Collaborative inquiry play

A design case to frame integration of collaborative problem solving with story-centric games

Asmalina Saleh and Cindy E. Hmelo-Silver
Center for Research on Learning and Technology, School of Education, Indiana University, Bloomington, Indiana, USA
Krista D. Glazewski
Department of Instructional Systems Technology, School of Education, Indiana University, Bloomington, Indiana, USA
Bradford Mott
Department of Computer Science, North Carolina State University, Raleigh, North Carolina, USA
Yuxin Chen
Center for Research on Learning and Technology, School of Education, Indiana University, Bloomington, Indiana, USA, and
Jonathan P. Rowe and James C. Lester
Department of Computer Science, North Carolina State University, Raleigh, North Carolina, USA

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Abstract

Purpose – This paper aims to present a model of collaborative inquiry play: rule-based imaginary situations that provide challenging problems and support agentic multiplayer interactions (c.f., Vygotsky, 1967; Salen and Zimmerman, 2003). Drawing on problem-based learning (PBL, Hmelo-Silver, 2004), this paper provides a design case to articulate the relationship between the design goals and the game-based learning environment.

Design/methodology/approach – Drawing on conjecture mapping (Sandoval, 2014), this paper presents an iterative development of the conjecture map for CRYSTAL ISLAND: ECOJOURNEYS and highlights the development of the story and tools in CRYSTAL ISLAND: ECOJOURNEYS, an immersive game based on PBL pedagogy. By articulating this development, the authors highlight the affordances and constraints of designing for collaborative inquiry play and address challenges in supporting learner agency.

Findings – The PBL inquiry process served as the foundation of collaborative inquiry play. Attending to the rules of inquiry fostered student agency, and in turn, playful engagement in the game-based learning environment. Agency however meant holding students accountable to actions undertaken, especially as it pertained to generating group-based explanations and reflecting on productive collaboration. Moreover, socially shared regulation of learning and systems thinking concepts (i.e. phenomenon, mechanisms, and components) must also be externalized in representations and interactions in the game such that students have the agency to decide on their learning paths.

Originality/value – This paper presents the model of collaborative inquiry play and highlights how to support player agency and design content-rich play environments which are not always completely open.

Keywords Play, Socially shared regulated learning, Problem-based learning, Collaborative inquiry, Game-based learning, Complex systems

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Educational research has shown that game-based learning environments provide playful contexts that allow participants to immerse themselves and extend their identities, engage in collaborative problem solving and complex literacy practices, and develop expertise in their communities of practice (Turkle, 1995; Gee, 2003; Klopfer *et al.*, 2005; Squire, 2006). In these contexts, play can be defined as grounded in real social experiences yet includes imaginary contexts and roles that extend the individual beyond their current abilities (Fein, 1981; Leslie, 1987; Nicolopoulou, 2007; Vygotsky, 1967). In a similar vein, scientific inquiry in games can also involve authentic experiences that leverage challenging and meaningful roles. Thus, games can provide the context for rich scientific inquiry, encouraging learning of content and engagement with scientific practices. However, supporting inquiry through game-based learning environments is not a straightforward task in part because of the difficulties in defining inquiry and the challenges of integrating play in educational contexts (Pedaste *et al.*, 2015; Dichev and Dicheva, 2017). Moreover, the success of inquiry-based technologies for learning and teaching depends on multiple factors such as support in the classroom and at the institutional level (Kim *et al.*, 2007). These difficulties are further compounded when one is interested in designing for collaborative inquiry learning.

Given these issues, the current article discusses collaborative inquiry play, an approach that utilizes problem-based learning (PBL), an effective social constructivist pedagogical model. Collaborative inquiry play is defined as:

- rule-based imaginary situations that provide challenging problems; and
- experiences that support agentic multiplayer interactions.

To unpack this definition, the article presents a design case of a collaborative technology-based learning environment, called CRYSTAL ISLAND: ECOJOURNEYS. The main aim of the research project is to deliver adaptive scaffolds for collaborative inquiry in the context of learning about ecosystems by using intelligent agents. To understand how to design this effectively and understand the nature of facilitation, the research team undertook a series of design iterations, starting from focus groups to larger classroom studies. Drawing on embodied conjectures (Sandoval, 2014), the article highlights the development of two aspects of the design:

(1) the problem space, or context of the game-based learning environment's story; and
(2) the brainstorming board, a shared collaborative space within the learning environment.

The article illustrates the evolution of the embodied conjectures, and the importance of small-scale iterations before concretizing these principles more broadly in a game-based learning environment. In this case, the initial design of the problem space in the story-driven game shifted from a focus on collaborative inquiry and the associated content outcomes, to one that addressed the social interactions in collaborative inquiry more explicitly. Given that design iterations of how learning is integrated in game-based learning environments are not always reported, it is hoped that shedding light on the process will illuminate how researchers might effectively design collaborative story-driven games that also support inquiry processes (Ke, 2016). The article first presents an overview of the design case and the theoretical framework that informed the design of CRYSTAL ISLAND: ECOJOURNEYS, a game-based learning environment developed as part of a five-year research project. Then, each iteration of the embodied conjecture and associated field tests from the first three years of the project are highlighted. Finally, key takeaways for designing for collaborative inquiry play are presented.

The design case

To address the challenges of integrating collaborative inquiry with game-based learning environment, the current article presents a design case of how collaborative inquiry play shapes the integration of learning content into the player experience in CRYSTAL ISLAND: ECOJOURNEYS. A design case is a description of how a particular artifact or experience is designed (Boling, 2010). By highlighting the iterations of the design, the article presents an argument for how collaborative inquiry play can promote agency without subverting player interests, even in a constrained environment with specific pedagogical goals. Furthermore, the design case can couple with conjecture mapping, a framework that articulates the relationship between design and conjectures as a formalized way of building on theoretical, design, and research precedent (Sandoval, 2014). Embodied conjectures refer to the way in which design goals and theoretical propositions might be reified within design environments including tools, material, activity structure, and social interactions (Sandoval, 2004). Embodied conjectures have several characteristics:

- they should be specific so that they can be empirically refined;
- be reflected in multiple ways throughout the design;
- articulate the anticipated learning outcomes; and
- they should envisage interactions within the designed context.

