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THE HUMAN MICROBIOME WORLD: USING MINECRAFT TO ENHANCE MICROBIOLOGY LEARNING

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We designed an activity-based science curriculum that used Minecraft to support microbiology learning for students enrolled in the Lang Science Program at the American Museum of Natural History (AMNH) in New York City. Minecraft offered an option to consolidate complex science content into digestible activities for modeling concepts and demonstrate student mastery. We will (1) present a background of the course, design processes, and how we used Minecraft in the curriculum, (2) describe the design of the educational Minecraft activities, (3) articulate design issues, adjustments, and constraints, and (4) discuss future changes.

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DESIGNING A CURRICULUM THAT USES MINECRAFT TO TEACH MICROBIOLOGY

The American Museum of Natural History (AMNH) in New York City paired Minecraft, a popular, open-ended sandbox building game, with an activity-based science curriculum to support microbiology learning for 14-17 year old students enrolled in the Lang Science Program. The Lang Science program is an extracurricular educational program for middle school and high school students that focuses on the sciences covered at the museum (e.g., biology, anthropology, earth sciences, etc.). Students are enrolled in the fifth grade and make a seven-year commitment to attend science classes during the summer and school year. In this paper we will (1) present a background of the course, design processes, and how we used Minecraft in the curriculum, (2) describe the design of the educational Minecraft activities, (3) articulate design issues, adjustments, and constraints, and (4) discuss future changes.

BACKGROUND OF THE COURSE, DESIGN PROCESSES, AND HOW WE USED MINECRAFT IN THE CURRICULUM

Utilizing technology and multimedia to create meaningful classroom experiences has been shown to facilitate student learning (Mayer, 2009; Bransford, Brown & Cocking, 1999), enhance student motivation (Belland et al., 2009), and increase student performance in science, technology, engineering, math and language arts subjects (Schwartz et

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al., 2007; Chase et al., 2009). Engaging students in collaborative play emphasizes the importance of applicable skill sets in contexts outside the classroom. For example, students can potentially learn about team building and task delegation via an in-class collaborative activity, or design techniques and implementation approaches while working on a design project (Claypool & Claypool, 2005).

Using games in the classroom has also shown to facilitate such instruction and learning (Gee, 2007). Moreover, games are motivating to play and this enjoyment is routinely conceptualized as the motivational basis for learning (De Grove et al., 2012; Garris et al., 2002; Michael & Chen, 2006; Squire, 2005). We believe that Minecraft's creative tools and engaging gameplay mechanics can help facilitate collaborative learning activities and situated contexts that are beneficial for instructional content. Minecraft can serve as a strong vehicle for supporting education and student learning.

Teaching Science using Minecraft

Science topics like microbiology can be complex (e.g., hands-on experiments, terminology, etc.) and students unfamiliar with the content area may feel overwhelmed in a single class session (Johnstone, 1991). Minecraft can consolidate content into simple activities that can leverage student understanding of class topics in an approachable manner. For example, players can design and build an infinite number of creations with the in-game "voxel" blocks to flesh out ideas or work on projects, while educators can utilize the game's building mechanics to develop educational activities and embed instructional content that pair with in-class learning goals.

When introducing microbiology topics (e.g., microbe scale, microbe diversity and environmental influence, etc.) to a class, designing simulated in-game activities that offer contextual experiences relevant to the learning goals could strengthen students' understanding of course content. Black (2007) found students learn best when they can directly manipulate entities and observe changes in the virtual environment based on their input. When educators bridge direct lecture instruction with experiential learning facilitated by a game, they could help solidify concepts more so than when they deliver a lecture alone. Figure 1 shows how a teacher could introduce a lesson on the body's immune system and students could then explore the content in a simulated Minecraft activity.

BUILDING BLOCKS: MINECRAFT AND THE HUMAN MICROBIOME WORLD

The Minecraft & The Human Microbiome course, based on the special AMNH exhibit, "The Secret World Inside You," was an experimental course that explored the science of microbes inhabiting the human microbiome. Its creation was the result of educational initiatives by the Lang Science Program to incorporate new course design practices and technology into the curriculum. This two-week summer course included 14 students aged 14-17. Students were taught the fundamentals of microbiology (e.g., the roles of microbes, microbial relationships, etc.) and how to apply microbiological techniques (i.e., streaking plates, microorganism cultures, and cell staining).

Students attended the course at the museum and classes were separated by morning and afternoon sessions. Sessions lasted two hours each with an hour in between for lunch. The course was managed in pairs by one teacher, who had taught previous science courses, and a program consultant, who assisted with the technology and facilitated the Minecraft experience. The use of Minecraft in this class was not intended to replace typical classroom instruction methods (e.g., hands-on activities, science simulations, etc.), but supplement learning experiences with design-based projects where youth could leverage their content knowledge to design and communicate key ideas.

Course Development Process

Development of the course curriculum and Minecraft activities began approximately one month prior to the start of the class. The design team was comprised of five members who oversaw the entire process. The teacher was our science content expert, who designed the course curriculum, and taught the class. The program consultant managed the computers and facilitated the in-class Minecraft experience. The designer served as our Minecraft expert and created the game world and its activities. Two more team members managed the project and oversaw course development goals, deliverables, and needs.

Initial meetings focused on developing course content and discussing how Minecraft would be integrated. We believed the curriculum should tie closely to the museum exhibit, as it introduced patrons to the human microbiome and its impact on the body (i.e., digestion, weight loss, diseases, etc.). We also discussed using premade Minecraft activities with set learning goals versus freeform experiences that played to the game's building and creative mechanics.

We considered fully embracing Minecraft's building mechanics as the main driver of the activities because we believed that students would view building with complete freedom far more enticing. However, this idea was quickly rejected because the lack of clear objectives inherent in open-ended gameplay could not guarantee student learning, or that they would remain on target when completing tasks. We felt it was also important to incorporate broader science processes and hands-on practices to provide students with a deeper understanding of microbiology. Meaning, it was of particular importance that the Minecraft activities offered contextualized experiences that could help students leverage their

