de Pol et al., 2010). Evoking prior knowledge to formulate unique scenarios to be solved by students, such as a free play level that gives students autonomy to create their own solutions, provides them with opportunities to build and practice different learning concepts. If the goal is for students to engage in decision-making or problem-solving tasks, the game should elicit properties that allow students to do those tasks. Interacting with the software, allowing them to build their solutions without excessive guidance from the game or the instructor, is an example of implementing properties that elicit problem-solving with students. Engaging in problem-solving tasks within a game can actively capture different skills that align with the instructor's objectives in their lesson plan.

3. Teaching Foundations of Molecular Biology Through a Simple RNA Game

In this section, I present a prototype of a science game that could be used in the classroom as supplementary material for a gamified lesson in molecular biology. I then describe the proposed game, which draws on ideas from citizen science, gamification, and education theories. The game is meant to teach rudimentary concepts in molecular biology, specifically learning about RNA and the basics of its functions. The game has four levels, or lessons, in which students learn key terms, engage in interactive sequences of RNA strands, learn properties of RNA, and engage in free play to reinforce their knowledge of the lesson.

Analyses of game-based learning in science games reveal that when no learning theories are applied to an educational game, it does not benefit student learning (Li & Tsai, 2013). Game design alone can improve engagement, but not interest or retention of skills (Zhang et al., 2021). By analyzing all components for success and deriving ideas from multiple areas of expertise, the proposed game can encompass various important learning objectives and goals that enhance the educational experience for the student and the instructor.

The prototype was built using HTML and Javascript enabled the prototype to work directly in a computer browser. The Javascript extension package Matter.js was utilized to simulate the physics of the system. The game was built in consultation with Dr. Jeffrey Yoshimi, Dr. Zenaida Aguirre-Munoz, and Dr. Shahar Sukenik; experts in building scientific games (specifically in cancer research), STEM education, and biochemistry, respectively.

3.2 Content

The game is split into levels, increasing in difficulty as students navigate the game and learn concepts. The game starts with an introductory level and becomes more complex per level. Students first learn terms directly related to RNA and function to serve as a basis to learning rudimentary topics in molecular biology. The next level allows students to apply what they have learned by stringing together nucleotides to create RNA structures. Creating RNA structures guide students' understanding of how nucleotides bond together. Increasing in complexity, the third level builds off of the basics of RNA structures and focuses on the properties of base pairs, such as attraction and repulsion. Lastly, students engage in a freeplay level that incorporates previous knowledge to build their own unique structure.

Scoring and Badges

Scoring throughout interactive RNA-building levels is on a 0-100 scale, where 0 displays no progress and 100 exhibits correct lesson completion. I utilized a modified PBL approach to embrace the benefits of points and badges in motivation, leaving out competition as it is not necessary for my simulation (see Section 2.2). In the first lesson, where students perform definition-matching, scoring is based on a binary true or false value. In some cases, there can be more than one correct solution, as the requirements are dependent on the objectives of the lesson. For example, students can use varying base pairings while still completing the objective stated for the lesson. Specific actions or combinations in RNA building sequences may elicit a higher score, demonstrating the correct actions desired from the lesson, or may provide a decrease in the score, meaning the student needs to try different actions to finish the lesson. Once a student has earned a score of 100, they have done all the necessary actions to advance to the next level. This trial and error helps the student be aware of what is expected of them and what the learning outcomes are for understanding RNA structures and interactions.

Students are tracked on their progress throughout the lessons by badges. Earning badges signifies that they have completed all the objectives in the level and have done the procedures necessary to advance to the next lesson. There is one badge per lesson, meaning that four badges show that the student has completed all the lessons they were intended to learn and conceptualize. Badges are great for tracking progress as well as providing motivation for the student to finish each lesson, as it can be gratifying to receive and display a shiny badge. Students are more inclined to fulfill lessons with an incentive, such as badges, because it motivates them to earn rewards for completing each lesson.