Embodied conjectures are reified in conjecture maps that highlight the high-level conjecture about how learning must be supported, and these conjectures are then represented in an embodiment of the design. These embodiments in the design are then expected to foster mediating processes that lead to desired outcomes.

In the design, the initial high-level conjecture was as follows: *Successful collaborative inquiry learning depends on engagement with inquiry.* Figure 1 shows the initial high-level conjecture as instantiated in the early stages of the research. The high-level conjecture was shaped by PBL, a pedagogical model that is a good fit for the narrative structure of play while also supporting integration with curricular standards. In what follows, the article discusses how PBL informed the collaborative inquiry framework before tracing the evolution of this initial conjecture as instantiated in the embodiment, mediating processes, and desired outcomes.

Collaborative inquiry play

Research in science inquiry learning has indicated that inquiry is productive but challenging to support especially in technology-rich environments (Pedaste *et al.*, 2015; Dichev and Dicheva, 2017; Kim *et al.*, 2007). The challenges of inquiry learning are further compounded by working in groups (Dillenbourg, 1999). Yet, the fact remains that collaborative inquiry

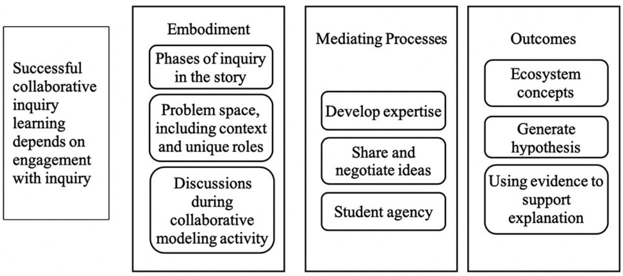

Figure 1. Conjecture map guiding the design of tools and context for CRYSTAL ISLAND: ECOJOURNEYS

learning is a critical element of science learning, as evident by the call for integrating inquiry practices and collaboration in workplace environments (Hilton, 2010; National Academy of Sciences, Engineering and Medicine, 2019). Despite these challenges, technology-rich environments such as game-based learning environments have demonstrated that productive inquiry learning can indeed be supported (Donnelly *et al.*, 2014; Ketelhut *et al.*, 2010). Even though research in educational games has provided useful frameworks for the design of story-centric games (c.f., Arnab *et al.*, 2015; Plass *et al.*, 2015), the integration of games in specific educational contexts remains underspecified (Dichev and Dicheva, 2017). Given that the design of educational games should be informed by learning theories, a theoretically-principled approach toward the game design could allow an articulation of how student interactions with rules can offer insights into play and learning. Thus, the research team utilized PBL, an instructional approach that draws on a constructivist paradigm.

As a pedagogical model, PBL informed both the collaborative inquiry play framework and the design of CRYSTAL ISLAND: ECOJOURNEYS. PBL draws on several assumptions: the interactional nature of inquiry learning, cognitive puzzlement, and social negotiation (Savery and Duffy, 1995). Indeed, these fundamental assumptions about learning are integral to Vygotsky's (1967) approach to learning in that students appropriate ideas from their social interactions into their own individual repertoires. Play is best supported when learners face challenges with either the social and/or material environments (e.g. tools, concepts, etc.). Although integrating play with scientific inquiry is not a novel idea, it is not yet clear how one might design for collaborative inquiry play. This article highlights how PBL, or a collaborative inquiry framework can support play, especially in an immersive context that is challenging yet supports student learning and engagement. Thus, collaborative inquiry play is defined as:

- rule-based imaginary situations that provide challenging problems; and
- experiences that support agentic multiplayer interactions.

An important aspect of articulating collaborative inquiry play is that the definition of play rests on the assumption of agency within the constraints of a cognitively challenging learning environment. This definition takes the perspective that play is grounded in social experiences that allow learners to reflect on the rules that govern these social processes and adopt roles that push them beyond their current practices (Elbers, 1994). Moreover, the learning environment is defined as a system with rules in which students engage with challenges that lead to measurable outcomes. In short, the system provides rules or a structure which in turns fosters agency for individuals to react to and influence the ways that they engage with others (Salen and Zimmerman, 2003).

In PBL, students are assigned to work in groups to solve complex inquiry problems. Complex problems in PBL relate to real-world examples, and are often embedded in a story, which offers an imagined, realistic space for learners to engage in. To help students deal with the complexity of the problem space, the PBL inquiry cycle typically includes the following steps:

- identifying facts and learning issues that are relevant to the problem;
- generating hypotheses related to the problem;
- identifying gaps in knowledge;
- engaging in self-directed learning; and
- applying newly acquired knowledge to the prior solutions.

The inquiry process can be linear, but it is generally an iterative process where students refine their hypotheses as they collect more data. Throughout the collaborative inquiry process, it is critical for students to take ownership or have agency over their learning (Loyens *et al.*, 2008) . Because play is often thought of as agentic, PBL's focus on fostering agency demonstrates its alignment to traditional definitions of play. Designed tasks should therefore encourage multiple ways of engaging with content and provide students with opportunities to take charge of their learning. Taken together, the problem space, inquiry phase, and the nature of social interactions informed the characterization of collaborative inquiry play. Specifically, collaborative inquiry provides guidelines (i.e. rule-based) about how to approach these complex and challenging problems and is predicated on group-based interactions. The onus of learning is additionally placed on students, the facilitator's role is to guide them in their problem solving and to provide just-in-time feedback.

