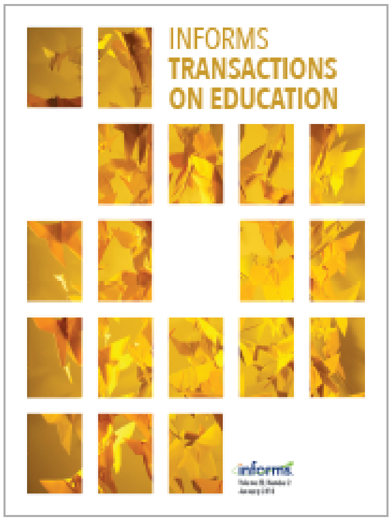

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Active Game-Based Learning of Dynamics Modeling and Simulation in Biomedical Systems Engineering

Nan Kong[a]

[a] Weldon School of Biomedical Engineering, Purdue University, West Lafayette, Indiana 47907
Contact: nkong@purdue.edu, http://orcid.org/0000-0002-4047-3414 (NK)

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Abstract. With widening application of systems modeling and simulation in healthcare industry, relevant courses have been created in many undergraduate biomedical engineering curricula to address the need in workforce development. However, it is challenging to teach systems modeling and simulation and effective teaching is demanded. To answer the call, I have used serious games in my teaching in the past few years. In this paper, I first present two interesting educational games and describe the design and implementation of two game-based active learning modules. I also report several learning outcome assessments and review my self-reflection during the teaching. Better game design and implementation, as well as further development of objective learning outcome assessments, are included in future plan.

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1. Introduction

Modeling and simulation of complex dynamical systems (e.g., high dimensional, nonlinear, stochastic) is an important technical skill for engineers (Sterman 2002, Hmelo-Silver and Azevedo 2006, Warwick 2007). However, it is challenging to teach it in conventional classrooms (Hmelo et al. 2000, Jacobson and Wilensky 2006) for the following reasons. First, conventional classroom teaching of systems dynamics theory in engineering schools is confined to ordinary differential equation (ODE) based modeling of low-dimensional systems and steady-state analysis of linear systems. However, most biomedical systems are high-dimensional, nonlinear, and stochastic. Additionally, in many cases, transient states deserve investigations. Second, many biomedical engineering students do not have necessary prerequisite to learn the subject of systems dynamics theory rigorously. They typically have only one math course covering differential equations and some exposure to linear algebra in their prior education. Finally, mathematical models for dynamic systems are often presented directly to students in the classroom with limited discussions on how to develop and analyze these models. In response to these challenges, I introduced two game-based instruction modules to the course "Mathematical Modeling of Complex Biological, Medical, and Healthcare Systems," offered as a technical elective course to junior and senior students in the Weldon School of Biomedical Engineering at Purdue University. In this paper, I describe the design of the two games. I also describe my initial implementation of the corresponding active learning modules and report preliminary assessments on the active learning outcomes.

In a standard biomedical engineering curriculum, aforementioned challenges of teaching dynamics modeling and simulation are partially addressed in some graduate-level courses for students who have chosen to conduct research in the area of systems science and engineering and for students who have taken sufficient mathematical prerequisites. Acknowledging the importance of systems modeling and analysis in the field of biomedicine, many biological and biomedical engineering departments have offered a technical elective course on the subject. However, these courses tend to focus on specific aspects of biomedicine and biomedical systems at a specific scale (e.g., quantitative biology, physiology). Recognizing the need of teaching general principles and techniques of systems modeling and simulation, I undertook a series of changes since 2011 in the systems dynamics course in the Weldon School of Biomedical Engineering at Purdue University. I included lectures on systems modeling and analysis of disease natural history and biomedical intervention, both at the individual and population levels. Specifically in terms of systems modeling, I included teachings on simple stochastic processes (e.g., Markov chains, birth-and-death processes), individual-based state transition modeling, and cellular automaton. In addition, I introduced model-based optimization for public health policy and management with focus on topics such as cancer screening and infectious disease vaccination. As mentioned earlier, challenges arose when teaching these new topics. To address the challenges, I suggested offering active learning to students majored in biological and biomedical engineering.