Lesson 1: Basic Concepts

As an introductory level, there is a definition-matching game where students identify what RNA and its structures are in a list of definitions. This is intended to supplement learning RNA by transitioning the lesson from traditional lecture to a game that reinforces instructional topics in a gamified way to motivate engagement (Section 2.1). By dragging the arrows across the screen, students assign terms to definitions. Students can check their answers by looking for a red "X," signifying an incorrect answer, or a green check indicating a correct answer, shown in Figure 3. Once students pair all terms and definitions correctly, they move onto the next lesson, which explains the primary structures within RNA. An virtual avatar (Section 1.2) could also be introduced at this level to guide students through initial onboarding.

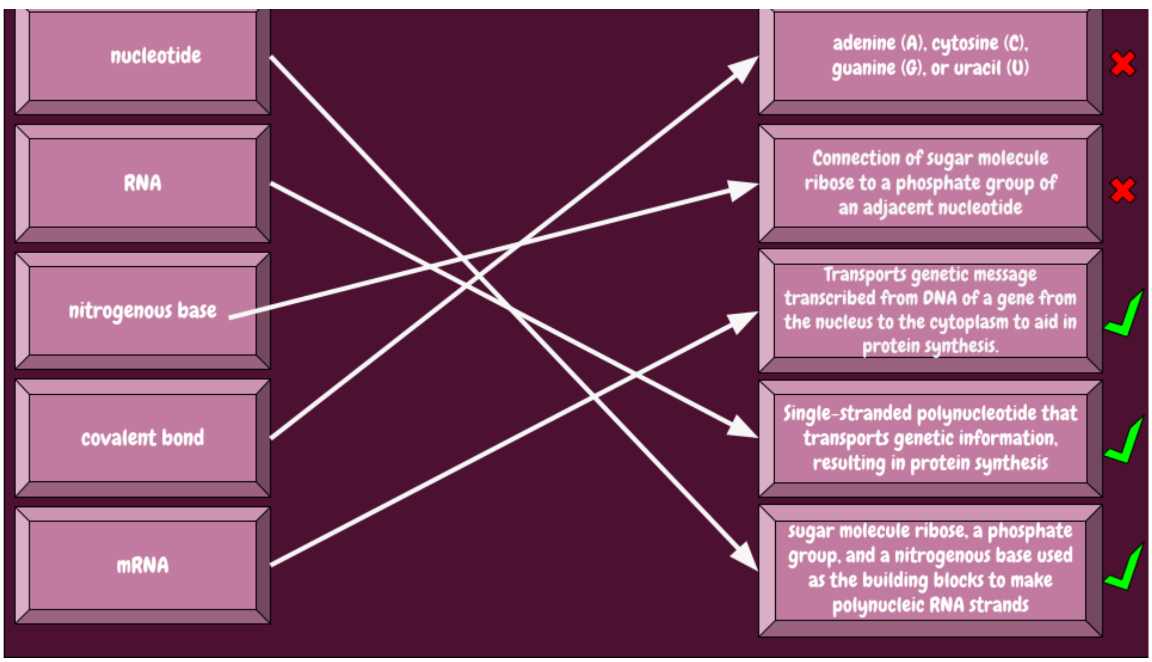

Figure 3. Level 1 introductory level, where students are asked to pair the term with the correct definition. Red X's indicate incorrect answers, while green checks indicate correct answers.

Lesson 2: Primary Structures/Sequences

Leveling up, students assemble a sequence structure for their RNA strand. Their sequence can contain a string of nucleotides linked together by covalent bonds, called a primary structure. These structures contain nitrogenous bases adenine, uracil, guanine, and cytosine. These bases are denoted as “A,” “U,” “G,” and “C,” respectively. Any sequence of these bases is a primary structure. Primary structures determine how an RNA folds, but in this level students just get used to creating a specified structure. Students are asked to do different manipulations to demonstrate different properties. First, students are guided to make a specific sequence, such as ACGUC, to get familiarized with the controls. The interface is shown in Figure 4. The level is scored by allotting 12.5 points to each nucleotide properly colored according to a set of instructions, requiring students to make a primary structure with 8 correct nucleotides to pass the level; this is indicated by earning 100 points. Students can track their progress by their score (Section 2.2). If they are correctly building the primary structure, their score goes up. If they do an action that is incorrect, their score decreases, incentivizing the student to go back and fix their mistake to increase their score again.