As part of the PBL cycle, student groups use a structured whiteboard to document their inquiry processes (Hmelo-Silver, 2004). The traditional PBL whiteboard is divided into four columns: *Facts, Ideas, Learning Issues*, and *Action Plan*. In the Facts column, students share information that they have gathered with their peers whereas the Ideas column allows students to generate hypotheses based on these facts. Based on what they have found, students then create a list of questions that they place in the Learning Issues column. Finally, the Action Plan column allows the team to track tasks and other relevant group management issues. The whiteboard scaffolds the problem solving process, providing students with a shared regulation tool, wherein they can direct their focus on relevant issues and negotiate their understanding of the goal at hand (Hmelo-Silver and Eberbach, 2012).

As a pedagogy, PBL has been used to design games such as *Alien Rescue*, where middle school students work together to solve a problem centered on relocating displaced aliens within the Solar System (Liu *et al.*, 2014). The authors report that over half of the students expressed having fun as they were learning, which suggests that games designed using PBL can offer opportunities to incorporate play and learning (Liu *et al.*, 2013). A key takeaway from the *Alien Rescue* work is that learning does not happen spontaneously. For example, a notebook was provided to students so that they could identify critical information, organize, and then evaluate the information that they find. Such organization is especially critical in complex inquiry environments where the problems are often ill-structured. Thus, a combination of in-game scaffolds, support from expert facilitators, and students' own development of expertise as they engage in the problem are important to help students learn the targeted content (Hmelo-Silver *et al.*, 2007; Tawfik and Kolodner, 2016). As part of this problem solving process, facilitators also provide consistent scaffolds to assist students in becoming independent learners. They then gradually fade their support when students begin to take responsibility for their own learning (Hmelo-Silver and Barrows, 2006; Saye and Brush, 2007). In the design of CRYSTAL ISLAND: ECOJOURNEYS, the PBL inquiry cycle and the whiteboard tool were useful in providing the structure of the story (i.e., rules underpinning the imaginary context and regulating the problem solving process) whereas understanding the role of the facilitator provided insights into how to provide students with cognitive challenges that they can pursue on their own. Taken together, the PBL inquiry cycle, whiteboard tool, and need to foster student agency shaped our initial conjecture and design of collaborative inquiry play.

Design iterations and data sources

The research project is currently in the third year of its design and implementation and will present data from the first three years of the five-year research project. Utilizing an instrumental case study approach (Stake, 1995), the article discusses the design priorities as exemplified in the design conjectures and the associated research studies related to the three iterations of the design conjecture. Across the three years, 96 students and two teachers participated in the different studies. In the first year of development, design work was centered on embodying the processes of collaborative inquiry in the story. The high-level conjecture was that *successful collaborative inquiry learning depends on engagement with inquiry*. This was primarily embodied in the story and a collaborative modeling activity, which was designed in place of the traditional whiteboard. To differentiate the design of this collaborative space from the traditional PBL whiteboard, the article refers to this space as a brainstorming board. The story was centered on supporting inquiry learning and understanding of ecosystems content. Specifically, students learned about systems thinking based on the Phenomenon-Mechanisms-Components (PMC) framework (Jordan *et al.*, 2014; Hmelo-Silver *et al.*, 2017).

In the first iteration, data were collected from eight focus groups conducted with 6th grade students from after-school clubs (N = 16, seven female and nine males) across ten sessions. The two main aims of these sessions were feedback on:

(1) character and story; and

(2) collaborative problem solving activities.

In three of the sessions, students provided feedback on the problem space (i.e., context and setting), characters, and story. In another five of the sessions, students engaged in collaborative model-building activities using a digital or pen and paper board (Saleh *et al.*, 2018a). In the last two sessions, students worked in groups of three or four and were provided the problem context in a choose-your-own-adventure format (i.e. story delivered in a pen and paper format). Students in these two sessions were also tasked to create an explanation as to why the problem was occurring. Findings from these focus groups contributed to the initial design of the brainstorming board.

In the second iteration, two field tests (Study 1a and Study 1 b) were conducted to examine the impact of the story, the designed context, and a Know-Want to know-Learned chart (KWL) (i.e., brainstorming board) on students' collaborative inquiry and ecosystems learning. The KWL chart served the same purpose of the structured PBL whiteboard and is often used with primary and secondary students (Torp and Sage, 1998). The high-level conjecture was revised based on the data from the prior studies to be: *successful collaborative inquiry learning depends on engagement with inquiry and socially shared regulation of learning*. Study 1a was conducted with a mixed-aged science classroom (N = 19, 5 females and 14 males). In this study, students played the prototype version of CRYSTAL ISLAND: ECOJOURNEYS in a single two-hour session (Saleh *et al.*, 2018b). Students worked through the game's narrative, presented in a format similar to a graphic novel, and interacted with characters and objects in the environment. During gameplay, students also used a chat tool built with the Bazaar platform, an architecture for designing multi-party collaborative agents, whereas a KWL chart took the place of the brainstorming board tool (Ogle, 1986; Kumar and Rose, 2010). After the classroom implementations, the team conducted study 1 b, which consisted of two focus group sessions to understand the nature of student interactions in using other chat tools (N = 8, 6 females, 2 males). The tools and designs for the studies in the second iteration will be further elaborated in the sections discussing the development and iteration of the embodied conjectures.

