Exploring How Student Designers Model Climate System Complexity in Computer Games

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Abstract: We present results from a design-based research project in which 8th-grade teachers and students explored climate change by designing computer games using Scratch. We analyzed 174 games based on (a) systems complexity and (b) triadic game design (TGD). The analysis of system complexity shows that two-thirds of the students designed systems using 1-directional linear connections, while one third designed complex systems based on multiple connections and included feedbacks, or loops. TGD analysis shows that the most frequent topics were human choices that impact climate change (54 games) and actions that mitigate climate change (53 games). The majority of games were based on a quiz (32), shooter (31), action (27), or pong (29) genre of gameplay. The underlying teaching purpose of the games fell into 2 categories: (a) teaching about climate change directly through text or indirectly through gameplay, or (b) raising awareness by having players make responsible choices in-game (e.g., walking, not driving). Choices of teaching purpose and gameplay entailed important design considerations for students; this result has implications for how game-design tasks within particular domains such as science might be framed in future.

Introduction

The Building Systems From Scratch project is developing, implementing, and studying an intervention that integrates computer-game design and climate science in an eighth-grade curriculum unit taught by science teachers. Using a systems and socioecological approach, students create computer games using Scratch to teach other students about climate change. Given the demonstrated affordances of game design in supporting systems thinking, we conjecture that immersion in a design task to create a game that teaches others about climate change will result in students' learning skills in specific science and computational practices—systems thinking and modeling. In this paper, we analyzed a body of student games from Year 2 of this project to consider how they modeled systems in their games.

Theoretical Framework

Computational thinking practices. Wing (2006) has described computational thinking (CT) as a general analytic approach. First defined in the context of computer science, CT also includes a range of practices central to other scientific and mathematical disciplines. In addition to widely recognized computational practices such as decomposition, iteration, and algorithmic thinking (National Research Council [NRC], 2011), scientific practices such as modeling and simulation, and systems thinking, can be considered as CT (Weintrop el al., 2015). In the context of this project, we describe CT as "CT practices (CTP)" since student data reveal thinking only in the context of what students say and do.

Teaching CTP has become increasingly familiar in K–12 education (Denner, Werner, Campe, & Ortiz, 2014; Grover & Pea, 2013). Coding, or programming, is often used to teach students CTP (Grover, Pea, & Cooper, 2015). Sengupta, Kinnebrew, Basu, Biswas, and Clark (2013) review the synergies between CT and other disciplines that have been identified by various researchers since 1988, but they point out that CT has not been systematically integrated into K–12 curricula, despite the fact that calls for integrating programming with curricular domains such as science and math have been made for some time (ACM K–12 Taskforce, 2003). We will report data on student CTP more fully elsewhere; in this paper, we focus on systems thinking, including practices such as defining a complex system, understanding system relationships, and managing complexity, and on modeling, including designing and constructing a model.

Modeling complex systems has been a foundational tool in the development of scientific understanding of current and future impacts of climate change. As Wilensky and Jacobson (2014) observe, the science of complex systems "provides both a framework and a context for the practice of computational thinking" (p. 328). We use Ingham and Gilbert's definition of a model as a simplified representation of a system, which concentrates attention on specific aspects of the system at the expense of others (Ingham & Gilbert, 1991). When constructing a model, the designer must make many decisions—defining the boundaries of the system, deciding what to include, and conceptualizing the behaviors of components in the model. Then, the learner integrates information about the structure, function, and causal mechanisms in the system, including only features that are important to understand the system being modeled (Weintrop et al., 2015; Windschitl, 2013). Game design requires many modeling practices, such as representing processes through abstractions and deconstructing problems into a series of ordered steps. Furthermore, game design can be effective in teaching about systems (Puttick, Strawhacker, Bernstein, & Sylvan, 2014; Puttick & Tucker-Raymond, 2018; Puttick, Tucker-Raymond, & Barnes, 2017).

Learning through game design. Game design as a tool for teaching programming and CT has grown in the past decade or two with the advent of visual programming tools such as Alice and Scratch (NRC, 2011). Game design has proved to be highly engaging at middle and high school levels (e.g., Aydin, 2005; Reppening, Webb, & Ioannidou, 2010), facilitating creative thinking, social cooperation, and broader participation (e.g., Denner, Werner, & Ortiz, 2011). However, programs that use game design to focus on areas of STEM are only now growing more prevalent (e.g., Denner et al., 2014; Puttick & Tucker-Raymond, 2018; Salen, 2007; Tucker-Raymond, Torres-Petrovich, Dumbleton, & Damlich, 2012).