Educational games are serious games explicitly designed with educational purposes. Well-designed educational games have long been known to resemble real-world situations and stimulate students' interest to make learning more enjoyable and improve learning outcomes (Van Eck 2006). The learning process built in the games is what makes them more enjoyable (Bainbridge 2007). Game-based learning provides an "anchored" experience during the gameplay that multiple students or even the entire class share with each other (Cognition and Technology Group at Vanderbilt 1992). Such "anchored" experience is expected to partially address the learning challenges. Game-based active learning can promote the learning of systems dynamics for the following reasons. First, games can represent some of the more complex dynamics than differential equations can. Two, gameplay is clearly more fun than solving mathematical problems. Three, games, as close to reality, can help students understand the interaction between models and data, especially with well-designed learning modules.

In my class, I used one existing game and adapted another one. Both games closely resembled complex forms of competition between different types of agents, species, and/or cohorts. Both games required students to actively participate as decision makers. I designed two active-learning instruction modules that utilize the two games to teach modeling and analysis of complex systems. For the implementation, I tailored the modules to be well suited to the general population of biomedical engineering junior/senior students. As a result, the active learning experience offered an excellent context for students to make immediate connection between enjoyable gameplay and modeling and analysis of complex system dynamics. Moreover, the two modules emphasized operational-level decision making and its consequences. Hence, they can easily be adapted as stand-alone pieces to other systems biology and healthcare systems engineering courses, potentially through a massive online open course (MOOC) platform.

The two "playful" educational games used are *Humans vs. Zombies in the Avatar World* and *POX: Save the People*. The first game, which is a web-based Flash game, was adapted from the live-action game predominantly played at U.S. college campuses and believed to be analogous to cancer invasion with the evolutionary game theoretic perspective (Gatenby and Gawlinski 2003). The second game is a board game with the aim of stopping disease spread through herd immunity (Keeling and Rohani 2008). The gameplay dynamics well resembles the intricate dynamics in a real-world public health system after disease outbreak. Students were required to participate actively as decision makers in both games. The impact of their decisions on the system behavior was immediately assessed by algorithms intrinsic to each game. I coupled the gameplay with thought-provoking questions prior to, and after the gameplay to enhance the active learning experience. I implemented the two game-based learning modules in my class in 2013 and compared the class performance with that in 2015 when I taught the course again but did not run the learning modules.

The remainder of the paper is organized as follows. In Section 2, I introduce the backgrounds on game-based learning, my nonlinear system dynamics course, and the biomedical engineering undergraduate curriculum with focus on systems science and engineering. I also introduce the origins of the two games. In Section 3, I discuss the adaptation of the games and associated game-based learning modules. In Section 4, I report preliminary learning outcome assessments, and provide my reflection on the module design and implementation. In Section 5, I draw conclusions and outline a plan of further improvement.

2. Background

2.1. Game-Based Learning

Serious games have long been employed as a means of education (Kahne 2014). These games are designed to balance subject matter with gameplay so as to enhance players' ability to apply the subject matter to real-world practice. They are used to inspire motivation through active learning, which includes constant interaction during the gameplay and prompt feedback to the game players. Moreover, serious games encourage teamwork, and provide a flexible and safe virtual environment for skill enhancement (Pivec 2009). Most serious games substantiate problem-solving scenarios that spark creativity (Liu et al. 2011, Shearer 2013).

Game-based learning is a type of gameplay with defined learning outcomes. It is an increasingly universal character throughout college and continuing education (Johnson et al. 2009). It is an expansive category, ranging from simple paper-and-pencil games such as word searches all the way up to complex, massively multiplayer online, and role-playing games (Johnson et al. 2010). The success of game-based learning lies in active participation, in which interaction is at the center of the learning experience. To some extent, this success reflects that current learning methods are not engaging students enough (Green and Bavelier 2012).

There are three main approaches to creating games that stimulates learning are: integrate existing games; building games from scratch by the instructor; and creating games from scratch by the students. The most time- and cost-effective approach is to incorporate existing games into the classroom with understanding of the learning outcomes that the instructor has for the course (Van Eck 2006). In my class, I used one existing game and adapted another. Both games involve role plays, which allowed students to apply acquired knowledge to construct their decisions, experiment their decisions in the virtual game environment, and receive prompt feedback in the form of quantifiable consequences or rewards.