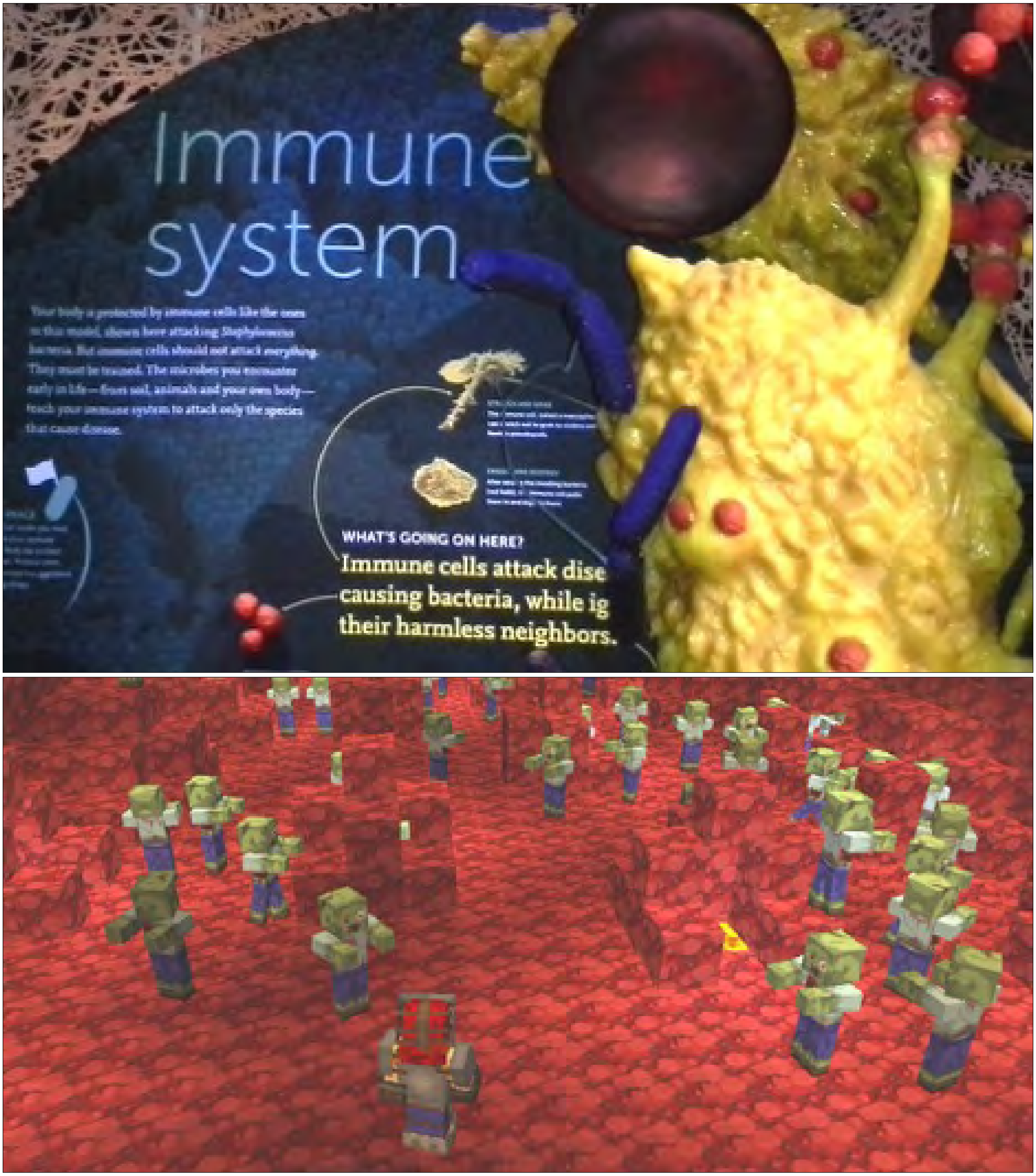

FIGURE 1. (Top) By visiting the Secret World exhibit at the museum, students were introduced to the concept of how the body's immune system protects itself from foreign bacteria. (Bottom) This learning objective was then mirrored in a Minecraft activity where students role-played as white/red blood cells and antibiotics to combat the virtual bacteria that invaded the body. (Left image used with permission from American Museum of Natural History).

understanding of in-class topics. To this end, we opted to create activities that included set objectives and freeform gameplay to better tie activities to particular class topics.

Each class day had an overarching theme with its own learning goals and activities that (1) taught students a particular aspect of microbiology, (2) provided them with hands-on learning experiences, and (3) offered a contextualized Minecraft activity where students could apply that understanding in a situated experience. For example, one particular day focused on how environmental conditions (e.g., temperature, location, etc.) impact microbial survival. Once students were introduced to the topic, they created a Winogradsky column in class, which is a cylindrical culture to show microorganism diversity. They then toured museum exhibits to collect information on microbial life, and then played a Minecraft farming activity that tied with those tasks. We felt that maintaining this relationship between the content and activities would help provide students with contextual experiences and a wider body of knowledge that could be leveraged in future coursework.

Minecraft Activity Development Process

Starting with the learning goals gave us a clear understanding of the content we wanted to include in the activities. We next began brainstorming ideas with the Minecraft designer to develop the activities students would play in class. There was some debate about how many activities were needed and if students could choose which ones to play.

Our initial idea was to create approximately five to ten different activities and give students the freedom to choose what they wanted to play. We believed that the plethora of choices would help keep students engaged and give them more opportunities for situated experiences. However, there were glaring complications with this first pass. What if students selected activities that did not tie to the day's content or learning objectives? More importantly, there would be a limited opportunity to solidify their understanding because they would all be drawing from different experiences.

To address such concerns, we explored the idea of embedding all of the activities into one "adventure map" that students would complete in a linear order. The map could give students a sense of presence as they role-play as the microbes they learned in class. Additionally, the creative freedom we wanted students to leverage could be built into the activities themselves. While an activity map that tied to microbiology was enticing, offering players relative freedom in the activities risked creating an unfocused experience that would not necessarily guarantee student learning.

Instead, we opted for activities that included set learning objectives and instructional content, while also allowing students some freedom to use their creativity in completing them. We believed that limiting player agency throughout the activities was unnecessary and risked negatively impacting engagement with the embedded material. By providing multiple pathways for completing the same problem, we enabled students to provide their own unique skill sets and experience into the activities. This in turn can benefit the entire class during reflection exercises and subsequent classes.

As a result of our discussions and design plans, each activity was made standalone and situated in one map file for easier management. In addition, areas of the activity that introduced students to a topic would be direct in explanation and gameplay, while the sections where they apply that understanding would offer them the most creative freedom. More importantly, we opted to create collaborative activities over self-directed, individual experiences because it would allow students to have a more nuanced understanding of the content due to the shared experience. We wanted to strike a balance between directing students to the goals we wanted them to complete, as well as embrace the creative nature of Minecraft into flexible experiences that could be easily managed.

The Human Microbiome World

The concept of the adventure map began as a simple construct that would house the individual activities. Students would simply walk from one area to another to play them depending on the topic for that class day. However, we believed that building a map in such a straightforward fashion would rob the class of a unique, contextually relevant experience. Utilizing the building mechanics of Minecraft, we considered the possibility of creating a map to resemble the human body. This type of map would also allow us to strategically place the activities in key areas of the "body" to better reflect scientific accuracy. Additionally, it would help students connect their experiences to a broader context of how microbes impact certain areas of the body.