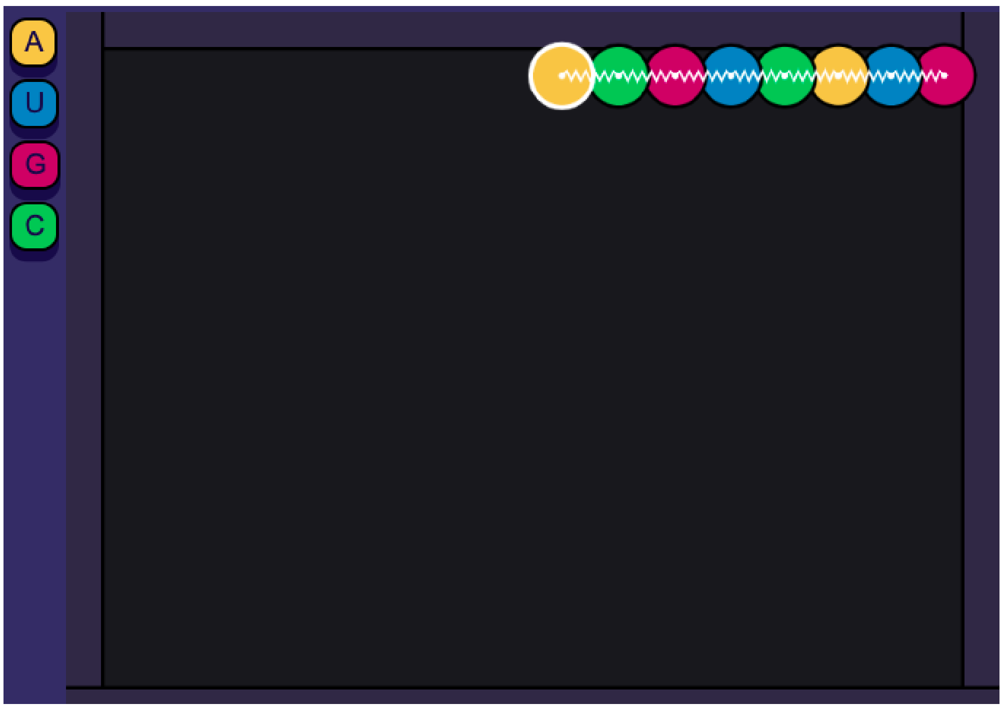

Figure 4. Base pairings. Students click the circle to interact, then click the corresponding base-pair button to build their unique sequence, observing interactions by doing different combinations of base pairs.

In the next part of the lesson, students learn more about how bases can display attractive or repulsive properties. This part of the lesson prompts students to observe RNA nucleotide pairings and understand the importance of different base-pair interactions. Neutral nucleotides— fictional nucleotides that do not have positive or negative value, that have not been assigned a “letter” — demonstrate what attraction and repulsion may look like with base pairs, shown in Figure 5. Students adjust the slider bar from left to right to observe how bond strength affects the properties of the nucleotides, making them attract or repel. As students transition to lesson 3, the base pairs become more complex as they learn and engage with different bond strengths within specific base pairs.