2.2. The Standard "Systems Science and Engineering" Curriculum in BME

Biomedical engineering (BME) students, under a standard undergraduate curriculum, obtain basic understanding of systems from the Signals and Systems course in their junior year, which is typically offered by the Electrical (and Computer) Engineering department. This course focuses on development of analytical tools and techniques for the design and analysis of discrete- and continuous-time linear systems. The primary topics are thus convolution, transforms, and sampling theory. Nevertheless, it does not give students much exposure to nonlinear systems of high dimensions and their dynamics. Furthermore, the course does not include any teaching on how systems science can be applied to biomedical systems. As for the mathematical foundation, BME undergraduate students take a course on ordinary differential equations in their freshman or sophomore year. In that course, they mainly focus on analytical solution techniques for one or two-degree ODEs. When the students advance to junior or senior year, it is difficult for them to see the connection between the ordinary differential equations course and any course dealing with the analysis of higher-order dynamical systems.

2.3. A System Dynamics Course

The course "Mathematical Modeling of Complex Systems in Biology, Medicine, and Health Care" is an undergraduate technical elective course offered to BME juniors and seniors. In the first half of the course, we introduce key concepts on systems dynamics, such as phase plane, bifurcation, stability diagram, and discuss classic examples such as harmonic oscillation. We derive all the results based on the ordinary differential equation representation of the system dynamics. In the second half, we introduce alternative modeling approaches of systems dynamics and their mathematical foundations, including stochastic processes, discrete-event simulation, and state-transition model. We also focus on mathematical modeling in cancer and infectious diseases, and use real-world applications to examine the materials covered in the first half of the semester. For an outline of the class schedule, please see Online Appendix A.

2.4. The Game *Humans vs. Zombies in the Avatar World*

The game *Humans vs. Zombies in the Avatar World* was adapted from the live-action reality game *Humans vs. Zombies* (https://humanvszombies.org). Since the live-action game began to be played in 2005 at Goucher College in Maryland, it has gained popularity throughout U.S. college campuses. The game has now developed an international fan base and received prominent press coverage from the *New York Times*, the *Washington Post*, National Public Radio, and the Associated Press. Many students in my class had experience with the live-action reality game.

The original live-action game is a game of tag. The objective of the zombies is to win when all human players have been tagged and turned into zombies, whereas the objective of the humans is to survive long enough for all of the zombies to starve. All players begin as humans, and one is randomly chosen to be the "original zombie." The original zombie tags humans and turns them into zombies. A zombie must tag at least one human every 48 hours by reporting the victim's ID. Otherwise, it starves to death and is out of the game. When tagged by a zombie, humans are required to surrender their ID cards. One hour after being tagged, the humans tie a bandanna around their heads and turn themselves into members of the zombie team. Now they can tag humans. On the other hand, humans may stun a zombie. A stunned zombie may not interact with the game in any way for 15 minutes. This includes shielding other zombies from bullets or continuing to run toward a human. If shot again while stunned, the zombie's stun time is reset back to 15 minutes. For this game, some areas on campus are designated to be "no-play zones," where the game is permanently suspended and no players may be stunned or tagged. These areas include bathrooms, health centers, libraries, indoor athletic facilities, academic buildings, and so on. Some other areas on campus are merely "safe zones," where gameplay continues but humans cannot be tagged. These areas include dorm rooms and dining halls.

In systems science and engineering language, this live-action game is a game played by two types of competing entities in a largely decentralized fashion even though some collaboration among the entities of the same type may emerge as the game goes on. The objective of each type of entity is to survive by attacking and annihilating the other type. This spirit of the game can be seen in many ecological and biological systems with competing entities. In my class, I teach the Lotka–Volterra model, a classic mathematical model that captures the dynamics of prey and predator populations. For teaching the model, I adapted the game *Humans vs. Zombies* to a computer-based serious game. I present more details on my adaptation in Section 3.

2.5. The Game *POX: Save the People*

The *POX: Save the People* game implemented in my class is a direct use of the game *POX: SAVE THE PEOPLE* (http://www.tiltfactor.org/pox), invented by Mary Flanagan and the Tiltfactor laboratory at Dartmouth College. The game is a board game that challenges a team of players to vaccinate and cure people until herd immunity is established (i.e., the disease is fully contained). In addition to the physical board game set, its iPad version is available to download with a minimal fee.

At the beginning of the game, a deadly disease is assumed to have broken out. The game is won when the disease can no longer spread to infect others, no matter which direction its spreads. The game is lost if five people die or if all infection chips have been played. A game set is composed of a squared game board comprising an equal number of vertical and horizontal lines, 28 POX scenario (outbreak or spread, explained below) cards, 50 blue (immunization) chips, 40 red (infection) chips, and 5 black (death) chips.