In the third iteration, two classroom field tests (Study 2a and Study 2 b) were conducted. In this phase, the high-level conjecture remained the same but the embodiment of this conjecture in the tools and participant structures changed as a result of the previous studies. In this iteration, students played CRYSTAL ISLAND: ECOJOURNEYS with an embedded chat tool, to-do list, and brainstorming board tool. In Study 2a, nine students (3 females, 6 males) participated in a three-day implementation. In Study 2 b, 45 students played CRYSTAL ISLAND: ECOJOURNEYS across nine sessions (22 females, 23 males). In these two studies, each group of students was assigned a facilitator who worked with them during the brainstorming board sessions (see details below). The main focus of these two studies was to examine the relationship between in-game facilitation, collaboration and student learning of content.

First iteration and field test I: Designing the context and collaborative interactions

One area of focus in the initial design was the problem space and how the phases of inquiry would be embedded in this problem space. Another area was the shared collaborative space, or the brainstorming board. In the first iteration, the brainstorming board was designed as a modeling tool. In what follows, the article highlights the instantiation of the high-level conjecture in two aspects of the design, the context (i.e. story and problem space) and the brainstorming board tool. These features were selected because they illustrate how the conjecture was embodied, especially with an eye toward how the PBL model informed the design (Smith, 2010).

Embodying play in the context, story and problem space

There were two legacy sources that informed our workthat informed our work: an existing ecosystems curricular unit and the original game called CRYSTAL ISLAND, both of which were adapted and integrated into the current design. The ecosystems curriculum consisted of three inquiry-based units that leverage a suite of technology tools designed to support middle school students' understanding of aquatic ecosystems (Jordan *et al.*, 2014; Hmelo-Silver *et al.*, 2017). For this project, the team began by streamlining the legacy ecosystems curriculum, a unit focused on a eutrophication event in a temperate lake in the USA, for a one-week classroom unit. To balance learning and play, the complexity of the problem had to be refined to ensure that students were able to grasp the targeted content yet remain immersed in the imaginary context. In the legacy version of CRYSTAL ISLAND, 8th grade students adopted the role of a medical field detective trying to solve an infectious disease outbreak impacting a team of scientists located on a remote tropical island. Because the original ecosystems unit was centered on North America, the curriculum had to be adapted to suit a tropical setting. The team chose to situate the problem in the Philippines, where tilapia farming is important to the local aquaculture economy (Guerrero, 1985). In the revised story, students learned about how tilapia fish farmers depend on fisheries as a means to support their way of life. When they arrived on the island, an emergency at one of the hatcheries occurred and students were tasked to investigate why the tilapia at one of the local hatcheries were sick.

Another element that was embodied in the design was the PBL inquiry cycle. The PBL inquiry cycle provided guidelines about how students can engage in the problem solving process. In the focus group sessions, students were first oriented to the problem and subsequently provided with more data on the problem. In the collaborative problem solving activities, students used the information to generate an explanation as to why the fish might be sick. Student interactions with the initial design of the storyline indicated that students understood the nature of the problem and could use the information in their problem solving tasks. Additionally, students' expertise came in the form of different topics that they were assigned to research. Students collected different data that pertained to the relationships between biotic (living) and abiotic (non-living) components of the system, such as the relationship between tilapia health and the amount of dissolved oxygen. To mitigate student absences and provide redundancy of access to information, critical concepts and facts were introduced to at least two students on each team. The story was also designed such that future iterations would allow the system to redistribute tasks if students were missing critical pieces of information. It should be noted that although individual story paths were predefined, students had agency in their dialogue choices with the environment. This provided students with variations on how they wanted to interact with the in-game characters. To ensure that the setting would appeal to 6th grade students, the team gathered feedback on the game's interactive storyline, which framed students' investigation of the scenario and the setting (i.e. physical location, characters).

Field test I finding: Salience of middle-school roles and authentic tasks

Students in the focus groups were presented with two background scenarios for the aquatic ecosystem investigation: a field trip or a journalist story. In the field trip story, students and their schoolmates are on a field trip, visiting an island to learn about its natural environment. There, students are asked to help determine why the fish are dying. In the journalist story, students would take on the role of award-winning environmental journalists who were sent to investigate why the fish on an island are dying. The research team did not provide the age of the students in the field trip. Instead, the team members asked students which age they would prefer when engaging in the storyline. Out of the nine students who participated in the narrative focus groups, seven students expressed excitement about the field trip. Students noted that it would be "awesome that you could be anyone, teenagers or anyone" whereas journalists were mostly grown-ups. Students also noted that it would be inspiring and that everyone could struggle together in the problem solving process. Another student noted that this would be similar to the Magic School Bus series, which the student enjoyed. Moreover, being an award-winning journalist would mean that there would be "a lot of pressure" and that the students could not afford to "mess up." Ultimately, students thought that middle-school aged students were more believable because one should "play as kids to learn how to go about stuff." Overall, students appeared to favor narratives featuring middle schoolers visiting an island as part of their field trip.

However, students' selection of middle schoolers on a trip presented an interesting tension in terms of creating the problem context. In most game-based learning environments, students are provided with roles that are intended to encourage students to adopt professional identities such as scientists and journalists (Klopfer *et al.*, 2005). These roles have the dual function of cognitively challenging students so that they learn the targeted content, but also support students' normative and cultural understanding of what it means to be a scientist (Rogoff, 1995). In contrast, in the design of CRYSTAL ISLAND: ECOJOURNEYS, the team made the decision to explore how students might explore their role as learners, as opposed to providing professional roles. The field trip context involved students participating in a cultural exchange program in which they learned about how tilapia fish farmers depend on fisheries as a means to support their way of life. Although the tropical island setting itself was imaginary, the history of aquaculture and tilapia farming in the Philippines was essential in building the narrative. Given that authentic contexts are critical for student engagement in PBL, the team attended to these details in constructing the narrative. In the story, the students were invited to help with a problem facing Jasmine, one of the new fish technicians. Specifically, the problem was that the tilapia in her hatchery were sick. Subsequent focus group sessions highlighted the importance of these authentic contexts. Students were surprised when told that these problems and contexts were based on facts, but noted that this was motivating because it could happen in real life. Rather than be given pre-assigned roles, students were given the agency to express themselves in whatever roles were more salient. Several interactive game elements were also introduced to support the imaginary elements of the context. As students explored their environment, they engaged in interactive tasks such as taking water samples, or cleaning an aquarium tank to get samples of cyanobacteria, a greenish slime growing in the tanks. More critically, these activities were authentic tasks scientists might undertake when collecting data about water quality indicators. In the focus group sessions, providing students with unique storylines was critical to their collaboration and sense-making (Saleh *et al.*, 2018a). In particular, students adopted roles that mimicked specific facilitator moves such as revoicing or encouraging other students to participate. Additionally, the different information allowed students to develop competing models that utilized the ideas that were presented to them. This was critical because students in most of the sessions with productive discussions only had minimal facilitation.

