Designing for the Epistemological Entailments of Physics through Game-centered Dialogical Activity Cycles

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Abstract: This study examines a secondary-level science curriculum centered on a multi-user, "serious game" called *Escape from Centauri 7*. The game engine depicts qualitative physics phenomena via dynamics tied to player actions. Players progressively engage the epistemological entailments of charged particles through new phenomena they encounter as the game unfolds. We engineered discretely bounded gaming episodes to arrange transitions between game play, small group, and whole class discussions. Together, these elements of game play and discussion constitute recurring, game-centered dialogic activity cycles. Through this design, we investigate how gaming fosters intuitive physics understandings, how activity structures and materials engage learners and enlist gaming experiences in discussion, and how both game play and discussion shape subsequent participation. Analyses of trajectories of participation in and across cycles underscore the plausibility of this approach while also illuminating emerging tensions that we discuss in terms of epistemic reflexivity.

Introduction

This study details our efforts to design for engaged participation across a series of problem scenarios involving the dynamics of charged particles. Using the affordances of a gaming engine, we engineered a "curriculum-based ecosystem" (Barab & Roth, 2006) through which students engage the functional properties of charged particles as a means to escape from a distant planet and, in this pursuit, to seek out more knowledgeable others who can guide ongoing engagement (e.g., Lave & Wenger, 1991; Rogoff, 1990).

Throughout the curriculum, we strive to encourage learners to appreciate the productive tensions between formal science and the everyday world from which it emerges (Barab, Zuiker, et al., 2007). Generally, the work of scientists reifies natural phenomena in terms of seemingly abstract terms and principles. However, sociological studies of science illustrate the many ways in which such a process of reification generates a kind of audit trail (e.g., data files, log books, and charts) that ultimately points back to a very concrete origin (Latour, 1987). Schooling, though, often presents scientific formalisms as a sort of independent reality (Bruner, 1995). Rather than a process of reification that transforms concrete everyday experience into formal notions, science as seen through the lens of traditional curricula appears to exist apart from our everyday experiences. In an effort to strike a balance between the necessary value of both content *and* context, our design effort attempts to engage students in a context-of-use through which science content can become meaningful, rather than simply framing content with an artifice of context. To this end, we use a gaming engine to facilitate immersive experiences in a science-fiction narrative where physics phenomena are deeply relevant to participating in and advancing through a progression of events. Importantly, representing the physical world in terms of multiple, simultaneous events in a game space contrasts with the linear, succession of equations and texts.

In this curricular endeavor, we developed classroom activity structures that engage learners in a dynamic interplay between gaming, discussion, and reflection in order to support and extend students' intuitive understandings of physics (Chee, 2007). Such activity structures and supporting materials often remain under discussed, if not underspecified, in research involving technological innovations used in classroom communities (Bielaczyc, 2006). The complementarity that we arrange between gaming and classroom activity structures supports and illuminates students' sense-making practices. On the one hand, the multiple simultaneous features operating in the game embed the epistemological entailments of a formal discipline like physics (e.g., the interactions and relations that underlie Newtonian mechanics in the first place) as part of goal-directed activities. At the same time, these situated perspectives remain grounded in a player's intuitive understanding of particular game scenarios without an appreciation for their broader implications (e.g., Bereiter, 1997). Discursive activity in such scenarios helps to connect situated and general appreciations of physics by motivating deep reflection and a process of both negotiation and reification of individual experiences in relation to broader webs of meaning. Our efforts to embed game-based learning in classroom dialogic activity instantiate recurring cycles of experience and reflection. As we theorize these cycles, the curricular design arranges a trajectory of participation (Lave & Wenger, 1991) through which students work to reify game play in terms of the expert knowledge and the unique value system of scientists (Wenger, 1998; Rogoff, 1990). Given this perspective, three questions organize the design and analyses we report:

1. In what ways can game play foster intuitive understandings of particle-field interactions?
2. In what ways do students and teachers enlist the intuitive phenomena of *Escape from Centauri 7* to formalize their understanding of the dynamics of charged particles?
3. How does *Escape from Centauri 7* transform or perturb epistemic practices and modes of participation in classroom learning ecologies?