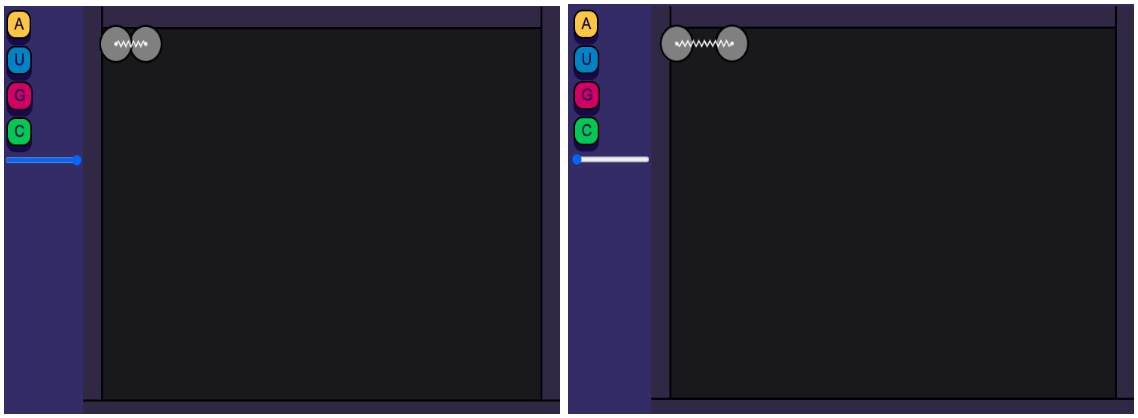

Figure 5. Lesson on attraction and repulsion. Students are shown neutral nucleotides and interact with the slider bar to observe what happens with different bond strengths.

Lesson 3: Attraction and Repulsion

Some bases attract, while others repel, leading to the next goal: create a molecular structure that demonstrates a tightly wound sequence. Students learn sequences that attract versus repel, and are asked to model what they have learned. For example, AU and GC bases attract. Students use these base pairs to produce tightly folded molecules, as in Figure 6 (left). The next goal is the opposite: make a sequence that maximizes the molecule's dispersion. This goal requires students to use their knowledge of repulsive bases to build this structure. Bases such as AC and GA (or any pair of same bases, such as AA or CC or GG) repel in the simulation, as shown in Figure 6 (right). Utilizing this knowledge allows students to successfully generate tightly folded or dispersed sequences based on primary structures they have created.

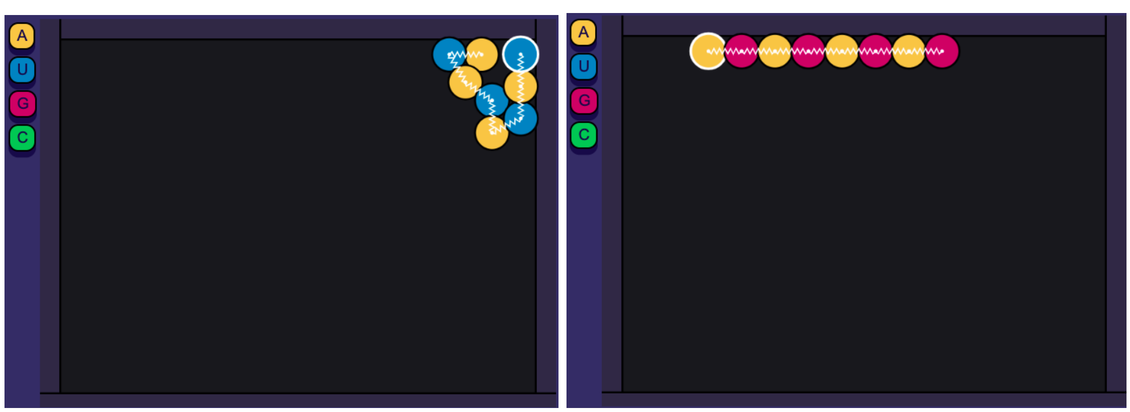

Figure 6. Attraction/Repulsion Level. Specific base pairs cause attraction, shown to the left, and others cause repulsion, shown on the right.