To start the game, a deck of cards is shuffled and placed facedown beside the board. A player places a red chip on each of the two red spaces on the board to indicate the originally infected people. Before play begins, players should agree to a difficulty level—the number of people allowed to die before the game is lost. The suggested difficulties correspond to the power of the intervention; for example, chicken soup is equivalent to four deaths, cough medicine three deaths, IV fluids two deaths, intensive care one death, and miracle zero deaths. Once the difficulty level is selected, the play begins. Players take turns. Each turn follows the same steps: (1) draw a card, (2) add red infection chips as directed by the card drawn (either spread or outbreak), (3) check to see whether anyone has died, and (4) vaccinate or cure as many people as the drawn card indicates.

Two types of cards can be drawn that imply the scenario faced. They are *spread* cards and *outbreak* cards. The scenario may state the direction to spread the disease, who will be infected, who can be vaccinated, or aftermath of the outbreak. When a *spread* card is drawn, every infected person spreads the disease, infecting healthy people in the direction(s) stated by the card. If, because of immunized people, no new infections occur, then one may vaccinate or cure twice the number shown on the card. When an *outbreak* card is dawn, a red infection chip must be placed on a healthy person matching the type shown on the card. If there is no such person, the outbreak cannot be next to someone who is immunized or infected. If there is no such person, the outbreak does not occur, and one may vaccinate two people instead of one.

Note that at the start of the game, there are three groups of characters: *infected*, *healthy*, and *vulnerable* people. The red spaces on the board indicate people who are infected at the start of the game. The infection may spread from them to adjacent healthy people. They may be cured and become immunized during the course of the game. The gray spaces on the board are healthy people. If healthy people become infected, they may be cured. The last group in the game is vulnerable people, represented by the yellow spaces. These are people who cannot be vaccinated, such as pregnant women, newborns, and people with weakened immune systems. Immunization chips cannot be placed on them, and they will die immediately if infected. In the last step of a turn, the player can vaccinate or cure people according to the drawn card. Any healthy person may be selected to vaccinate. Once vaccinated, that person becomes immunized and can never become infected. Thus, a blue immunization chip is replaced on the board accordingly. Any infected person can be selected to cure. Once cured, the corresponding red infection chip is replaced with a blue immunization chip. Immunized people can never be infected.

Finally, there are two ways that a death may occur: (1) an infected person will die, if surrounded on all possible sides by infected people; and (2) whenever a person who cannot be vaccinated (a yellow space) becomes infected, that person will die. Dead people cannot be cured or vaccinated. The game is lost when too many people die, based on the game difficulty chosen.

In systems science and engineering language, this board game represents a control system with stochastic spatiotemporal dynamics and a finite control space. In principle, the gameplay dynamics can be modeled with cellular automaton. I introduced cellular automaton as a modeling approach first on cancer invasion models and then scheduled this game to offer an active learning opportunity. After the game module, I taught mathematical modeling in infectious disease epidemiology; thus this game also helped expose the students to basic concepts of infectious disease control and management. In Section 3, I introduce the instruction module design in detail.

3. Design and Implementation

In this section, I discuss the design and implementation of the two game-based learning modules. For the learning module *Humans vs. Zombies in the Avatar World*, we also describe the adaptation of the live-action game to a web-based game. The criteria for the learning module design and implementation are listed as follows. The modules must (1) facilitate active learning, which is the most important criterion; (2) be closely related to the subject of systems modeling; and (3) give emphasis to the application domain. In addition, the modules should not interfere with the course schedule nor should they give me and the students much more burden.

3.1. The Learning Module with *Humans vs. Zombies in the Avatar World*

I made several important changes when adapting the live-action game *Humans vs. Zombies* to a web-based computer game: (1) the human and zombie populations are of the same size; (2) each player is only allowed to move at discrete time points among a board with squares arranged on a grid; (3) the winning is determined by a prespecified set of decision rules developed by me, acting as an arbitrator; and (4) there are no "no-play zones" or "safety zones."

The computer game was built in Adobe Flash, which is a software platform used for creating vector graphics; animation; games; and rich internet applications that can be viewed, played, and executed in Adobe Flash Player. Adobe Flash is frequently used to add interactive multimedia content to web pages. In addition, PHP (hypertext preprocessor), a server-side scripting language, is used around the game to facilitate user login and play recording. Once a user has logged in, PHP creates a session variable to indicate that the user is in an active session. This allows the game to be loaded on the user's page. Then Adobe Flash instructs a code to be sent to PHP for the current active user session. The return information is used to determine which player is playing the game. In the game, there are five main components: Map, Player, Play Period, Action, and Battle Manager.