Theoretical Background

Relative to our three interrelated research questions, we theorize ways in which students and small groups formalize their learning experiences as they engage in increasingly complex forms of activity (Rogoff, 1990, 1995). Consistent with situative theories of learning, we conceive of meaning as inherently perspectival and embedded in pervasive background conditions (Greeno & van de Sande, 2007; Rommetveit, 1998). Meaning in this sense weaves together seemingly elemental aspects of perception and broader social themes. As one example, Varela, Thompson, and Rosch (1991) advanced an argument as to why even ostensibly fundamental qualities of our experience, such as color perception, remain inescapably embodied in both a biological and cultural history of structural coupling through which their meaning is instantiated. As another example, Geertz (2000) details how a Zande boy and western anthropologist use the "same" data to explain the boy's infection in terms of witchcraft and carelessness, respectively. From this standpoint, an individual's point-of-view coupled with a network of distributed epistemological entailments constitute meaning. Grounded in these inextricable ties between perception, cognition, and culture, we discuss how our design efforts instantiate and develop both a curricular design and local theory of game-centered dialogic activities.

Engaging the Dynamics of Charged Particles

Many of the central insights of physics remain sequestered to atomic or sub-atomic levels and thereby also remain elusive phenomena for learners to grasp. For example, students traditionally only engage electromagnetism quantitatively in terms of partial differential equations. While these equations provide an elegant summary, they remain an elusive shorthand for understanding the qualitative phenomena underlying electromagnetism. In fact, the calculus involved in predicting the behavior of charged particles in a field preceded its scientific understanding by several decades (Feynman, 1963). That is, only some time after Newton and Leibniz's mathematical inventions did physicists conceptualize forces that act at a distance, suggesting that these equations alone, while useful, were not crucial for unlocking these ideas. Moreover, many science educators now promote the value of conceptual physics (Forbus, 1984, 1997) and intuitive understandings (diSessa, 1993, 2000). Complementing these trends, several different technologies have been used to arrange opportunities to engage physics qualitatively. As one such technology, interactive digital media provide an altogether different foundation for learning grounded in the learner's experience of a dynamic representational system and her efforts to manipulate it. For example, rather than allowing the dynamics of electromagnetism to unfold through linear texts and equations, games (Squire et al., 2004) and simulations (Dori & Belcher, 2005) provide multiple, simultaneous perspectives on physical phenomena that locate meaning in the player's efforts to uncover the functional relations between charged particles and fields.

Dialogic Activity Cycles in Game-Based Learning

Serious games are not a "technotopia" that can singularly transform classroom learning (Oppenheimer, 2003). Rather, games can be enabling tools insofar as they support social transactions among learners and with teachers. Bearing this in mind, we have deliberately designed for the interplay between game play and classroom discussion in our curriculum. Shared experiences engender a "reciprocal faith" (Rommetveit, 1985, p.189) that learners have had the same opportunity to learn (Gee, 2005). That is, common gaming experiences provide increasing degrees of collective intersubjectivity. These shared experiences, in turn, afford individuals credibility in their joint work of negotiating scientific meaning. We seek to leverage both affordances in order to engage learners in dialogic activity. Through discussion between groups and with the teacher, gaming experiences can be reified in terms of the concepts and language of physics. In this way, content emerges through context. As such, classroom discussions are shaped by prior experience while also working to shape subsequent engagement.

Our efforts to design complementary gaming and classroom activities in this study are grounded in Rogoff's (1995) three "planes" of sociocultural activity. Personal, interpersonal, and community planes mutually constitute sociocultural activity. Recurring game- and classroom-based activity structures arrange successive material-social transactions while students engage a looping sequence of activities. As it is represented in Figure 1 below, each cycle begins with small groups of students working together side-by-side as co-participants in the game space. By coordinating their actions to achieve functional ends, peers build increasing degrees of intersubjectivity through language, gesture, game commands, and other meaning-making strategies. The cycle continues as each small group works face-to-face to summarize and synthesize their shared experiences. The cycle concludes with a whole class activity in which selected groups debrief their peers and engage in critical discussions. As necessary, the teacher may also provide just-in-time lectures that capitalize on tensions that surface during discussions or presentations. In both the game and classroom spaces, student activity fosters a dialogic interplay in which learning is a transactional process of reifying gaming phenomena in terms of more formal physics notions. Consistent with Rogoff's planes of sociocultural activity, this cycle arranges a trajectory of participation through which students' personal experiences with the game and interpersonal discussions about shared game experiences create challenges that position the teacher to guide participation and mediate the practices of physics.