We drew on the theory of triadic game design (TGD) in designing this project. TGD suggests that the successful application of games in education requires an interdisciplinary approach in which three interdependent paradigms should be considered (Harteveld, 2011). *Reality* represents the connection between the game world and the real world, suggesting that any game contains an underlying *model of reality*, often deployed through the representation of real objects (e.g., cars) or the implementation of real-life physics and mechanics. *Meaning* represents the underlying message of a game (either intended or perceived) to the player, for example, entertainment, education, or awareness. Finally, *Play* represents the *genre* of a game, which often defines the characteristics of the gameplay, and the challenges players undertake (e.g., shooting at targets, deflecting objects, etc.). In the curriculum, each paradigm included specific criteria that need to be considered and balanced. Equally, we expected students to keep these three paradigms in mind as they conceived of and designed their games.

In this paper, we address the research question: To what extent can student designers model climate system complexity in computer games?

Methods

Design Context, Participants, and Data Sources

The data for this study are taken from Year 2 of a larger design-research project on teaching climate systems and CT through the design of computer games. Seven eighth-grade science teachers at two separate middle schools in a Northeast U.S. suburb adjacent to a major city taught four sections of approximately 22 students each. There were 21–28 days of instruction in classes of 50 minutes.

Instruction was conceptualized in terms of systems modeling and game design. The curriculum asked eighth-grade students (13–14 years) to create computer games using Scratch, a graphical drag-and-drop programming language (https://scratch.mit.edu), through which others could learn about climate change. Students explored climate systems and climate change through constructing physical models, exploring visual interactives and animations of climate systems online, and through concept mapping. They discussed game genres (e.g., arcade, adventure, multiplayer), played and critiqued a sample of online games related to climate change, and then became familiar with Scratch through various activities developed by the Scratch education community (scratched.gse.harvard.edu). Student pairs chose the topic for their game and used a design template based on TGD to create a design sketch. Finally, they programmed their games in pairs while engaging in rounds of play testing and critique. All games (N = 174) were archived in studios set up by the teachers on the Scratch website (scratch.mit.edu).

Analysis

Reality, Meaning, and Play. To quantify the TGD model in each game, two researchers qualitatively applied the three codes shown in Table 1.

Code and Definition	Examples
Reality: The climate change domain, topic, or content	Albedo, transportation choices that impact climate, the greenhouse effect, capturing CO2 emissions
Meaning: The purpose of the game, described in text in an introduction or end comment, or in gameplay	“Learn the reason why the ice caps are melting,” “Ditch the green energy idea, let’s make money by using fossil fuels,” “Make decisions with the goal of saving the environment”
Play: The genre or type of game (e.g., Arcade, Narrative, Strategy) which defines gameplay and player input	Arcade: Deflecting CO2 with an onscreen object, clicking objects randomly appearing on screen. Narrative: Player progresses through a game “story.” Strategy: Player participates in a real-life scenario with realistic interactions among the components

Table 1. Triadic game design coding scheme.

Systems complexity. To quantify the complexity of the climate system in each game, two researchers mapped the system components as a concept map, including the components both in descriptive text and in gameplay. With arrows, we connected components that had causal connections in the game. We then counted (a) the number of system components, (b) the number of individual causal connections between any two components, and (c) traced out the longest chain of causal relationships and counted the number of connections in it. We included the player-as-avatar as a system component if the avatar had a real-world counterpart that has a role in the climate system being modeled in the game. All games were consensus coded.

Results

Overall, games represented Reality by depicting the fact that human choices affect climate change (n = 54) through choices about daily actions (Table 2). These games typically included causal connections but less complex systems overall. However, games that countered human impacts with game actions that mitigate climate change (n = 53) obviously treated more than one climate topic at once. For instance, games to capture CO_2 often required the player to counter deforestation with reforestation, while games about transportation impacts posed alternative transportation choices to these such as cycling or taking the bus. Games in this second thematic category typically tended to have more complex systems and could include feedbacks. A third category of games addressed climate phenomena directly (n = 47) through depicting some of the impacts of climate change, for example, rising sea level, extreme weather, or how albedo or the greenhouse effect impact global temperature. These games also tended to have more complex systems and could include feedbacks. Finally, games that involved making trade-offs (n = 20), for example, making political decisions that had policy impacts, or making investment decisions, tended to have multiple interacting components and multiple feedbacks.