Lesson 4: Freeplay

As a final instructional level, students are prompted to engage their skills by constructing their own RNA strand and conceptualizing how it will fold. In this free play, students create their sequences without external guidance, applying a scaffolding approach which transfers responsibility to the student to encourage autonomy and use of prior knowledge (Section 2.3). Students are asked to create their own sequence, 15-20 nucleotides long, where some sections attract and others repel. Students are advised to explain their generated sequences and explain their interactions. Part of their grade is their ability to explain and reflect on the primary structure they have created, and how that structure produces a molecule that folds in a specific way (i.e. secondary and tertiary structure, though those concepts are not covered in this lesson plan). This can be a verbal or written activity, useful for consolidating learned information and transitioning back from the game to classroom learning.

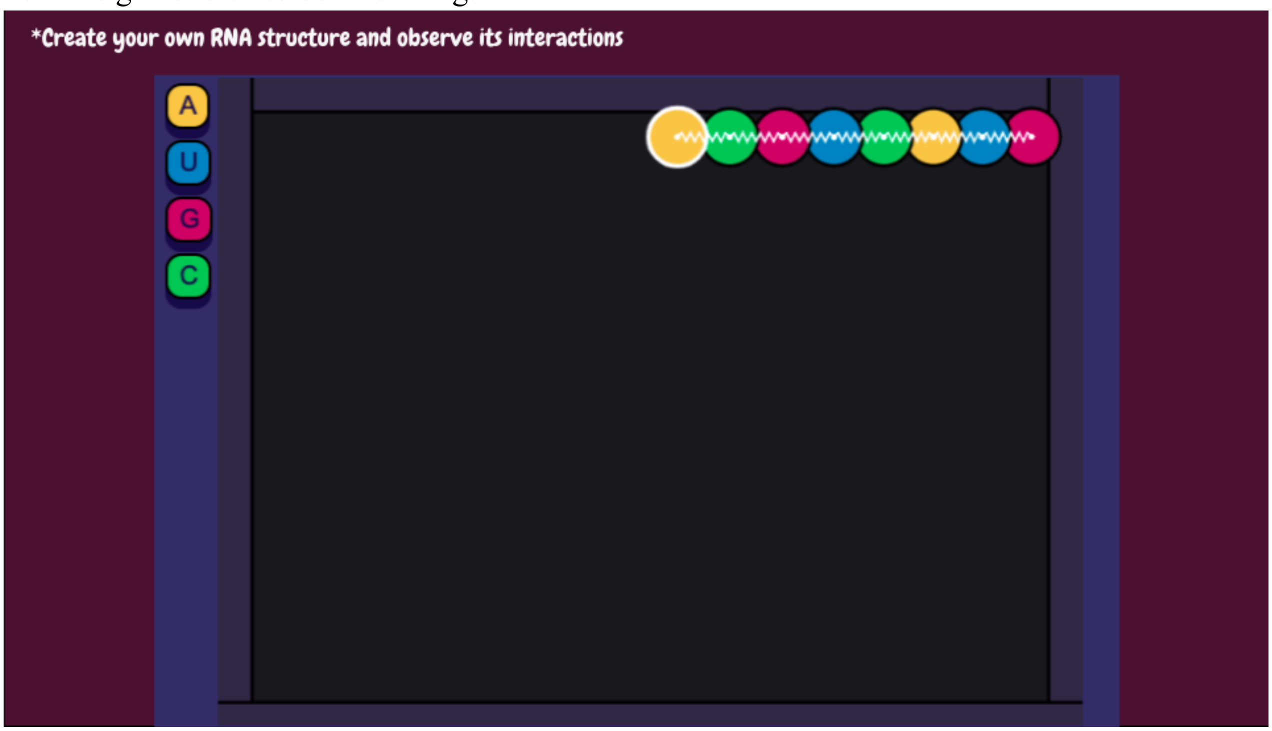

Figure 7. Freeplay level. As students choose which lesson to revisit, they can make unique connections and structures. They are instructed to form a structure of 15-20 nucleotides and observe its behaviors of attraction or repulsion.

Debrief and Test Preparation Level

The game ends with a debrief, shown in Figure 8. Students can reflect on and review what they learned by reading the text boxes. Following the debrief level, instructors are encouraged to test student retention by administering a quiz or follow-up assessment.