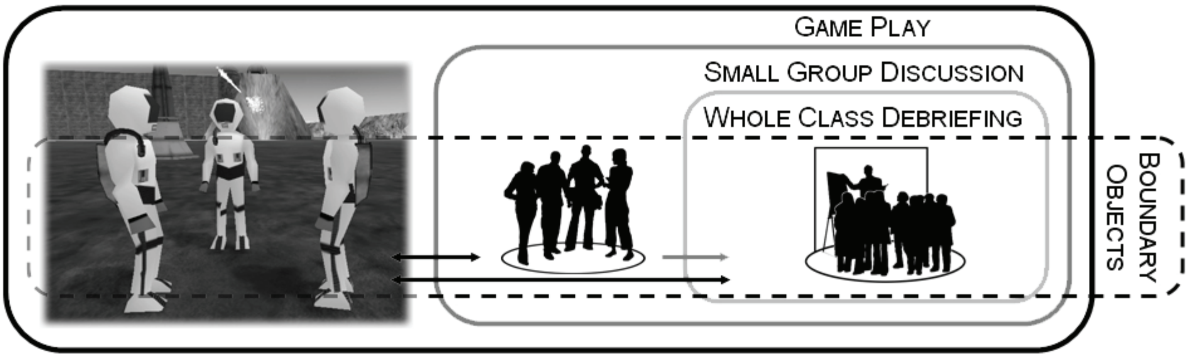

Figure 1. The interplay of activity structures across dialogic activity cycles.

Methods

We employed a concurrent-nested approach to multi-method research (Cresswell, 2002), using a quantitative measure of performance on pre-post assessments to complement an overarching qualitative analysis of student participation with the curriculum. After describing the participants and the curriculum, we provide details about the data we generated and how we analyzed it in light of our research questions.

Participants

We maintain an ongoing partnership with the physics department at a private, all boys secondary school in Singapore. We have worked with one teacher, Mr. Ong (all names are pseudonyms), during both the current study for which he served as instructor and one previous study taught by our team. Thirty-six students (ages 14-15) volunteered to participate in a 12-hour elective physics module. As "express stream" students, all participants performed nationally in the top 20% on high stakes assessments, which is similar to gifted programs in the U.S.

Curriculum

Building on current media and science discussions about Mars exploration, *Escape from Centauri 7* is a serious game that encourages students to assume the role of stranded astronauts. Using the dilapidated technologies of previous inhabitants, players attempt to activate a Gauss gun, or coil gun, in an effort to send distress signals back to Earth. Around this storyline, students encounter a succession of machines that enable them to position electric and magnetic fields in order to manipulate the speed and direction of charged particles pulsing through the atmosphere. In this way, player actions connect qualitatively to particle dynamics in order to illuminate underlying properties of field-particle interactions. These electrostatic principles operate across activities and phenomena in order to facilitate what diSessa (2000) describes as intuitive understanding. In addition to the range of specific interactive features that enable students to arrange electric and magnetic fields, we also created additional exaggerated features. For example, we attached phosphorescent trails behind moving particles in order to illuminate changes in both their speed and direction. We also elaborated on the sci-fi narrative by alerting players that astronaut respiration rapidly depletes oxygen tank levels. This created a fixed time limit that served to focus students on the game space and, thereby, ensure sufficient time to complete each dialogic activity cycle. Finally, we created a logbook that belonged to a fictitious astronaut previously stranded on Centauri that features an incomplete and often esoteric record of events, questions, photographs, and Post-it® notes from her experience on the planet. The logbook and the open questions that it presented served as a kind of boundary object operating between astronaut and student, Centauri 7 and classroom, and game and discussions.

Game play is complemented by the collaborative meaning-making activities that we characterized above in terms of a Dialogic Activity Cycle. The curriculum also features a final project in which each small group constructs a gaming manual that communicates the principles underlying both the particle dynamics and the game as well as their reflections about the experiences and process necessary to construct the manual.