Thematic category	Reality (Primary Climate Topic)	#		Play (Game Genre)	#
Human choices affect climate change (n = 54)	Multiple (e.g., energy use, transportation, diet)	39		Quiz	32
	Transportation only	8		Shooter	31
	Deforestation only	7		Action	27
Actions that mitigate or adapt to climate change (n = 53)	CO_2 mitigation (e.g., plant trees)	47		Pong	29
	Renewable energy	4		Platform	14
	Other (e.g., geoengineering)	2		Competitive/Multiplayer	14
Phenomena central to understanding climate change (n = 47)	Impacts of climate change	14		Storytelling	11
	Albedo, solar radiation, greenhouse effect	27		Maze	6
	Carbon cycle, fossil fuels, energy use	5		Building	4
Making trade-offs (n = 20)	Green energy vs. fossil fuels, forests vs. buildings	18		Strategy	3
	Political	2		Reverse Whack-a-mole	3

Table 2. Results of TGD analysis for Reality (left) and Play (right).

Regarding Play, the most frequent genre was *quiz* games (n = 32), in which gameplay structure was based on posing questions related to Reality climate topics that the player could answer by selecting among two to four to possible choices (Table 2). Other games involved more action-oriented gameplay, such as *shooter* (n = 31) in which the player has to shoot CO_2 molecules and clouds to clear the atmosphere in a short period of time, single or multiplayer *pong* (n = 29) games, or *platform* games (n = 14), in which the player has to jump to avoid objects that are bad for the environment (e.g., methane, CO_2, cars, nonrecyclable items) and has to try to collect "good" objects (e.g., trees, recyclables).

Regarding Meaning, the games were divided in two main categories: (a) *teaching* and 2) *responsible choice*. Teaching was achieved (a) *directly*, by showing text or graphical tutorials to players that explicitly instructed them on topics related to climate change, or (b) *indirectly*, as the player learns from feedback provided by the game itself (for instance, see *Albedo Pong*). Players were asked to make responsible choices in two ways, by either (a) *making responsible choices*, for instance by sorting different kinds of garbage in appropriate collectors (e.g., recycling, nonrecycling), or (b) *making irresponsible choices*, for instance by cutting down trees to see the effect of deforestation on the climate. The category of irresponsible choice is interesting in using reverse psychology, making game players do bad things to learn positive concepts.

The body of games taken as a whole revealed a considerable range in the complexity of systems represented in Reality, both in terms of the average number of systems components defined by student designers, and in terms of the numbers of connections they made between and among components (Table 3). An example of a game with three components (e.g., *CO_2 Project*) might involve the player using a tree to capture CO_2 molecules being randomly emitted from a factory smokestack, while a game with 19 components (e.g., *Save the Earth*) might involve the player in making trade-off decisions among many energy-related options to optimize resource use and minimize climate impacts. Many students found ways to connect all of the system components to at least one or two other components (an average of 5.38), while the longest continuous chain that students made ranged between 1 and 8 (average 3.2).

Average no. of components (range)	Average no. of single connections (range)	Average no. of connections in longest chain (range)
5.69 (3 -19)	5.54 (1 - 38)	3.20 (1 - 8)

Table 3. Components and connections in games (N = 174).

Three cases. We report three games from our analysis as representative cases of how the games designed in the classroom-studios ranged from simple to complex systems. We report the following three cases in order of system complexity: (a) *Albedo Pong*, (b) *Carbon Clicker*, and (c) *Government Simulator*, and describe how the three cases map to the TGD model.