Embodying collaborative inquiry in the brainstorming board tool

Initial designs of the brainstorming board featured the use of a modeling tool that utilized the PMC framework. The PMC framework supported students' understanding of how parts or components (C) of an ecosystem interact, and how relationships between these parts result in underlying mechanisms (M) of a phenomenon or ecological pattern (P). The PMC framework was utilized to help students break down the complexity of the problem that students were introduced to. In the story, students had to solve why the fish at the hatchery were sick. The major cause of their illness is eutrophication, or the abundance of nutrients that lead to an overpopulation of plant life thereby causing a lack of oxygen. Based on this definition, one can see that eutrophication is a complex problem with multiple interrelated variables. To assist students in managing the complexity of the problem and their learning, the team provided students with a central issue: what tilapia fish need to survive; namely quality of water, dissolved oxygen, food, water temperature, and space. In the focus groups, the team tested how to support problem solving by introducing a modeling tool aligned to the PMC framework (Saleh *et al.*, 2018a). The team created two mock-ups of the modeling tool; a pen and paper (Figures 2 and 3) and a digital version (Figure 4). Students were asked to generate a model explaining the decrease in fish population in a pond and were provided information about the problem in a journal (left side of Figure 2). The information was categorized according to Phenomenon (yellow), Explanations (green) or Evidence (blue). To build their model, students moved information from their journal to a brainstorming board (right side of Figure 2). To facilitate the construction of the model, only Components of the statements (e.g. fish population) can be manipulated by the students in the brainstorming board. Additionally, students could use arrows to demonstrate the relationships among the components, evidence, and explanation (Figure 3).

Taken together, these representational tools in the modeling tasks provided students with the scaffolds needed to guide their problem solving. For example, the questions helped model PMC thinking whereas the arrows help provide constraints on the kinds of relationships that students should be considering in terms of relations among model elements.

Field test I finding: Need for explicit representation of socially shared regulation of learning

Students in the focus group interviews noted that the game's central problem (i.e., the tilapia being sick) was sensible and they expressed interest in helping the in-game characters. Findings also indicated that the combination of the journal and brainstorming board tool supported students in sharing and negotiation of the content (Saleh *et al.*, 2018a). In the focus groups, the content was already pre-collected for students and publicly available on a shared