This Minecraft body world was created by the team designer via the Worldpainter program, a world-building tool, and housed five instructional activities that reinforced microbiology concepts and provided a medium for youth creativity and self-directed learning (see Figure 2). We designed a version of the map to resemble a male human body, while a second, female version was also created that would house the student final projects. The color of these body maps was made green for the purposes of racial ambiguity.

The Custom Minecraft Activities

The designer constructed five Minecraft activities in the body map. Each activity's learning goals and content were selected because of (1) their connection to the "Secret World" museum exhibit, (2) content is foundational knowledge in microbiology education according to the New York State Science Core Curriculum, and (3) how well Minecraft could accurately simulate the course learning content. Ideas were first storyboarded in weekly check-in meetings and their mechanics were tested in mock activities in the game world. Once a foundation of each activity was established, they were further refined during a daily iterative process of testing and feedback via Slack by other team members.

Instructional material was relayed in game via signposts and information blocks, system messages that would appear on the screen as students navigated particular areas, or facilitated by the classroom teacher. The designer also handled any needed changes or bug fixes to the activities. New versions of the map files were given to the program consultant for the students to use in class. While we expected a majority of students would have previous experience with Minecraft, we believed that simple activities would better serve our educational goals.

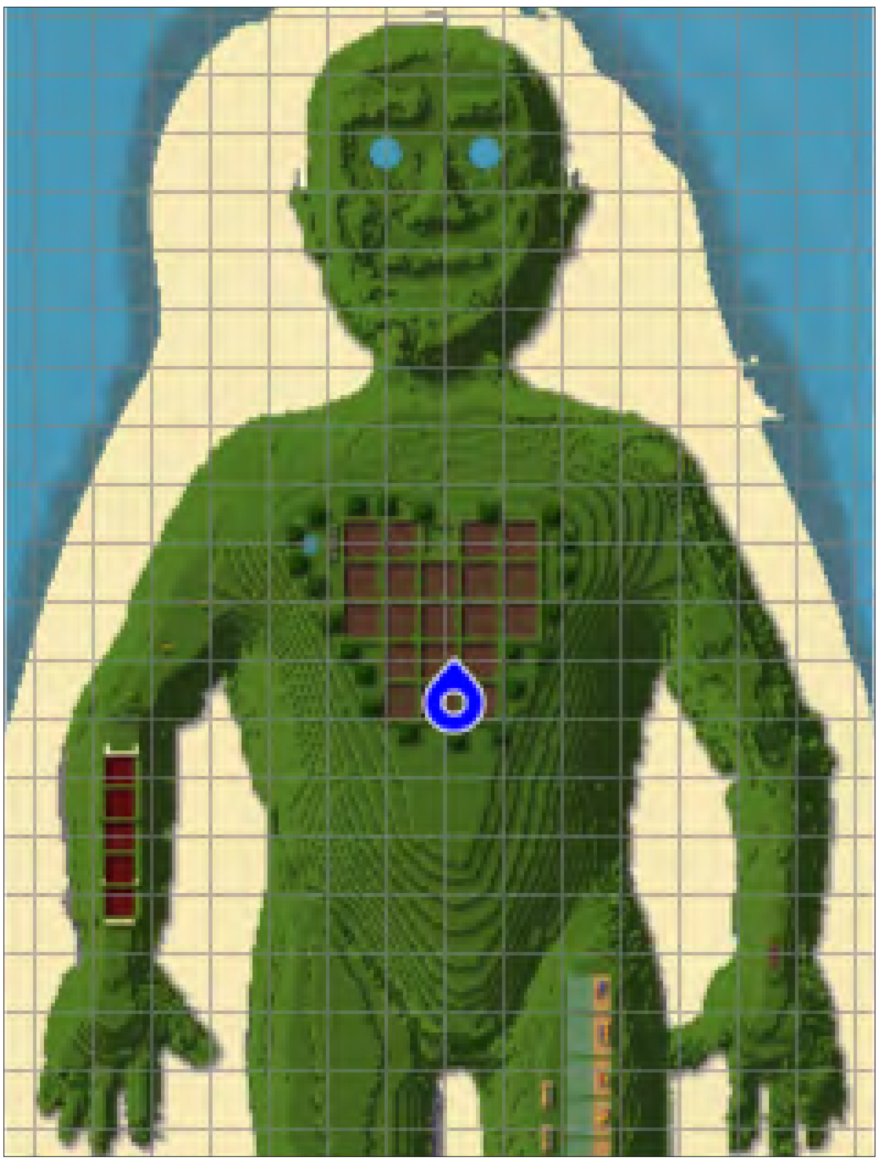

FIGURE 2. An overhead view of the male microbiome map made with the Worldpainter program.

Our team first designed a Microbe Scale activity where students learned about microbe structures at different scale sizes. Students were presented with voxel structures that represented a microscopic view of a microbe and were then required to construct a replica at different size scales (e.g., 2x, 3x, etc.). Students worked in groups of three or four for this activity to share design ideas and review microbiology concepts collaboratively. The Farming Diversity activity had students create their own farmland and learn what was needed to grow wheat, sugarcane, and trees. Located on the "skin" layer of the body map, our goal for this activity was to show how these growth principles connected to the ways microbes thrive in specific environments such as human skin.

The Body Defense activity had students work collaboratively as groups of white blood cells, red blood cells, or antibiotics to showcase how microbes defend the body from infection via a cut in the arm. Students played in groups of four on separate computers, selected their roles, and defeated several waves of infection using a series of in-game tools and weapons (e.g., swords, light, etc.) based on their roles.

In the Nutrient and Waste exploration activity students navigated a virtual stomach and intestines. In the stomach, students collected protein and carbohydrate voxel blocks to symbolize how the body absorbs nutrients. As they progressed through the intestines, students would observe how waste is processed and the ways microbes aid in digestion and nutrition. Because this activity was focused more on exploration and less on building, it could only accommodate small groups of three to four students.

The Microbe Scavenger Hunt activity was the final activity and was situated around the entire area of the map via hotspots at key locations (e.g., armpit, feet, mouth, etc.). This activity showcased how microbe species inhabited different areas of the human body. To further illustrate this, we placed different flowers in these locations and renamed them to represent specific microbes that actually thrive there. Students were given in-game journals (book and quill) to record the different microbes and locations they discovered. Because this activity took place around the entire map, it could easily accommodate the whole class at one time. For a summary of these activities and their connection to New York State P-12 Science Learning Standards, please see Table 1.