Building such an artifact challenged small groups to consolidate and generalize their intuitive virtual experience and classroom discussions. Completing these (pencil and paper) astronaut logs also concretizes each group's shared experiences relative to the range of game experiences and provides an accountability structure required by the school.

Data Sources

During classroom sessions, we simultaneously supported the curricular enactment, conducted informal in-situ interviews, collected written artifacts, generated observational field notes, video-recorded two student groups, and debriefed with Mr. Ong after lessons. Before and after the curriculum we administered pre-post assessments of physics understandings and conducted focus group discussions. Our learning measure featured a subset of eight multiple-choice items adapted from the Force Concept Inventory (Hestenes, Wells, & Swackhammar, 1992), which assesses relevant Newtonian concepts against commonsense beliefs.

Data Analysis

The research team met periodically during the implementation to summarize field notes and observations. We subsequently incorporated the range of data above with our initial impressions to comprise methodic naturalistic inquiry (Lincoln & Guba, 1985). To this end, we progressively developed interpretations of the data while simultaneously engaging in reflexive practices that illuminate and temper our subjectivities (e.g., negative case analysis). We focus on two groups in the same class as it provides contrasting degrees of participation and discourse. In this sense, the cases represent our efforts to feature maximum variation of the curricular enactment in order to better understand the plausibility of our design together with a qualified understanding of challenges and tensions that remain. We reviewed the notes in each individual's log and well as group presentation charts and final projects in order to inform our review of the groups' recorded activities. Consistent with interactional analysis (Jordan & Henderson, 1995), we initially generated content logs for each small group. We then met to discuss the documented group interactions with respect to our research questions and returned to the data to transcribe a subset of roughly fifty episodes across cycles of dialogic activity. Our aim in this process was to understand trajectories of participation across activities in order to trace how students appropriated intuitive understandings of gaming phenomena in group and whole-class discussions as well as how these achievements shaped subsequent cycles. Our findings in the next section present a paradigmatic series of episodes across one dialogic activity cycle together with more representative episodes that serve to qualify our successes and communicate some of the tensions surfacing in our ongoing efforts.

Analysis of Group Trajectories through Game-centered Cycles

We present case studies of two student groups from the same class across the curriculum. The first group sometimes provided a paradigmatic enactment of the intended curriculum whereas the second group challenged us more often to re-examine our design efforts to formally anchor serious games to dialogic activity cycles. To begin, we first determined that students in both classes developed a deeper understanding of the behavior of charged particles relative to commonsense distractors. A paired t-test of the pre-post learning gains suggests that gains for both classes were unlikely to have occurred by chance ($t(33)=5.0$, $p<0.00$). This measure provides a general sense of class-wide performance. While both groups that we consider here performed relatively well, our general descriptions and analyses of transcribed episodes qualify fundamental differences. We discuss these differences in terms of our three research questions and interpret them with respect to efforts to refine our designs and to evolve a theory of game-centered dialogical activity cycles.

The first group provides a paradigmatic enactment of the curricular intentions in and across cycles of gaming and reflection. The following descriptions warrant the plausibility of developing serious gaming curricula in terms of dialogic cycles; however they are not representative of the whole class. The three boys in this group collaborated productively and often appeared to be gaming seriously. They used *Escape from Centauri 7* to address the implicit physics questions raised in the logbooks, to collaboratively achieve game goals, and, in later cycles, to link logbook information to game play. In small group discussions, this group methodically prepared for presentations, working to formalize their experiences before writing or drawing. During whole class debriefings, they asked meaningful questions of other groups and presented reasonable explanations. In focus group interviews after the curriculum, one group member explained how a debate during the first debriefing framed subsequent inquiry during game play. Specifically, the boys in this instance used the game to test whether or not they could use electric and magnetic fields to stop particles from moving. Moreover, the group was among the four in the class that completed the game by effectively using the Gauss gun to send a distress signal to Earth. Regardless of the degree of success, we only claim that it is a transactional achievement between particular individuals and our curricular design.

We now shift from a descriptive to interpretive analysis of transcribed episodes across one dialogic activity cycle. The first group's (Gopal, Zhang, and Seng Chee) enactment of the curriculum illustrates transactional achievements in terms of the mediating role we intended our design to facilitate. The first excerpt presents an early episode during the first gaming session. The group is interrogating the game space and, through the language they use to structure their experience, they also appear to be surfacing physics phenomena.