I briefly describe these components as follows. The *Map* component displays current players on a grid. Before the game starts, the *admin* user (the instructor) needs to specify a number of following settings for the Map (e.g., the dimensions of the grid). A *Player* corresponds to a logged-in user. The admin user specifies whether each player is a human or a zombie initially. There are a number of attributes that apply to each player such as its position, its number of wins already cumulated, and so on. The admin user specifies the length of the *Play Period* as well. For a list of the parameters set by the admin user, please refer to Online Appendix B.

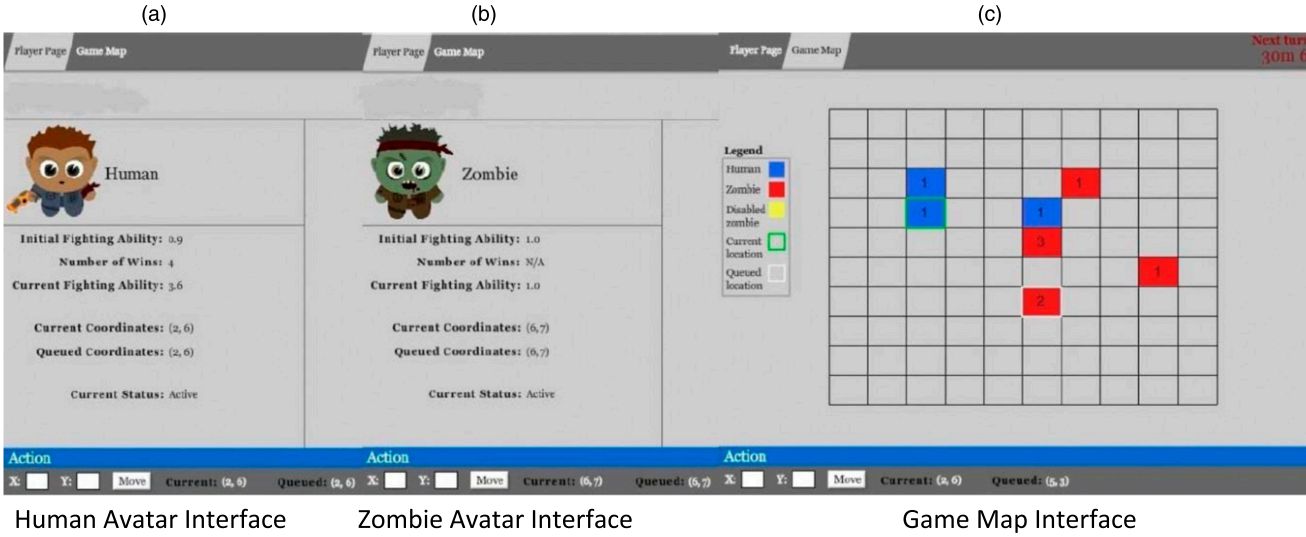
Within each play period, the *total length* parameter indicates the number of days the game is being played. Each period contains multiple sessions, and each session contains multiple turns. At one turn, each player is allowed to submit one action to indicate where it intends to move to. Hence, after each turn, the collective state of the players may be changed. The *Battle Manager* component is responsible to determine the outcome of the battle between humans and zombies at each square in each turn. To determine the outcome, an algorithm is used to generate a random number with a predefined formula based on the *fighting ability* of each human and zombie residing at the focused square. To configure the game play, the admin user also needs to specify the initial fighting ability, the battle winning reward, and the battle format. See Figure 1 for snapshots of the human and zombie pages as well as the game board. Please see Online Appendix C for more information about the game design.

With the PHP, log files can be generated at the end of each turn and released to the players through a secured file storage site. More important, it offers the convenience to gauge each student's interest and develop analysis questions based on the information collected. To benefit me and the students to review the gameplay, we use a downloadable Microsoft Excel macro for data visualization.

With this adaptation, this web-based game mimics the real-world game *Humans vs. Zombies*. The game, however, differs from the live-action game in several aspects. First and foremost, players cannot make any observation to determine their moves because each player's moves may be completely random and independent of previous moves, and it is only restricted by the board boundary. Second, the game is played within a fixed length of time, and each player can only make the move within prespecified time windows. Third, the outcome of the fight is partially determined by randomly generated numbers. Finally, a battle can be made between a group of humans and a group of zombies, and the battle outcome is determined collectively by the participants from the two sides.