Enhancing the Activities with MinecraftEdu

While Minecraft formed the foundation of what we used to design the activities, we wanted to be sure they could be easily facilitated in a classroom. Minecraft was not designed for classroom use and is missing several features that make facilitation more manageable (e.g., limiting player movement, providing items, etc.). Therefore, in conjunction with designing the activities, we also incorporated a modification called MinecraftEdu into our designs. Developed by TeacherGaming, this program provided additional functionality for specific use in educational settings, but retained the game's original creative tools and building mechanics.

For instance, embedded commands and in-game menus allowed us to easily tend to student needs (e.g., providing items, helping with construction, etc.), assign tasks, or move students around the game world as needed. The use of new voxel blocks (see Figure 3) also enabled us to highlight instructional content present in the activities and help guide students through the learning goals of each design. Additionally, the "build allow" and "build disallow" blocks prevented students from affecting the mechanisms of the activities or the game world, but allowed them to build in approved areas as required. These blocks were layered under the game world and could not be destroyed by the students.

The inclusion of this modification into the activities and body map was planned from the beginning of the design process, and we worked closely with TeacherGaming through development and implementation. While no additional development time was needed, team members were introduced to using the program (e.g., features, tutorial map, controls) during two training sessions prior to the start of the course. The teacher and design consultant spent additional time outside of these sessions for more hands-on experience.

Representing Microbiology in Minecraft

Working within the constraints of the game forced us to consider creative ways to represent microbiology and help students understand science concepts while playing. In Minecraft, players are not combating bacteria or observing microbial interactions. They are fighting monsters, building structures, or crafting items. To situate the activities in a microbiology context, in-game monsters, voxel blocks, and tools were renamed to what they represented in microbiology.

Additionally, the areas students played in and the actions they typically performed in Minecraft were re-imagined so they would be accurate in relation to the science content (see Table 2). For example, as students selected their roles in the Body Defense activity, an antibiotics player received a weapon called beta-lactam, red blood cell players were given hemostasis (clotting) blocks, and white blood cell players were given macrophage torches to ward off bacteria. On nearby information blocks, the purpose of each tool in real life was explained, while the invading "bacteria" were renamed zombie entities.

The goal of representing the course content in this fashion was to (1) maintain focus on the activity's learning objectives

ACTIVITY NAME	ACTIVITY LEARNING GOALS	NEW YORK STATE EDUCATIONAL STANDARD
Microbe Scale	(1) Microbe analysis (2) Magnification	(1) Structure and Properties of Matter 5-PS1-1: Microscopic scales. (2) Structure and Properties of Matter 2-PS1-3: Structure make up, complex systems, disassembly.
Farming Diversity	(1) Microbe growth; (2) Environmental conditions	Growth, Development, and Reproduction of Organisms MS-LS1-5: How environmental and genetic factors influence organism growth.
Body Defense	(1) Microbial relationships; (2) Body responses to infection	Structure, Function, and Information Processing 4-LS1-1: Internal & external structures affect survival
Nutrient and Waste	(1) Symbiotic relationships; (2) Nutrition; (3) Food and Energy	(1) Interdependent Relationships in Ecosystems K-LS1-1: Patterns of organism consumption and needs. (2) Matter and Energy in Organisms and Ecosystems MS-LS1-7: How food molecules are broken down.
Microbe Scavenger Hunt	(1) Microbe classification & diversity; (2) Growth locations	Interdependent Relationships in Ecosystems MS-LS2-2: Interactions of organisms in a variety of ecosystems.

TABLE 1. The designed Minecraft activities and their connection to New York State Educational Standards.

FIGURE 3. A selection of special MinecraftEdu voxel blocks that made class easier to manage. From left to right; build disallow block, attention block, home block, information block, and build allow block.

MINECRAFT TERM	MINECRAFT ACTION	REPHRASED
Sword	To attack	Beta-Lactam to defend
Torch	To provide light	Macrophage to ward
Netherrack Block	Placing blocks	Red blood cell clotting
Zombie	Attacks	Bacteria infects
Wolf	Attacks/Tameable	Bacteriophage

TABLE 2. Examples of how we reimagined Minecraft mechanics and entities into representations that connect with microbiology..

and instructional content we implemented during production, (2) help students situate their in-game experiences in microbiology contexts that connect with subsequent classes, (3) create engaging experiences that students can leverage during class lectures and reflection exercises, and (4) downplay the idea students were simply playing a game rather than playing to understand microbiology (see Figure 4).

Additionally, when asking students to debrief about their experiences, we urged them to avoid statements that describe literal interpretations of Minecraft experiences. For example, when students reflected on building structures within the game (e.g., "I placed dirt blocks in this way."), or using particular items during the activities (e.g., "I used my sword to attack the zombies,"), we instead asked them to rephrase their statements in favor of science-based descriptions that aligned with in-class topics (e.g., I used my beta-lactam weapon to ward off invading bacteria.")

COURSE DESIGN WEEK ONE: MORNING SESSIONS

Morning sessions during the first week focused on teaching students microbiology content. At the beginning of each class, the teacher showed a Powerpoint presentation with the day's agenda and what core microbiological concepts students would be learning. Morning sessions made use of instructional videos via screen projector, handouts, field trips to microbiology labs and Central Park, a visit to the Secret World Inside You exhibit to introduce students to microbiology, and cooperative in-class simulations (e.g., cotton swabbing, petri dish simulation, etc.) to reinforce student content knowledge. Minecraft was not used during these sessions (see Table 3 for a detailed schedule).

COURSE DESIGN WEEK ONE: AFTERNOON SESSIONS

Afternoon sessions during the first week focused on playing the Minecraft activities to reinforce student content knowledge and expand their understanding of microbiology. Each activity was connected to the main topic of the class for that day and the teacher referred to student experiences from previous activities when presenting them with new microbiology content. We evaluated the effectiveness of playing these educational activities through class reflection exercises such as journal writing or full-group discussions. We also utilized pinpointed debrief questions that gauged student learning and their thoughts about microbiology in relation to Minecraft (e.g., "What concept do you think the game was trying illustrate?").

Introducing Minecraft and Activities

Students were introduced to Minecraft on the first day of class via a tutorial world that was packaged with MinecraftEdu. A brief questionnaire was administered to gauge previous experience with Minecraft and this information would eventually impact how they were placed into teams for their projects.