Z: How do you change this thing? (points at screen)

G: Hmm. (looks at Z's screen) I have no idea what it is. You have to deflect the field onto the - oh, NOW I get the point of asking those questions (reference to astronaut logbook). Ey, cool, definitely cool. Okay, I- that's how the game works but I'm not very sure right now.

S: I didn't get it deflected. A bit too much

G: Agree, but I think I found out how the thing works. But I am completely messed up. Yeah, I am deflecting it in a wrong direction completely.

S: I'm deflecting it in the correct direction but a bit too much.

The group uses formal terms like "particles" and "fields" as well as game space indexicals that vaguely reference features with "this" and "it." In this way, the group works to understand the (physics) principles underlying the changes they effect or, as Gopal says, "how the game works." However, their language remains largely indeterminate to non-players. Only Gopal's advice—"you have to deflect the field"—suggests a functional understanding, albeit an inverted one in which particles act on fields. The running narrative in this transcript communicates the group's engaged participation and coordinated efforts to understand the dynamic relations between particles and fields. It is these kinds of shared gaming experiences that provide a productive foundation for subsequent discussions and debriefings beyond the game space. To this end, the group's discussion during the same cycle considers phosphorescent trails that particles emit, illustrating their ongoing efforts to make sense of the game.

G: (explaining to S) The length of the trail changes {…} the distance traveled by the particle away from the point in the field {…} so if it moves faster, the trail will be longer. The first time I didn't know what to do {…} maximum backwards, it bounced off and went backwards (gestures right then left).

Z: Mine was a curve (gestures a curving path)

G: Yes, same, was a curve. Backwards. Goes slightly in, moves around and "zing" (gestures an about-turn).

In contrast to the basic terminology that the group used during game play, Gopal and Zhang specifically explain the significance of particle trails in terms of speed. Gopal also comments on his initial puzzlement during game play. While this discussion clearly draws upon game features and prior game play to make meaning, the students accompany several descriptions with hand gestures. In light of the transition from gaming experiences to classroom reflection, this episode highlights a converging understanding in more formal descriptions that the students punctuate with gestures and, in contrast to game play, without game space indexicals. As a final example of the group's trajectory through one activity cycle, we briefly elaborate on their involvement in a debate during the aforementioned whole class debriefing. The group challenged another's assertions that particle trails represented wavelength and intervals between each particle represented frequency. Instead, they proposed that the length of particle trails represent speed. The ensuing whole-class debate arrived at the question of whether or not a field can "stop particles in their tracks entirely." This debate, in turn, shaped subsequent cycles of game play as the group worked to engineer conditions under which particles are motionless. Thus, small group discussions about the initial experiences with particles and fields culminated in a whole-class debate about stopping particles, which the group later described in interviews as an important goal of subsequent episodes of game play. This trajectory through the first of four dialogic activity cycles illustrates how the interplay between game play and discussion, and between rich experiences and reflective exchanges, allows negotiations between increasingly formal understandings that can position students to generate their own inquiry activities. In this sense, game play establishes a two-way literacy through which students make meaning of phenomena and also generate new phenomena.

The second group that we consider provides an important contrast to the interpretations above. The three boys in this group (Troy, Alex, and Kevin) intermittently coordinated their gaming activities and typically collaborated only when a presentation was due. They rarely discussed their logbooks, choosing to complete them individually instead. Their group discussions were often sparse as each member individually completed the logbook entries, and they completed presentation charts by dictating logbook entries as one of them wrote. Similar to the first group above, they describe game features informally during the first cycle of game play. However, the following excerpt illustrates a typical discussion for this group in which they attempt to navigate the game space.

T: I don't get it.

A: Oh I actually see the beam moving.

T: (looking at A's screen) How'd you do that? (laughs)

A: I don't know. I'm making the beam move. Go that way (presses arrow keys).

T: (reading instructions) Change speed using up arrow.

A: How to change speed? (A and T press arrow keys).
T: You can't even change speed!
A: Speed of what?
T: What are we supposed to do?