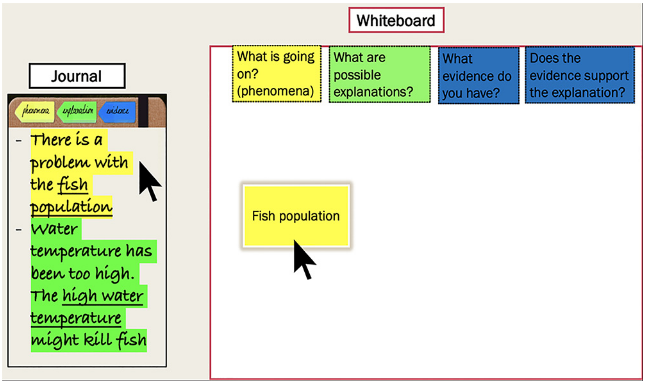

Figure 2.
Tools supporting model creation in the early pen and paper version

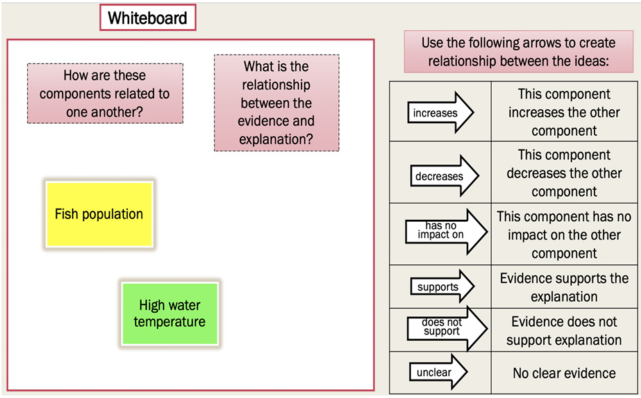

Figure 3.
Additional prompts for model creation in the pen and paper version

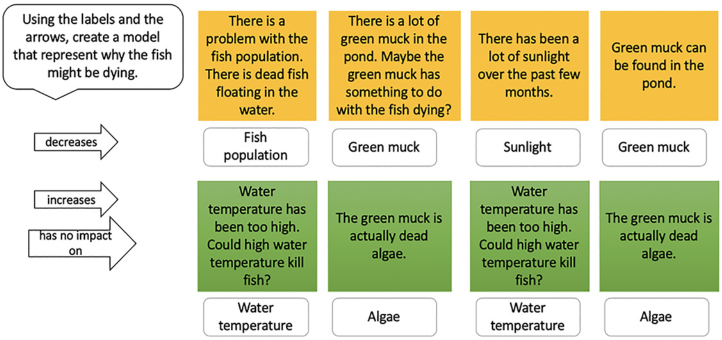

Figure 4.
Prompts in the digital modeling tool

brainstorming board. Because of this, students could focus on both task-oriented and content-oriented processes undertaken by other students. By making knowledge externally available for all students, students could also engage in regulating their understanding of their shared knowledge and how they might collaborate with one another. Additionally, the constrained nature of the brainstorming board (i.e., pre-selected evidence and elements of the model) did not impede students' agency. Students were able to engage in comprehending the task, setting goals, planning their steps, and addressing challenges associated with constructing their understanding. These steps mirrored the work by Järvelä *et al.* (2016) on socially shared regulation of learning (SSRL). Although the modeling tool supported productive negotiations via students' face-to-face interactions, it was less clear how we might shift these interactions into the game more explicitly. Moreover, the SSRL process itself remained invisible and surfaced only in students' verbal talk. Shifting students' discussion of content *and* their management of the process therefore required an explicit externalization of the SSRL process into the game-based learning environment. Given the research team's interest in tracing student collaboration and learning through game telemetry data, it was critical that these interactions be directly embedded as part of the game mechanics and not simply through face-to-face discussion.

Second iteration and field test II: Supporting collaborative inquiry and regulation of learning

Based on findings from the Field Test I focus groups, the team prioritized designing an immersive play environment that afforded an effective problem space that was challenging yet sensitive to student agency, and allowed for scaffolds to appear integrated as part of the play experience. Although PBL engages students in collaborative learning, it does not explicitly define the process. This was evident from the collaborative model-building activities, where roles had to be specified or developed organically from student interactions. In this phase, the conjecture map was revised to attend to SSRL (Järvelä *et al.*, 2016, Figure 5). Note that the revisions to the conjecture map appear in the highlighted boxes.

Embodying the story and problem space into the 2D prototype of CRYSTAL ISLAND*: ECOJOURNEYS*

To support the design of the narrative, a prototype learning environment was developed featuring 2D visuals. The 2D environment is a digital interactive story environment that was used to rapidly prototype problem solving scenarios and user experiences. To understand which aspects of the problem were easy or complex, the initial design of the narrative was broken down into three tasks:

(1) learning about ecosystems;
(2) using a brainstorming board; and
(3) getting more information on the problem.

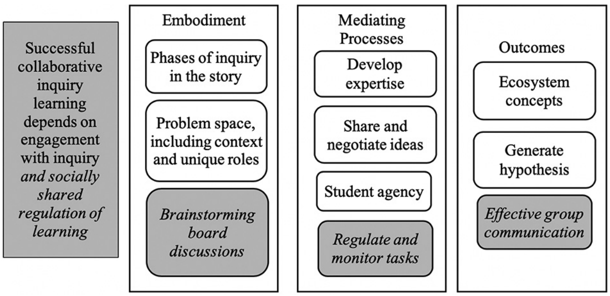

Figure 5.

In PBL, students are not typically constrained in terms of what resources they can use, be it books, videos, or any other media. In CRYSTAL ISLAND: ECOJOURNEYS, students had to follow a linear but multi-path story, which was intended to provide students with the necessary content before they can share and negotiate the meaning of their ideas with their peers. From a scaffolding perspective, dictating students' paths in the story meant they could focus on core ideas, as opposed to juggling multiple topics that may impose unnecessary cognitive load. Additionally, it was expected that a more constrained path that limited students' agency in terms of their in-game interactions (i.e. data collection, exploring the environment) would mean more time would be spent on negotiating (Adams *et al.*, 2012). Student learning was also supported by designing the story from different perspectives. Each student in the group was assigned a unique storyline as told by in-game characters and collected different data and information. The decision to create a multi-path story was also informed by PBL, in that individual students often bring new information so that the group can then negotiate its relevance and apply the finding to the problem (Hmelo-Silver, 2004).

Field test II findings: Supporting sharing in the collaborative space

In the first classroom study during Field Test II, the team utilized Google sheets as a prototype brainstorming board to structure students' collaboration. In the sheet, students used a Know, Want to Know, Learned chart (KWL, Ogle, 1986) to share their findings and articulate their next steps. There were three columns that helped students organize their ideas:

(1) What do we know?
(2) What are two guesses that we have that suggest why the fish might be sick?
(3) What evidence can we find to support why the fish are sick?

Students also used a physical worksheet that was structured according to the PMC framework. When using the Google sheets, students shared their ideas from their notes via a chat tool. To scaffold interactions, a human facilitator provided collaborative and content prompts that asked students to share, solicit information from their peers, and reach a shared understanding about the problem. It is critical to note that this version of the brainstorming board was open-ended, students could add what they wanted to the KWL chart and chatted freely to share their ideas with their teammates.

Results indicated that students used the Google spreadsheet to organize their ideas according to the different needs of tilapia fish and how a decrease in these factors might have an impact on the tilapia (i.e., relationships between components). A main issue with the free-form sharing of notes however was that students did not always share pertinent information to their team and had trouble attending to the amount of information provided. This meant that hypothesis generation and consensus making came in very short spurts of activity. Additionally, students needed a way to support consensus making. Due to the open-ended nature of the Google spreadsheet, students found it hard to determine who contributed ideas. Moreover, all information had to be manually entered, which meant that it took considerable time to share information and less time was spent on negotiating ideas.

Embodying socially shared regulation of learning

To support collaborative inquiry more effectively, the team drew on SSRL, or the processes in which multiple individuals manage their joint activity (Hadwin and Oshige, 2011). The team attended to SSRL principles:

- understanding the task;
- setting goals;

- planning actions related to these goals;
- acknowledging challenges; and
- addressing group challenges that members might face (Järvelä *et al.*, 2016).