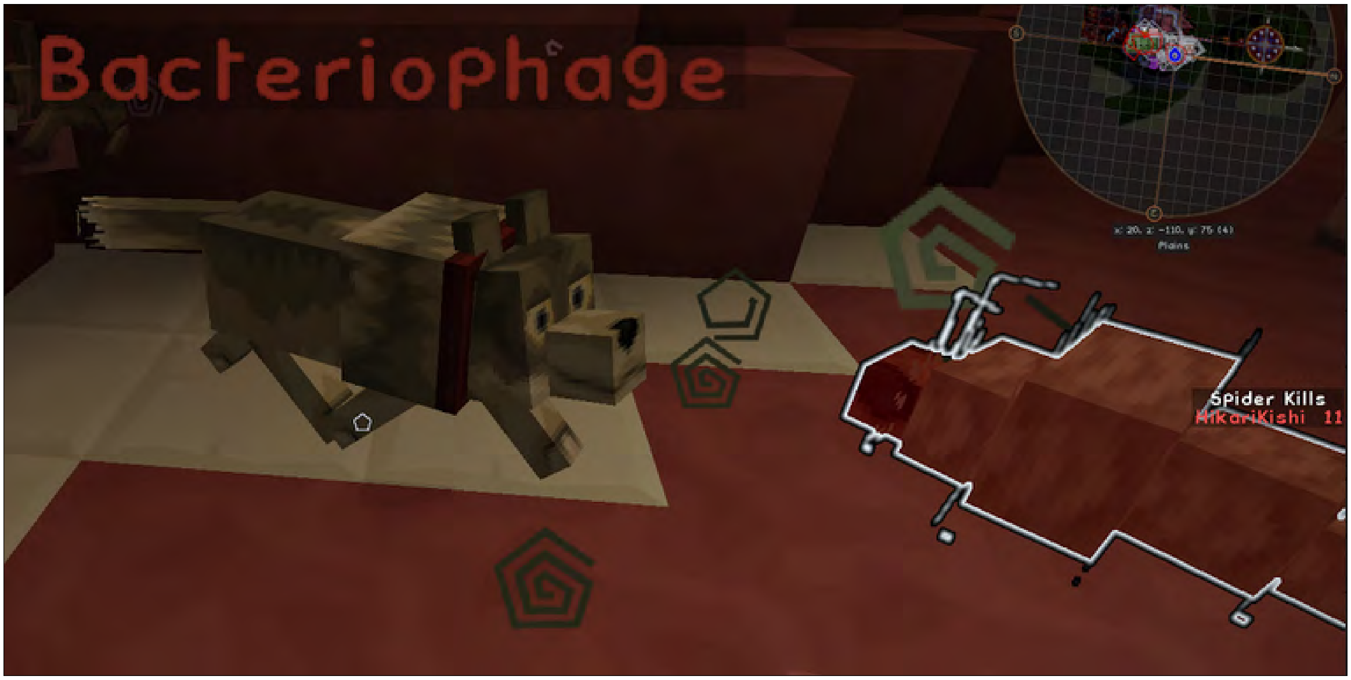

FIGURE 4. The Minecraft Wolf (left) representing bacteriophage as it attacks a mutated strain of Tuberculosis (right).

	MONDAY	TUESDAY	WEDNESDAY	THURSDAY	FRIDAY
MORNING SESSION	Intro to the course	Intro to Microbes	Microbe Relationships & Roles	Microbiology Lab Trip	Microbial Evolution & Biodiversity
AFTERNOON SESSION	Minecraft Tutorial	Microbe Scale & Farming Diversity Activities	Body Defense & Nutrient and Waste Activities	Minecraft Scavenger Hunt Activity	Minecraft Activities & Project Brainstorm

TABLE 3. Snapshot of student schedule for week 1.

Each student was then given an Alienware laptop (Windows 8 OS) with the Minecraft software and a computer mouse to control the game. Licenses for Minecraft were packaged with MinecraftEdu. The program consultant hosted the game world on a personal laptop and students connected to the server remotely on the same Wi-Fi connection.

The tutorial process was facilitated by both the teacher and program consultant, who walked students through the process of playing, and taught the class how to control their character, interact with the game world, and describe the concepts that support Minecraft (e.g., exploration, construction, and play). Students also received a printed reference sheet of the game's controls for them to review as needed.

We finished the tutorial session with a class debrief and asked students about playing Minecraft in class and if they had any issues or questions about doing so. Students then created posters that described Minecraft basics (e.g., controls, acceptable behavior, etc), which were displayed on the walls of the classroom for the rest of the course. After the first day, subsequent afternoon sessions focused on the Minecraft activities that were created for the course.

For the activities that could not accommodate the entire class, students in groups of four were rotated into the activity by the program consultant. Remaining students were provided with in-class (e.g., worksheets or brainstorming tasks) and computer-based (e.g., online research, visit science-based websites, etc.) assignments that also connected with the Minecraft activity. During this time, the program consultant projected his screen via projector so students could follow along as they played.

At the conclusion of each activity, students were instructed to reflect in their physical journals about what they were learning and their experiences with the activity (e.g., "What was your reaction to the various types of microbial relationships [in the Minecraft activity]"; or "What concept do you think the game was trying illustrate?"). These reflection exercises helped students (1) debrief about their in-game experiences and reflect on their learning, (2) solidify their understanding of microbiology content, and (3) see how the

	MONDAY	TUESDAY	WEDNESDAY	THURSDAY	FRIDAY
MORNING SESSION	Minecraft Plan and Second Exhibit Visit	Yeast Fermentation Lab and Building	Winogradsky Activity, Building, and Feedback	Playtest Session and Feedback	Building and Address Feedback
AFTERNOON SESSION	Plan Feedback and Building	Microbiology Lab Tour and Building	Re-design, Building, and Reflection	Re-design, Building, and Reflection	Final Playtest and Submission

TABLE 4. Snapshot of student schedule for week 2.

Minecraft activities represented microbiology and connected to the learning goals presented in the lectures. Table 2 summarizes the morning and afternoon sessions for week one.

COURSE DESIGN WEEK TWO: MORNING SESSIONS

During morning sessions of the second week, students were assigned the final class project and worked in groups to design their own educational Minecraft activities that connected with the course's microbiology content (see Figure 6). Before the process started, we grouped students based on their previous Minecraft experience outside of the classroom, their responses on a worksheet about the areas of microbiology they were interested in, and how well we felt they would work together.

Students then created a project plan that detailed the topic and learning goals of their activity, additional research that was needed, and what they required to build in Minecraft. We then scheduled a second visit to the Secret World exhibit and set aside time in class for them to use laptops to research additional sources as needed. Build sessions each morning gave students the time they needed to complete their projects, and additional microbiology simulations were included (i.e., yeast fermentation lab, microorganism ecosystem simulation, etc.) to further solidify student content knowledge (see Table 4 for a detailed schedule).