Figure 8. Debrief level, reviewing terms and key takeaways from the lessons.

3.3 Future Directions

The game can serve as a foundation for exploring and modeling increasingly complex phenomena. A benefit of a simplified game is the ability to continuously build upon it to capture different ideas and theories within microbiology. A direction to pursue is capturing the Lennard-Jones potential, which models the interactions between two nonbonding, or neutral, molecules with their distance. Lennard-Jones potential has van der Waals interactions, indicating that molecules interact on distance-dependent interactions that designate repulsion if close in proximity, attraction if in moderate proximity, and no reaction if in an infinite distance. These values of repulsion and attraction can be calculated in the equation below:

$$V_{LJ}(r) = 4\varepsilon[\left(\frac{\sigma}{r}\right)^{12} - \left(\frac{\sigma}{r}\right)^{6}],$$

Where *r* signifies distance, *ε* is dispersion energy, and *σ* is distance when potential energy *V* is zero between two particles, also denoted as “size” with how strong the repulsion or attraction values are.

Paired molecules in the Lennard-Jones potential model move following thermodynamics, where molecules’ distance is affected by temperature and Brownian motion. Brownian motion is random motion amongst particles, influenced by temperature, affecting the motion of molecules in the model and the system’s behavior. With different collisions between molecules, Brownian motion works to change and adjust the kinetic energy between molecules, resulting in different velocities and distances dependent on temperature. Higher temperatures increase kinetic energy, causing molecules to repulse from higher velocities. Inversely, lower temperatures decrease kinetic energy and cause molecules to attract. These interactions with thermodynamics reveal how molecules interact within the model and can aid in predicting specific molecule behaviors.

Many concepts assist in learning the Lennard-Jones model, such as thermodynamics, Brownian motion, pair-molecule interactions, and attraction and repulsion. Gamifying this process and making it interactive can help students understand how these processes interact with visual, physical, and logical learning styles to shape an enhanced learning experience. It can build off current dynamics in the proposed molecular manipulation game, such as the attraction and repulsion lesson, and explore the complexities of underlying physics mechanics. The flexibility of the proposed game facilitates varying levels of education, starting at rudimentary concepts, and can transform to capture more complex lessons within STEM education, demonstrating the versatility of the molecular manipulation game for K12 and higher education. In collaboration with Dr. Shahar Sukenik in the Department of Chemistry and Biochemistry at the University of California, Merced, efforts to build this game have begun.

Conclusion

The incorporation of games in educational context has been studied for decades as educators attempt to revolutionize traditional learning in the age of technology. I describe a game based on foundations in educational research and citizen science methodology. Combining the distinct methods from both disciplines while considering their drawbacks motivated a game in which students interact with objects to participate in virtual hands-on science. I believe more games like this have the potential to enhance the benefits of gameplay in the classroom and transform teaching in STEM education.

References

Achterman, R. R. (2019). Minds at play: Using an online protein folding game, Foldit, to support student learning about protein folding, structure, and the scientific process. Journal of microbiology & biology education, 20(3), 10-1128.

Ahmad, T. S., Hussin, A., Yusri, G., Sembilan, U. T. M. N., & Campus, K. P. (2019). A review of learning theories for gamification elements in instructional games. In Conference: Malaysian International Conference on Academic Strategies in English Language Teaching (MyCASELT). At: Sutera Harbour Resort, Kota Kinabalu Sabah.

Andrade, G., Ramalho, G., Gomes, A., & Corruble, V. (2006). Dynamic game balancing: An evaluation of user satisfaction. In *Proceedings of the AAAI Conference on Artificial Intelligence and Interactive Digital Entertainment* (Vol. 2, No. 1, pp. 3-8).

Barata, G., Gama, S., Jorge, J., & Gonçalves, D. (2013, October). Improving participation and learning with gamification. In Proceedings of the First International Conference on gameful design, research, and applications (pp. 10-17).