This web-based game and its live-action counterpart were introduced in the first lecture of the course as a motivating example. Students were given a rule sheet at the end of the first lecture. In the ensuing lectures (i.e., the preparation phase), the students were encouraged to ask questions about the gameplay and

Figure 1. Snapshots of the Interfaces Appearing in the Game *Humans vs. Zombies in the Avatar World*



Notes. In panels (a) and (b), the interfaces also show the game clock to the next turn, as shown in the right upper corner of panel (c). For the interest of space, it is omitted. The parameters in the middle of panels (a) and (b) indicate the attributes and variables of a human and a zombie, respectively. A player enters the action information at the bottom of the window for the next move. The map displays the current game status.

its connection with our course. Meanwhile, the students were asked whether one-dimension systems could be applied to modeling the dynamics of the live-action game or at least some aspects of the gameplay dynamics. A hint was given when discussing one-dimension population dynamics models. The students were given bonus points when good answers were provided.

Two one-month gameplay periods were installed during the semester. The first one started in the first month, typically after a couple of weeks into the semester. The second one started in the third month, about two weeks after the second midterm. During each play period, each play session lasted a few hours in a day. The start time of a session was recommended to be 5–6 p.m., and the end time was recommended to be midnight to 1 a.m. This period was typically when undergraduate students were awake but not committed to class attendance. An automatic reminder about the gameplay was generated and sent to students every day. In addition to providing bonus points to students who played well, I would provide bonus points to students who played actively. I, together with the teaching assistant, periodically checked the log files to identify students who were not active. Based on our experience, the active level of playing this game was positively correlated with academic performance and final grade. So in class, I would encourage those relatively inactive students to participate more through periodic in-class discussion about the gameplay. During these discussions, I repeated a set of questions to assess the students' interest, facilitate their reflection on the gameplay, and enhance their understanding on modeling of the gameplay dynamics.

After the first play period, all the gameplay data were released to students who were then motivated to analyze the data to discover knowledge that may be useful in the second play period. A set of questions was given to the students between the two play periods to guide them in the data analysis. These questions ranged from basic descriptive statistics to pattern characterization—for example, how many moves did each student play during a fixed period of time, what were the average number of moves and the variation among the players, what was a good model to describe the number of moves, and what was a strong indicator of the better performances (e.g., with respect to the number of moves, common time of each move, and board position where moves were made). The questions were posted progressively, based on their difficulty. Along with asking the questions related to descriptive statistics, I asked students to conduct self-learning via online tutorials on simulation input modeling. Along with asking the questions related to pattern characterization, I encouraged the students to think about entity specification and cohort stratification. At the end of the second month, students were challenged to propose tools to simulate the gameplay dynamics and further synthesize their playing strategies to achieve better outcomes during the second play period.

After the second play period, the same set of questions as before were posted with less instruction while more emphasis was given to systems modeling and predictive analytics. In addition, I discussed in class the application of cellular automaton after the second play period. So during my class discussions, I asked the students to identify the applicability of advanced modeling approaches, such as cellular automaton, to model the gameplay. Finally, toward the end of the semester, I solicited the students to complete the conceptualization of the simulation model.

3.2. The Learning Module with *POX: Save the People*

Infectious disease prevention and control is clearly of national importance. Using applications from this area has been rewarding from a learning standpoint, as students gain social consciousness and learn how to create socioeconomically and ethically sensible solutions, which are important learning outcomes in engineering curricula. Implementation of an active learning module on infectious disease prevention and control helps the students achieve these learning outcomes in addition to learning the scientific subject.

The learning module with the game *POX: Save the People* was scheduled in a 50-minute lecture in the third month of the semester when mathematical modeling of infectious disease was the lecture subject. One week before the lecture, I asked students to learn the rules of the game and visited the website of the Tiltfactor Laboratory at Dartmouth College. During those few lectures, I held in-class discussions to confirm students' self-learning. I also introduced the classroom where the lecture would be held. It was a classroom in the Purdue's Discovery Learning Research Center (DLRC). The center aimed to transform education, especially in science, technology, engineering, and mathematics (STEM) and STEM-related disciplines, through research and implementation of research-based practice to improve learning. The classroom in DLRC we used was arranged in a way that benefited students' group learning during the gameplay.