One 30-minute playtest session was also administered to gauge each activity's playability, clarity of instructional content, and accuracy of the activity's mechanics and features as it tied to microbiology. This playtest was also an opportunity for the students to receive feedback from guest reviewers to iterate on their work.

Following the playtest, we held a debrief session so students could (1) reflect on the feedback they received from reviewers, (2) ask questions about their activity and to strategize on how it could be improved, and (3) understand that addressing user feedback was a normal part of the design process. These questions helped pinpoint where the students needed to adjust their projects to be more in line with the course's educational goals. We also wanted to hear their thoughts about working with Minecraft to design an educational activity in class and how effective the experiences were for them.

COURSE DESIGN WEEK TWO: AFTERNOON SESSIONS

During afternoon sessions of the second week, students continued designing their activities and received direct feedback from instructors via one-on-one meetings and their peers in a second playtest. At the conclusion of each afternoon class, students also engaged in reflection exercises that prompted them with questions to check in about their progress, to help streamline their designs where possible, and assist them in incorporating instructional content as needed. Such questions included, "how does your activity connect to microbiology content taught in the course," and "how will you make your activity understandable to the user?" This was also an opportunity to discuss any challenges students were having with their activities too. Table 3 summarizes the morning and afternoon sessions for week two.

DESIGN ISSUES, ADJUSTMENTS, AND CONSTRAINTS

We experienced several notable design constraints during the Minecraft and course development process. Additionally, there were two major unanticipated design issues; (1) Minecraft's complex building mechanics and the fragility of the game world, and (2) time requirements for the final projects, as well as two unexpected revelations; (1) the value of reflection exercises to aid in content knowledge transfer, and (2) the merits of the design-based student projects. The following section will expand on these design issues and revelations, and the constraints we experienced when developing and implementing the course.

Design Constraint: Course Development

When first developing the course, we knew that experience with Minecraft was integral to designing a curriculum that could connect with the game and its capabilities. Knowledge of the game would ensure that we could consider multiple avenues when designing in-game activities that best achieved our learning objectives. We would also be better equipped to handle unexpected issues as they occurred (i.e., troubleshooting, activity stopped functioning, etc.).

To this end we felt it was important that all team members take an active role in all aspects of course development including designing the curriculum, play testing, and providing feedback on the Minecraft activities. Specifically, the teacher worked within the game to verify the accuracy of science content (i.e., play testing activity mechanics), while the design consultant worked with the Minecraft designer to implement approved instructional content. As mentioned, multiple meetings were also scheduled to train each team member on how to play the game and use MinecraftEdu.

Despite this pre-planning and training, we believed that a single teacher would be insufficient to manage the course and the technology. While we anticipated issues when using Minecraft (e.g., bugs, computer problems, etc.), we wanted to ensure that the teacher could focus on keeping students engaged with class tasks. In addition, the teacher had limited experience with Minecraft prior to the training sessions. As a result, the program consultant assisted the teacher in class as a facilitator, supported the students as they worked in Minecraft, and addressed any technology issues as they occurred.

Design Constraint: Minecraft Activity Development

Our initial time working with Minecraft revealed that even simple activities required complex systems to support them. For example, when designing the Farming Diversity activity, a distribution system was needed so students could get the tools and items they needed without requiring teacher assistance. Our initial idea was to simply place all of the required items in chests for students to collect and use. However, chests in Minecraft can only hold a limited quantity of items and teachers would spend valuable time manually restocking them. There was also a risk that particular students would take more materials than they required thus compounding the problem. As a result, we created a dispenser system that would provide items at the push of a button. With a little bit of Minecraft coding via Command blocks, we ensured that items would spawn indefinitely (see Figure 5).

There are often multiple pathways to solve the same problem in Minecraft and that is where the game's complexity is ultimately revealed. That is not to say there are no simple solutions to complex problems in Minecraft, but the quasi-freedom and sandbox nature of the game make it easy to get overwhelmed by the number of choices available. Ultimately, a designer experienced with Minecraft is needed to create such activities within a short time frame. While we anticipated the need for a designer prior to the start of the project, this option may not be available for other institutions. We recommend prospective educators gain as much familiarity with the game as possible. This includes the types of blocks, making electrical circuits via Redstone, and

FIGURE 5. The finalized distribution system for the Farming Diversity activity. When students press a button they receive the corresponding item in their inventory.

building complex systems. Doing so could help them identify instructional content that could be accurately re-created within Minecraft.

Another constraint we experienced during the development process was creating an educational experience in a game that was not designed for formal learning environments. This is because what players typically do in the game does not necessarily translate to a teachable moment that can be leveraged in a classroom. It is one thing to design an activity and simply tell students how it relates to what they're learning in class, but it is entirely different matter to create an authentic experience that incorporates accurate science content. As we were designing and playtesting the activities, we often had to ask ourselves; (1) In what ways do the activities relate to microbiology content; (2) Do the actions that players perform match such actions or behaviors in real life; and (3) In what ways can the entities that players encounter be reframed to better represent science concepts (see Figure 6)?

Such questions were often at the forefront of our minds because we wanted to deliver an engaging experience that educated students about microbiology. As a result, a significant portion of our development time was dedicated to these activities. Multiple playtest sessions of each activity were required to ensure they connected with course learning goals, as well as accurately incorporated educational content in clear and approachable ways. While such time requirements were not unexpected, the expertise needed to design effective educational activities cannot be overstated. Not only does the designer have to consider the look, feel, and authenticity in relation to the educational content, but they must also balance time constraints, troubleshooting, and play during class.

Design Constraint: Course Implementation

Aside from the prior knowledge required to work with Minecraft and develop educational activities, there were technological limits as well. Without access to a computer

FIGURE 6. In-game flora placed at accurate locations on the body to represent microbial growth for the Microbe Scavenger Hunt activity.

lab, we opted to use Alienware laptops for the duration of the course. While laptops gave students the flexibility to move around the classroom and work with particular students, there were several downsides with this option.

Due to the age of the laptops, we expected errors or issues running Minecraft efficiently and had to keep computers in reserve. Regarding the individual game files themselves, while only the host computer required the Minecraft map files for students to connect to remotely, any updates to the game or its files needed to play on the map (e.g., modifications, scripts, etc.) had to be done on each computer individually.

As the course progressed, several students asked to use different modifications for the game because it enhanced their activities or made their functionality possible. As a result, all of the computers had to have these modifications installed on them or students would not be able to access the map with those computers. Otherwise the game would prohibit their access. To counteract these time requirements, several teaching assistants were kept on staff to support educators on days that required more computers on playtests and build days.