In the design, it was critical for students to understand that they needed to engage in fact finding before generating hypotheses (i.e. setting goals and planning actions). Similarly, addressing gaps in knowledge and challenges in group work often go hand in hand (Glazewski and Hmelo-Silver, 2019). Thus, the next design task was creating the brainstorming board in a way that maintained the story of the tilapia being sick, provided agency to students, and supported collaborative inquiry.

To make the SSRL process more explicit and better integrated into the gameplay, the brainstorming board tool was re-designed to explicitly refer to the five hypotheses. A KWL chart was also embedded in the brainstorming board tool in the subsequent iteration. The KWL chart was used because it:

- made explicit the process of inquiry;
- provided a space for students had to share what they know;
- reflect on what they needed to know; and
- (at later stages) document what they have learned.

Instead of having students use the modeling tool to support their problem solving (as in the earlier Field Test), students were expected to create a model as a final activity. Thus, the PBL and SSRL processes were made visible to both teachers and students by providing them with a task list that provides a checklist of things that students have to do in the game. Together with the chat tool, students can check in with their team mates in chat about their assigned task and ask for help as needed. To understand how students interacted with the 2D prototype of CRYSTAL ISLAND: ECOJOURNEYS, two studies were conducted. The first study was a classroom implementation whereas the second set of studies were more exploratory in nature (i.e., focus groups).

Field test II findings: Supporting regulation of collaborative learning

Another key area in supporting SSRL was the need to remind students of what it meant to collaborate effectively with one another. Although the students across the different contexts were often on-task, students sometimes did not address the goals of the task as a team. Moreover, interpersonal challenges such as trying to get distracted team members to work on the same task were left unaddressed. For example, there were instances when a particular student did not have to contribute to group work because this student was known to get distracted easily. Given that this was not an effective strategy to resolve such situations, it was necessary to address these issues. Fortunately, simple debrief prompts provided by teachers in the classroom were often sufficient for students to engage with their peers and determine their gaps in knowledge, as well as determine their next steps. This suggests that these interactions could be further supported by asking students to engage in reflection as part of their classroom activities.

Third iteration and field test II: externalizing inquiry and supporting classroom interactions

In the current iteration of the conjecture, several aspects of the design were revised or added: the brainstorming board (i.e. the game-based version of the PBL whiteboard), an agreement index, the to-do list, and the group contract. Additionally, the interactive story was broken up into chapters so as to help support student content learning and to better align the story to the PBL inquiry phase. The agreement index was added because it was necessary to externalize aspects of the inquiry process, such as sharing, and negotiating ideas. This index was integrated as part of the brainstorming board (see section below). Finally, the to-do list and group contract were additional ways of embodying the principles of SSRL. Due to space constraints, only the agreement index and brainstorming board are discussed (Figure 6).

Embodying inquiry, sharing and negotiating ideas in the brainstorming board

To support sharing of notes and consensus-making over what counts as evidence, the research and development team re-designed the brainstorming board. In the current iteration of the brainstorming board, students are presented with five columns that show different hypotheses as to why the fish might be sick (Figure 7) .

Drawing again on the PMC framework, students oriented themselves to the phenomenon (i.e. why are the fish sick), and learned about the components of the system (e.g. abiotic and biotic components that the tilapia need) by engaging with the story. In subsequent chapters of the story, students learned more about the relationships between these components and other mechanisms that are related to the tilapia (e.g. respiration). Thus, the PMC framework was threaded throughout the story and students must collect information related to these parts of the system. After

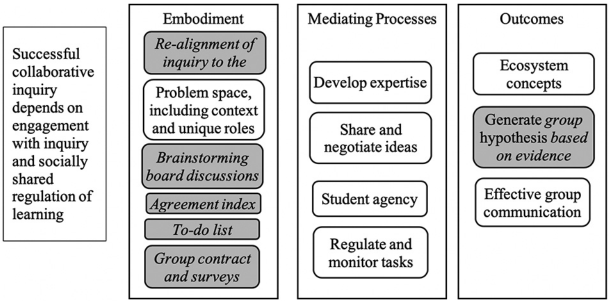

Figure 6.
Italicized changes to conjecture map

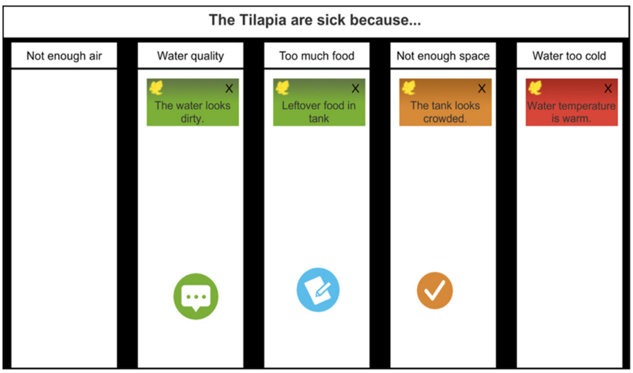

Figure 7.
An overview the brainstorming board, chat (green icon), student notebook (blue icon), and the task list (checkmark icon)

collecting data in the narrative, students shared notes by placing them in the appropriate columns. In doing so, students used this information as evidence in support of or against the hypothesis. After placing their evidence, students then evaluated each other's notes and indicated whether the piece of evidence supports, does not support, or might support the hypothesis. In doing so, students could see which pieces of evidence have the team's shared consensus (the evidence turns green) or if there were some pieces of evidence that need to be discussed and negotiated (evidence is red). At the end of the students' data collection sessions, the students decided if they needed to remove a specific hypothesis or simply move on to collect more evidence.