Albedo Pong has six components, six connections, and one feedback loop. It uses the structure of an *arcade* game, in particular the popular pong game from the 1970s. Through a simple ponglike gameplay, the game teaches the player about concepts such as ice-albedo feedback and rising ocean level, both of which phenomena are central to global warming. We consider this game to have a *simple* system complexity, in that it includes five components linearly connected. Yet it provides immediate feedback to the player, who learns about the effect of ice-albedo feedback directly on his or her avatar. In fact, the player uses a platform-paddle made of ice, which shrinks every time solar radiation enters the ocean (see Figure 1, left); this is a simple yet powerful example of an in-game reinforcing feedback loop. Besides the paddle shrinking, the ocean level rises when solar rays strike its surface because of thermal expansion as the effect of warmed-up water. *Albedo Pong* is a good example of how students can create a complex systems representation based on simple, yet elegant, interactions, by using few key components (i.e., a sun ray, an ice-paddle that melts, the ocean that rises, a temperature gauge).

Carbon Clicker uses the Play structure of *storytelling* to simulate the environmental impact of current economic and technological progress in our society. We consider this game to have moderate system complexity, since it includes seven components that are connected linearly, yet overall it presents a solid systems view based on how the components are interconnected (Figure 1, middle). Likewise, the TGD analysis shows visual and rhetorical power.

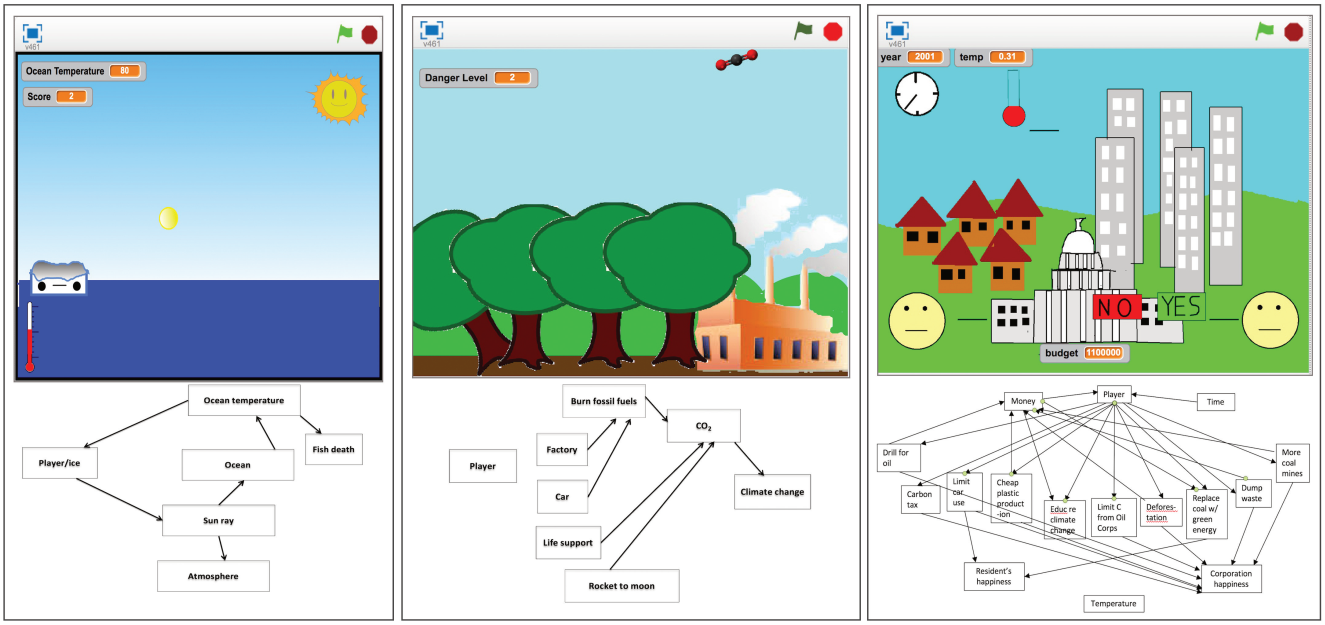

Figure 1. Screen shots (top) and coding for system complexity (bottom) for Albedo Pong game (left), Carbon Clicker game (middle), and Government Simulator game (right).

Carbon Clicker represents aspects of Reality such as deforestation, factory building, the intensive use of medical devices to support dying humans, and the use of cars. It demonstrates how these technologies accumulate CO_2 in the atmosphere and gradually endanger the life of humans and of Earth. The Meaning of the game is about raising awareness about the consequences of irresponsible use of technology, which results in unsustainable CO_2 emissions; this always leads to dramatic consequences at the end of the game—Planet Earth will overheat beyond tolerable levels and eventually die. Regarding the gameplay, the player is guided through the game and presses specific keys for advancing the story plot. In the final level, the player can choose between two possible endings: (a) provide life support to a dying human and go on a rocket to the moon, or (b) do not provide life support and let the human die; in both cases Earth becomes uninhabitable and dies as a consequence of global warming. Although *Carbon Clicker* has just one more component than *Albedo Pong*, the system representation in-game is more complex in that it displays a wider variety of phenomena that are related to climate change.