At the beginning of the lecture, I took about five minutes to present a real-world scenario that the Centers for Disease Control and Prevention (CDC) faces: the challenge of establishing herd immunity in several major metropolitan areas, including New York, Los Angeles, Atlanta, and Houston, following an infectious disease outbreak. I asked students to discuss the concept of herd immunity within the specific context. Then the students were divided into four groups of five to six people. One person in a group was designated to be the gameplay scribe who did not participate in the gameplay. During the gameplay, the group members decided whether they wanted to discuss the next move together or leave the decision solely to the person who was in charge of the turn.

There were two gameplay sessions of 15 minutes each. At the beginning of the first play session, I handed the scribe a prompt sheet to record the gameplay dynamics. See Online Appendix D for the prompt sheet. There was a competition among the groups. When a group established the herd immunity, the group would announce it to the class, and I recorded the number of moves and time it took. I then asked the group members to see whether they could replicate the gameplay based on the recording and asked them to comment on whether individual or collective decision making is preferable. After the first play session, I asked the winning group to reflect on its decision-making strategy and asked the groups that did not establish the herd immunity to reflect on their shortcomings. In addition, I asked the following questions in class:

1. How can the game be more difficult other than allowing fewer people to die?
2. If you were a malicious agent, in addition to spreading the disease in a particular direction, what else could you do?
3. Were you able to record all system phenomena with the prompt sheet? Are there additional features about the gameplay dynamics you want to include?
4. With the gameplay log, can you replicate the gameplay?
5. How much time did you spend on making a vaccine/cure decision on a turn?
6. Was there any argument among your group members? Were you interactive or passive during others' turns?

The above example questions had different emphases on the teaching. The first two questions were used to provoke student's thoughts on the gameplay dynamics and its correlation with the game parameters. The next two questions were used to challenge students to think about how to describe the dynamics of a complex system. The last two questions were used to evaluate the group decision making. After spending five minutes on these questions, we moved to the second play session, in which the difficulty level was increased. Again, when a group established herd immunity, they would announce it. After the second play session, I again asked several winning groups to reflect on their decision-making strategy. I also asked questions related to system modeling and playing strategies. Sample questions are listed as follows:

1. Can you model the system phenomena you observed? What would be a good modeling approach for this system?
2. Can you summarize your gameplay strategies that seem to be beneficial so far?

In addition, I attempted to provoke thinking on enhancing social consciousness with the game. I asked students how they thought the game could be improved to help the general public understand herd immunity. Students responded positively to the above questions. We had good interactions in class. Some of the students raised their own questions based on these sample questions. I could see they were using the answers as cues for their decision making in the gameplay. Moreover, these sample questions prompted students to consider the real-world scenarios on infectious disease control. I also made several additional remarks on implementing this module. First, the class size was first about 45 students in 2009–2011 and dropped to about 25 students after 2012, when BME undergraduate students were no longer mandated to take this course. With the former size, we needed two lectures. With the latter size, we needed only one lecture. Second, I announced the bonus points given to the winning team(s) to encourage students' active participation. Finally, in the final exam, students were asked to write a reflective essay on how to improve the module.

4. Preliminary Assessment and Self-Reflection

For preliminary assessment, I first made real-time observations during class time on the two games and the effectiveness of the two game-based learning modules. In addition, I conducted an end-of-the-semester student survey in December 2013 when the game-based learning modules were implemented for the first time. I also conducted self-reflection at the end of the semester for continuous improvement.

For both modules, my real-time observations suggested most students enjoyed the games and appreciated their classroom use as an additional learning tool. As for the design and implementation of the two learning modules, my observations suggested modest ineffectiveness. For the module on *Humans vs. Zombies in the Avatar World*, the students seemed to become inactive playing the game as the semester went on even with increasing encouragement from me (e.g., promising a bonus toward the final grade). The evidence was that fewer students actually read the online log files. Next, data modeling and analysis questions were enticing, but most students treated them simply as additional homework assignments. Several students asked me to clarify how to report gameplay statistics as a result of a lack of prior knowledge on probability and statistics. In addition, knowledge on data-driven modeling and situation-based control did not seem to be well disseminated during the gameplay. Finally, some students felt that the play sessions were too frequent and the complete randomness on the system state made the game less meaningful.

For the module on *POX: Save the People*, some students did not familiarize themselves with the game rule prior to the learning module even though they were requested to. As a result, the class did not progress as quickly as I expected. In addition, the group decision making made some students quite passive in the gameplay, especially in the second session. Those thought-provoking questions were good, but more pre-class reading was needed, and the questions should be released prior to the class to give the students time to prepare. Some students suggested the first play session be longer and the second play session be shorter. In summary, although almost all the students thought the game was interesting and potentially viable to serve as an active learning experience, the design and implementation of the learning module should be improved.