Notably, interactions at the brainstorming board were more aligned to PBL and SSRL (i.e., to learning), but appeared less play-like. However, students' agency in deciding what notes were viable pieces of evidence and which hypothesis may or may not be relevant meant that they could shape the nature of their discussion. The information provided to students in the different chapters was organized such that there were gaps that students needed to fill in, either by getting them from their peers or to move on to the next chapter to collect more information. The gaps in information was meant to support cognitive puzzlement and challenge students to acknowledge the limitations of the current information that they have. In using a puzzle-like approach to kinds of information provided to students, the problem or imaginary context remained a salient issue for students. Moreover, framing the notes as clues or evidence maintained the play context. Even if students were engaged in more traditional school-like activities when using the brainstorming board, clue finding and sorting helped maintained the play context while allowing students to engage in problem solving processes.

Field test II findings: Productive collaborative inquiry learning, but is it play?

Two classroom implementations were conducted to examine the impact of the current design on student learning and collaborative inquiry outcomes. The driving question or the framing of the brainstorming board was different in each of the implementations (e.g., the Tilapia are sick versus Components that Tilapia need to live). Results indicated that the framing with the stated hypothesis (Figure 7) was more salient to students and was crucial in reminding them of the task. Across both implementations, sharing notes was facilitated by the brainstorming board. Students could easily move their notes from their notebook onto the board. Moving notes to the appropriate column also fostered discussions about the relevance of the note or whether it could be used as evidence for a particular hypothesis. The agreement index moreover supported productive discussions about why students were agreeing or disagreeing with one another. However, the number of notes that students collected meant that students had to spend significant time examining, discussing, and evaluating the notes with their peers. Although this was the desired inquiry learning interactions, it does mean that these interactions are less play-like in nature. The team is currently in the process of reviewing the data and design to determine how play can be better integrated during the brainstorming board. Fortunately, debriefs with students after playing the latest iteration of CRYSTAL ISLAND: ECOJOURNEYS were encouraging. Students reported that they were still playing even if they were doing more school-like activities. However, future work is needed to unpack how students perceived play and their agency in the context of the design.

Coda: Designing for collaborative inquiry play

As a pedagogical model, PBL provided a useful framework to support the iteration of the design. The high-level conjecture shifted from a focus on inquiry processes to including social interactions that are crucial to collaborative inquiry learning. A key tension in designing for learning and play, however, is to manage the process of learning without compromising the imaginary context and agency. Below, several key takeaways are highlighted on how one might design for collaborative inquiry play.

Unpacking and defining frameworks underlying the problem

In order for problems to be successfully utilized by students, it is necessary to attend to four major issues: the breadth of knowledge required, difficulty level of concepts used, skills required to problem solve, and the relationship among variables in the problem space (Jonassen and Hung, 2008). In addition to these guidelines, it is also possible to draw on learning progressions and other content frameworks. The current article utilized the PMC framework (Jordan *et al.*, 2017) to define parts of the problem and how they might intersect with one another. Helping students manage the complexity of the problem also meant attending to both process and content. Both PBL and models of SSRL provide guidelines on how to support students in problem solving and collaboration. Specifically, PBL focuses on supporting individual fact finding, agency, process of hypothesis testing, and aims to help students see gaps in their knowledge. On the other hand, supporting SSRL includes attending to task understanding, goal setting, planning, supporting acknowledgement of challenges to collaboration, and strategizing on how to overcome these challenges. Given that play must also be challenging, unpacking the processes of collaborative learning is important. Being mindful of these processes mean that students' resolution of problems would be better supported, especially when encouraging students to engage in consensus-making and helping them acknowledge that setbacks in learning and/or collaboration are part of the learning process.

Accountability: Empowering the student role in designed narratives

In terms of providing roles that encourage students to push themselves, the recommendation is to encourage students to engage in play contexts as themselves so that they may decide on paths that are more salient to them. Students found it more believable that they needed to learn the problem because they may not have the expertise that a professional would. In the current design, students take on the role of middle-school students who are participating in a cultural exchange program. Although students were provided pre-determined stories in the multiple path narrative, the unique perspective provided opportunities for students to shift between various roles. Feedback from the students indicated that they were able to take on multiple roles as they engaged in the story, including being a student, an adult, a teacher, a scientist and so on. The notion of accountability here is critical (Engle and Conant, 2002); in engaging with the story, students realized that they were responsible for the choices that were made and must solve the problem in an effective manner.

Externalizing content and process for supporting agency

Research on supporting science inquiry learning has documented the benefits of providing representations that students can utilize (Ainsworth *et al.*, 2011; DiSessa, 1999). When designing for a game, this body of research still remains salient and critical. In the current design, the brainstorming board, or the whiteboard tool, provided an external representation of multiple hypotheses that players work on. Individuals made their choices on which hypothesis ought to be removed but group consensus must be achieved in deciding which hypothesis were viable. Additionally, individual notes were made visible to the group. This meant that students in the same group could examine and evaluate these notes, and negotiate their agreement or lack thereof. Because of the different colored indicators, students were also aware of which ideas require negotiation or required input from other students.

Concluding thoughts

In sum, our work highlights how learning principles from PBL can be productively mapped to definitions of play, imaginary contexts and roles that extend the individual beyond their current abilities. The embodied conjectures allowed the team to be aware of the affordances and constraints of the design and offer support on how these designs were iterated. Notably, the focus on problem solving has meant that the definition of play is based on the roles that students choose to adopt in the designed context. Although this does not align with typical definitions of play, especially those that define play as involving fun – the importance of agency cannot be underspecified. Designing challenging yet constrained collaborative contexts do not mean that students neither enjoy themselves nor engage in play. Indeed, students reported that they took on adult roles that they specified for themselves, and highlighted that sharing and negotiating ideas provided enjoyment when using the brainstorming board.

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Corresponding author
Asmalina Saleh can be contacted at: asmsaleh@indiana.edu