Government Simulator uses the Play structure of a *strategy* game in which the player acts as a politician (i.e., a government official) and makes political and economic decisions that impact the environment. The system is what we consider complex—it features 38 individual connections among the 16 climate-related components in the game, with six feedbacks, three of which are balancing and three of which are reinforcing (Figure 1, right). The game connects the player with Reality by letting him or her make decisions that resemble the ones politicians must take in real life, and the player can see their effect over time. Specifically, the player decides how to spend public money on resources and invest in either fossil-based or renewable energy; decisions affect the satisfaction of both local residents and corporations as well as global temperatures. Feedbacks from these decisions either reinforce the climate impacts (e.g., investment in fossil-based energy increases money with which to make further investments) or balances climate impacts (e.g., imposing a carbon tax results in less fossil fuel investment, which feeds back to lower temperatures). The Meaning of the game is to raise awareness of how political decisions impact the environment over time, and how to make responsible choices. The Play structure is simple: While the years pass (the game features a clock in the upper left corner that shows the annual flow of time), the player clicks buttons to decide between two possible choices at a time (e.g., investing in building more factories vs. planting more trees). Ecofriendly decisions make the population happy and lower the global temperature. On the contrary, less ecofriendly decisions are more profitable and make investors happier but raise global temperatures because of higher CO_2 emissions. This game represents a good example of a complex game that has many components, and it incorporates interactions in such a way as to demonstrate ways in which the behavior of complex systems can be emergent.

Discussion

When designing their games, students were confronted with a suite of decisions, as is true for all modelers (Wilkerson-Jerde, 2014). They defined system boundaries, concentrated attention on specific system aspects, and conceptualized system behaviors. They drew on the climate science they had learned, and they had to integrate it with considerations of what they wanted the player to learn from playing the game, and of what the player experience would be like.

We began our analysis with an assumption that simple games would necessarily model simple systems. However, a third of the students either included at least one feedback or a loop connecting two related phenomena, thereby modeling more complex aspects of systems behavior. There are many possible reasons why, for many, feedbacks were not realized in their game designs. First, programming the logic operations and setting up the variables necessary to create feedbacks are advanced programming skills. Many students began participation in the unit not having had any prior Scratch experience and may not have had sufficient time to develop these skills. Second, the task of balancing Reality, Meaning, and Play is a complex one that even seasoned game designers struggle with (Salen & Zimmerman, 2004). Third, students were empowered to choose any topic within the general area of climate change; for some, it is possible that the Play consideration dominated their choice of topic. Hence, arcade-type games, in which the player races the clock to complete a task such as making CO_2 molecules disappear, or navigating a maze, or dodging obstacles, were the most frequent genre of game. Future research will enable us to elucidate these possible explanations and further refine instruction so that systems complexity can be taken up by the majority of students.

On the other hand, the three cases we discuss in this paper all demonstrate that simplicity of Play does not necessarily mean that the system Reality being modeled cannot be complex. For example, the designers of *Albedo Pong* carefully chose a few systems components, yet created a game that powerfully demonstrates the functioning of the important phenomena related to climate change. Despite the apparent simplicity of the game, the designers modeled a climate feedback, which is a central feature involved in polar warming and important in many other aspects of the complex global climate system as well. In this, their modeling represented mature practice, as described by, for example, Ingham & Gilbert (1991) and Windschitl (2013).

The curriculum framed the design task—designing a game to teach others—with the rationale of making game design an authentic task about an important and complex problem that has global ramifications, one that is meaningful to young people everywhere. The careful attention that these student designers paid to the Meaning aspect of their games attests to the success of this approach. It has implications with regard to framing the design task for others who would include game design as a tool to teach science. Finally, the results we present here continue to persuade us that game design has the potential to support systems thinking. Future research will elaborate how curriculum can be further refined, and how students can best be supported to represent their understanding of complexity in climate systems.

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