The four survey questions (see Online Appendix E) were adapted from the four Accreditation Board for Engineering and Technology (ABET) learning outcomes for this course, which are currently effective at Purdue BME. I intended to assess the benefit of the game-based learning modules for improving the learning enthusiasm. As suggested by our assessment results (Table 1), students felt that they learned relevant subjects more actively and improved their abilities more actively.

To explore the impact of the game-based learning modules, I used standard outcome assessment activities (homework assignments and exams) to compare the effect of the course on the same four ABET outcomes between in 2013 and 2015 when the modules were not implemented. Our results suggested that, irrespective of the differences between the two cohorts, the learning outcomes seem to be improved. However, the improvements were not considered to be statistically significant, which may suggest that more studies need be conducted to investigate the association between the active learning modules and the potential learning outcome improvement.

After carrying out the two learning modules in 2013, I conducted self-reflection at the end of the semester for continuous instructional improvement.

Table 1. Student Assessment on the Use of the Game-Based Learning Modules (n = 19)

Question	Strongly agree	Agree	Neutral	Disagree	Strongly disagree
Q1	13	4	2	0	0
Q2	12	3	3	1	0
Q3	6	8	3	2	0
Q4	5	10	4	0	0

I make specific remarks on improving the implementation of each learning module. For the first module, the data analysis part somewhat fell short. To improve the learning experience, an introduction to probability and statistics is required. Alternative modeling approaches other than ODEs should be taught earlier in the semester to be coordinated with the gameplay. For the second module, to make the learning more socially relevant, some background knowledge on the CDC and its infectious disease control policies should be provided to the students. In class, more sophisticated and challenging scenarios for disease control should be designed. The associated questions should be asked more sequentially. Finally, I have also planned to develop the Flash version of the game. With the computer game, I could have implemented this module in a manner similar to the first one throughout the semester.

Personally, I felt that the one improvement needed the most is to develop more explicit connections between the gameplay and mathematical modeling. This has been quite challenging from an instructional viewpoint. With the gameplay, the students clearly enjoyed the class more but did not necessarily improve the learning outcomes. I felt this would need better design in both the games and the learning modules. The games should be made more interactive, and the learning modules should have a clearer application context. Good thought-provoking questions must be designed to facilitate students' learning. These questions should also be placed more effectively in the modules. Finally, to make the games more realistic, additional environmental factors should be incorporated. For example, the game grids for *Humans vs. Zombies in the Avatar World* could be modified to include more realistic geographic boundary—for example, a particular campus for the first period and a particular city for the second period. Finally, to teach systems optimization together with system dynamics modeling, outcomes should be associated to each move and tallied automatically, and the results should be made available to the students.

5. Conclusions and Future Work

In this paper, we report the design and implementation of two game-based learning modules for my class "Mathematical Modeling for Complex Systems in Biology, Medicine, and Healthcare." Preliminary observation and assessment were conducted. Self-reflection also was made for improving the modules and enhancing active learning experience.

The design and implementation criteria are related to several key challenges on teaching complex systems dynamics and operations research applications. More specifically, these challenges lie in the teaching of (1) alternative modeling approaches, (2) modeling and simulating higher-dimensional systems, (3) analyzing transient states of the system, and (4) data-driven modeling. Through self-reflection and survey data, I identified improvement directions.

In terms of future work, I plan to systematically design objective learning outcome assessment metrics and tools to investigate the effect of game-based learning modules. In terms of module design, I plan to focus more on achieving better interaction with students not only through better game design but also through better implementation of the learning modules and additional active learning materials (e.g., asking the students to adapt/refine other games on their own). Better thought-provoking questions must be designed. I also plan to design a semiquantitative questionnaire focusing on how game-based learning can improve the overall BME ABET learning outcomes (e.g., the four items in Online Appendix E) and potential future needs at the interface between data science and biological science. I plan to administer it at different time points to acquire cross-sectional data. Meanwhile, I plan to hold multiple informal interviews with students to better gauge their interests in a real-time fashion. Additionally, I plan to transfer the two modules to massive online open course (MOOC) units and explore the possibilities of embedding the modules in other residential courses. Finally, I plan to recruit student groups of larger sample size with the establishment of the MOOC course for conducting the hypothesis testing.

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