Additionally, MinecraftEdu required a reliable internet/Wi-Fi connection where everyone had to be on the same network connection for remote access to occur. Meaning, students could not update their own activities at home as there was no way to access the server. In addition, if students decided to make a copy of the map files and update them offline at home, there would be no reliable means of incorporating such changes into the main class map files. As a result, a majority of in-class time during the second week had to be dedicated to students building their own activities.

Complex Building Mechanics and Minecraft's Fragile World

While Minecraft's individual game mechanics are not challenging to grasp (e.g., destroying & placing blocks, interacting with objects, etc.), reworking them to fit within an educational context for student consumption and learning is complex. Repurposing such mechanics to work within the activities often required a great deal of knowledge on the inner workings of the game itself. In the Nutrient and Waste activity, students mined nutrient blocks in the stomach and deposited them in a chest to proceed to the next area. These blocks were sorted via complex circuitry below the activity to open a door when students provided the correct block (see figure 7). Additionally, because Minecraft worlds can be altered or reshaped with relative ease, this also meant that the activities (and any changes we made) were ironically fragile.

With the wrong click of a mouse (i.e., left click to remove objects and right click to interact with them) a student or teacher could inadvertently destroy an integral part of an activity. Frequent use of the "build disallow" block alleviated some of these concerns, but some activities required students to build or destroy a particular area. In these instances, the program consultant had to follow student groups in the game world to replace blocks (e.g., information signs, switches, etc.) that were accidently removed.

Keeping frequent backups of the map files was helpful here, but saving approved changes while reverting unwanted

FIGURE 7. The complex circuitry to manage the collection minigame in the Nutrient and Waste activity.

ones was challenging due to the fluid pace in which students played. This was why we cycled student groups into activities that could not accommodate the whole class. Once they completed their activity, we simply reset the server to revert any changes that were made in preparation for subsequent students.

Reflection Exercises and Knowledge Transfer

As the course unfolded, we had to make adjustments to how we conveyed course material and connected it with the Minecraft activities. Specifically, observations revealed that students had difficulty seeing in-game items, blocks, and creatures as representations of microbiology content from class. For example, when recounting on their experiences with the Body Defense activity, students described the simple actions they performed in the game (e.g., "I used my sword to attack the zombie.") rather than detail what occurred through a microbiology lens. To address this, we added additional written reflection exercises after students completed each activity. We felt that students needed more opportunities to articulate their understanding of the course content in their journals or during group discussion.

We also revised the reflection questions to avoid focusing on the course material itself or about the functionality and challenge of the Minecraft activities (e.g., "How was it playing the Minecraft activity?"). Instead, we opted for questions that probed students' understanding of the content and required them to illustrate connections between the class material and in-class simulations with the Minecraft activities. For example, we asked students why playing the Microbe Scale activity was important to understanding microbes, how the Body Defense activity enhanced their understanding of how antibiotics help protect the body, and what environmental conditions are needed for microbes to survive as they observed in the Farming Diversity activity. We also placed more information blocks in our activities with richer descriptions of embedded course material.

Based on our observations of student behavior in subsequent class sessions, we saw how students demonstrated their microbiology knowledge in several new ways. First, when asked to describe to illustrate connections between the course material and the Minecraft activities, students provided rich descriptions of their experiences and used microbiology terms to describe their in-game actions (e.g., "I am role-playing a microbe in the digestive tract," etc.). Second, as students designed their final projects, they adopted the facilitation strategies we used to better convey the learning goals and content to the player. These included informing players about how their activity closely connected to the science via information blocks and signs, representing in-game entities through a microbiology lens, and probing users' understanding of activity content during playtests and facilitated feedback exercises.

Time Requirements of Final Projects

Time constraints negatively impacted student design sessions during the final week of class. While we anticipated the relative time commitment required to complete the student activities, we underestimated just how much they needed. Once students selected their topic, we gave them relative freedom to work on their activities within the boundaries of the map as long as their work adhered to their project plan. However, with this freedom we underestimated how much time students needed to create effective and informative activities.

By not requiring students to select a clear, actionable topic that can easily be represented in Minecraft, we failed to maintain focus on the course's learning objectives and remained fixated on the processes of building in the game. Only after a clearer idea began to emerge from the building

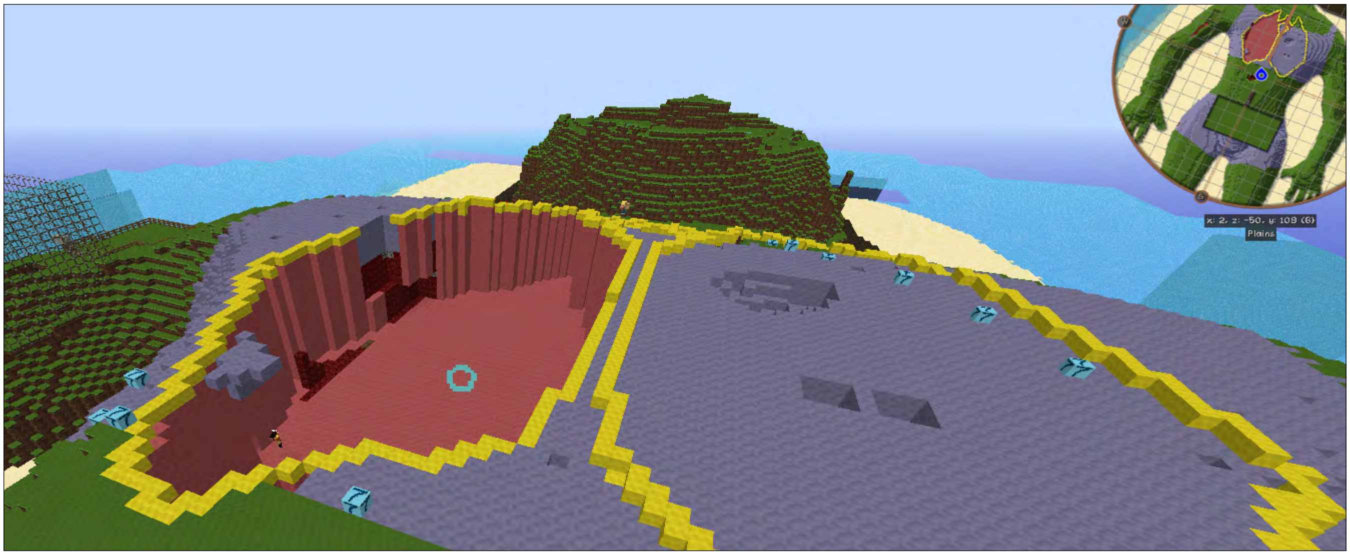

FIGURE 8. Students commonly took on ambitious projects and underestimated their time requirements. One group decided to house their activity in the body's lungs and had to excavate the entire area.

and playtests did we begin impressing upon students the importance of embedding the learning content and adhering to the deadline.