Clark, R., Kirschner, P. A., & Sweller, J. (2012). Putting students on the path to learning: The case for fully guided instruction. American Educator, 36(1), 5-11.

Deci, E. L., & Ryan, R. M. (2012). Self-determination theory.

Domínguez, A., Saenz-de-Navarrete, J., De-Marcos, L., Fernández-Sanz, L., Pagés, C., & Martínez-Herráiz, J. J. (2013). Gamifying learning experiences: Practical implications and outcomes. Computers & education, 63, 380-392.

Franco, J. (2012). Online gaming for understanding folding, interactions, and structure. Journal of Chemical Education, 89(12), 1543-1546.

Farley, P. C. (2013). Using the computer game “FoldIt” to entice students to explore external representations of protein structure in a biochemistry course for nonmajors. Biochemistry and Molecular Biology Education, 41(1), 56-57.

Gutierrez, A. F. (2014). Development and effectiveness of an educational card game as supplementary material in understanding selected topics in biology. CBE—Life Sciences Education, 13(1), 76-82.

Huang, B., & Hew, K. F. (2015, November). Do points, badges and leaderboard increase learning and activity: A quasi-experiment on the effects of gamification. In *Proceedings of the 23rd International Conference on Computers in Education* (pp. 275-280). Hangzhou, China: Society for Computer in Education

iCivics (2022). *People's Pie* [Unity].

Inoue, N. (2007). Why face a challenge?: The reason behind intrinsically motivated students' spontaneous choice of challenging tasks. Learning and Individual Differences, 17(3), 251-259.

Jones, S. M., Katyal, P., Xie, X., Nicolas, M. P., Leung, E. M., Noland, D. M., & Montclare, J. K. (2019). A ‘KAHOOT!’approach: the effectiveness of game-based learning for an advanced placement biology class. Simulation & Gaming, 50(6), 832-847.

Li, M. C., & Tsai, C. C. (2013). Game-based learning in science education: A review of relevant research. Journal of Science Education and Technology, 22, 877-898.

Malone, T. W. (2018). Superminds: The surprising power of people and computers thinking together (p. 113). Little, Brown Spark

Nicholson, S. (2013). Exploring gamification techniques for classroom management. Games+ Learning+ Society, 9, 21-27.

Paras, B. S., & Bizzocchi, J. (2005, June). Game, Motivation, and Effective Learning: An Integrated Model for Educational Game Design. In DiGRA Conference.

Schoenau-Fog, H. (2011, September). The Player Engagement Process-An Exploration of Continuation Desire in Digital Games. In Digra conference.

Small, R. V. (1997). Motivation in Instructional Design. ERIC Digest.

van de Pol, J., Volman, M., & Beishuizen, J. (2010). Scaffolding in teacher–student interaction: A decade of research. Educational psychology review, 22, 271-296.

Vohland, K., Land-Zandstra, A., Ceccaroni, L., Lemmens, R., Perelló, J., Ponti, M., ... & Wagenknecht, K. (2021). The science of citizen science (p. 14-18). Springer Nature.

Vorderer, P., Hartmann, T., & Klimmt, C. (2003, May). Explaining the enjoyment of playing video games: the role of competition. In Proceedings of the second international conference on Entertainment computing (pp. 1-9).

Werbach, K., Hunter, D., & Dixon, W. (2012). *For the win: How game thinking can revolutionize your business* (Vol. 1, p. 84). Philadelphia: Wharton digital press.

Whitton, N. (2007). Motivation and computer game based learning. Proceedings of the Australian Society for Computers in Learning in Tertiary Education, Singapore, 1063-1067.

Wood, D., Bruner, J. S., & Ross, G. (1976). The role of tutoring in problem solving. Journal of child psychology and psychiatry, 17(2), 89-100.

Zhang, Z., Muktar, P., Wijaya Ong, C. I., Lam, Y., & Fung, F. M. (2020). CheMakers: playing a collaborative board game to understand organic chemistry. Journal of Chemical Education, 98(2), 530-534.