In retrospect, we should have worked more closely with students as they were selecting their topics and spent more time planning on what they would create. Doing so would help them focus their designs. If changes to their approaches needed to be made, we could then work with students on fine tuning their ideas and guide them away from large, unmanageable projects.

However, while this was certainly a systemic issue, we discovered that running consistently short on time was largely caused by the myriad of options one can explore when building in Minecraft. For example, suppose a student wanted to construct a series of doors that would open when players placed particular objects in a chest (similar to our Nutrient and Waste activity).

One option would be to instill an "honor code" system where players are not required to place objects in the chest to proceed but are merely instructed to do so. Another approach could involve creating a hopper system that sends electrical signals to the door when players place the required items into the chest. We found students often selected the latter, more complicated option because this was seen as more appealing to them (see figure 8).

Merits of Design-Based Activities

Based on our observations, students engaged with Minecraft throughout the class. They were eager for more time with the game, as well as in the activities we created. Additionally, they spent considerable time building their activities and maintained a strong sense of ownership over their designs. They were eager to showcase their work and carefully considered how feedback would impact their projects. Students also directed their own learning as they researched their selected topics and worked to incorporate instructional content into the game.

During class, students were eager to express the learning goals of their activities, explain how their work connected to the course content, and help peers navigate their creations. Playtests and teacher feedback strengthened student understanding of the design process and how ideas can change over time. This point was demonstrated by their willingness to continue improving, testing, and iterating on their designs throughout the remainder of the course.

FUTURE DEVELOPMENTS OF THE DESIGN

The Minecraft & The Human Microbiome experimental course was designed to use Minecraft as an engaging component that consolidated science content into digestible activities for students. Our experiences have informed our ability to redesign the curriculum in a number of ways. First, our intention of assigning reflection questions for student journaling was to encourage them to think through their responses before sharing with the class.

However, these journals were not collected to see if students' written reflections were changing in response to how we adjusted our reflection questions. While we did notice a difference when students reflected as a group (e.g., situating their experiences through a microbiology lens), not collecting the journals was a missed opportunity to receive a more complete understanding on how to improve future coursework. If this course were offered again, we would be more explicit about assigning the journals with the understanding that they would be collected at the conclusion of the course.

FIGURE 9. Students often exhibited a strong sense of ownership over their experiences and activities.

While technical issues cannot always be fully accounted for, more time was needed to ensure the laptops remained functional before and after use. Even though computers were checked one hour before each class, the program consultant needed to work closer with the TAs in maintaining the computers as needed. We also found that more time was needed to finetune the activities and test them on the student laptops. We discovered that the activities would work perfectly on the computers we used to design them, but would break down on the laptops. We recommend testing a designed activity on the actual computers students would use. This may uncover compatibility issues that can easily be fixed prior to the beginning of class. In addition, we would prefer to use a computer lab over individual laptops, as any changes made to one machine could be easily deployed on the others more efficiently.

Regarding the educational content of the Minecraft activities, we quickly learned as the class progressed that students had some difficulty transferring their microbiology knowledge from Minecraft to the context of the classroom. As mentioned, we observed this when students reflected on their experiences and had difficult recounting microbiology content over Minecraft terminology. We adjusted for this by asking pointed questions about the connections between the activities and the learning content during reflection exercises. We also embedded additional instructional content in the activities via information blocks and used microbiology terms when describing the Minecraft activities.

However, for future iterations we would better alert students to the connections between Minecraft and the course content. This would be done with additional classroom facilitation as students play the in-game activities, "pause" moments so students could reflect and reconnect, and in-class activities that call upon previous Minecraft experiences (e.g., simulations or assignments that specifically mention Minecraft activities).

Future iterations of our design, or similar coursework that would make use of Minecraft, should better account for the time commitments students need when completing projects. We found that too much time was spent on these class projects, while microbiology lectures and in-class simulations were getting pushed off the schedule in favor of more design time. If we were to offer this course again, we would place stricter requirements on students and spend more time with them individually to ensure they select a clear, actionable topic that can be easily represented in Minecraft.

A more attainable goal for their student projects will also make the assignment more manageable given a limited schedule. Additionally, more time for strategizing and planning (i.e., writing a design document) before actual building occurs, as well as ensuring that each design day have a set objective or deliverable, would be ideal. Once building is underway, students would receive individualized feedback on their projects at frequent intervals rather than just after each playtest session. Such adjustments could help provide more time for instructional content, help students have a greater understanding of course topics, and offer more technological flexibility.

Despite having a co-instructor assist the teacher and a design team to create the curriculum and Minecraft activities, we believe that our efforts could be replicated in other classrooms without the need of such substantial support. Prospective educators do not need to create elaborate activities as in-depth as those we developed. Simple activities tied to course content can still provide rich opportunities for students to apply their content knowledge in a contextual experience. The activities also do not need to be housed in a giant map and could instead be provided via individual map files as well. As mentioned, requiring our staff to spend time working with Minecraft allowed us to create more complicated activities and systems. However, the beauty of the game is that a very basic construction or solution can serve just as well as a complicated one. Creating educational activities within the game does not require a great deal of prior knowledge or commitment. While MinecraftEdu helped keep students on task because of its educator controls, its use is optional and not required to properly facilitate classroom work.

CONCLUSION: USING MINECRAFT TO SUPPORT LEARNING

The use of games in instructional contexts can support student learning (Squire, 2005) and emphasize the importance of 21st century skills (e.g., critical thinking, negotiation, simulation, etc.) (Jenkins, et al., 2009). Teachers and educational designers continue to face the challenge of pairing sound instructional approaches with gamified experiences while balancing time constraints and content.

In this paper, we discussed the design and implementation of an activity-based science curriculum over a two-week period that used Minecraft to support science instruction and student learning. Pairing Minecraft activities with typical classroom instruction provided students with an opportunity to apply their understanding of science content in a digital landscape. Minecraft allowed us to bring students into the "human body" without the need for expensive lab equipment or training. They could see how microbes assist in digestion, help ward off infection, and thrive in many different areas of our bodies. Based on our classroom observations of the Minecraft activities, targeted reflection exercises, and student projects, we believe our students acquired a deeper understanding of microbiology topics. We hope that others can learn from our experiences and consider developing these kinds of activities in a classroom.

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Play the activities that our students created at https://www.amnh.org/explore/ology/microbiology/human-microbiome-minecraft-map/

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