Although they struggle to manipulate particles, Alex uses the term "beams" to note that he can bend, or "move," particle trails. However, the group does not re-engage this encounter as the conversation proceeds. Subsequent group discussion centering on the logbook introduces particle trails again and provides the group with a second opportunity that they do take up collectively.

T: The particles should be like protons and electrons because they will be affected by whatever field the vehicle is emitting.
K: I notice, right, that they are shorter (pointing to logbook figure) that means they have slowed down.
T: No, it's just the stupid graphics. Look at this, this one also,
K: No, these (pointing at same logbook figure) are shorter. These (pointing at another logbook figure) are the same. This one (pointing at first logbook figure) is like one long stream.
A: What? What?
K: This has one long stream, and this has- (dotted motion along paper) describes the wave.
T: It means these are affected by the field emitted by the vehicle.
K: They represent wavelength, right?
T: Because it's a particle. Particle has mass. Has weight. Is affected by forces.
T: (To K) What do they represent? (pause but no response) I'll just write down everything.
K: The speed at which they travel.

Troy and Alex enlist a variety of physics terms, but Kevin explains the significance of the particle trails using the logbook photos at hand and suggests an accurate explanation of what they represent. Ultimately, an interpretation of trails as wavelengths, and not speed, is featured in the group's debriefing presentation, sparking the aforementioned debate with the first group about stopping particles. In contrast to the first group, however, this trajectory is without the necessary reciprocity in the conversational exchanges underlying their dialogic activity cycles. In both transcripts above, group two struggles to productively engage one another's comments in a way that builds shared understandings.

Conclusions

In this design study, we attempted to anchor cycles of dialogic activity to the shared contextual grounding that *Escape from Centauri 7* provides to classroom players. Based on a situative perspective of learning, we engineered a process through which learners might formalize the intuitive understandings they develop with the game. In particular, we used logbooks as a boundary object across activities in order to illuminate a concrete process of formalizing physics much like Latour (1987) describes in the laboratories he studied. We investigated this concrete process in terms of Rogoff's (1995) three planes of analysis by asking how gaming fosters intuitive physics understandings, how activity structures and materials engage learners and enlist gaming experiences in discussion, and how both game play and discussion shape subsequent participation. The cases we considered suggest that groups engaged in rich and challenging collaborations as they played the game. Their engagement fostered a range of intuitive understandings, suggested by often cryptic comments during play and subsequently illuminated as students used gestures and game-specific descriptions to talk about the formal physics principals underlying the game mechanics. At the same time, the multiple, simultaneous features presented in the game dynamics sometimes confused and frustrated players. In anticipation of this range of experiences, we discretely bounded the game in order to arrange discussion and debriefing activities. The first group we examined enlisted their gaming experiences to methodically formalize their understanding of physics phenomena and challenged others to do the same during debriefings. These discussions in turn shaped later play. However, understanding the less immediate influences of these cycles remains a challenging analytical task. While it is reasonable to assume that students anticipated the prospects of discussions and debriefings in the later cycles of game play, the relatively short duration of the curriculum obscures the ways in which it shapes subsequent participation. Meanwhile, with respect to the second group, sequences of dialogic activity suggested that efforts to make sense of their experiences were at times reframed in terms of a patchwork of physics concepts and at other times loose constellations of conversational turns, neither of which cohered into a process of formalizing the dynamics of charged particles. In summary, these somewhat disparate cases suggest that classrooms can foster a synergistic interplay between game experiences and group reflection but also that their utility is a variable outcome of the learning ecologies through which they emerge.

Discussion

A key assumption of serious gaming underscores that *Escape from Centauri 7* can only ever frustrate and facilitate various trajectories of participation. In this sense, games are tools for mediating individual and collective goals if anchored in social activity. In our study, we deliberately partnered with a school that organizes module courses on cutting-edge topics in order to arrange both a stable physical place and a relatively flexible game space in which to work. Therein we aimed to develop a curriculum in which "learning is a way of being in a social world, not a way of coming to know about it" (Hanks, 1991, p. 24). Our findings suggest that game-centered contextual grounding facilitated students' efforts to formulate epistemic stances, or positions, on the dynamics of charged particles. The lethal mutations we observed in these cases and elsewhere suggest that dialogic activity in serious games may entail something more than a process of argumentation. In spite of learners' shared experiences with the game space, their collective intersubjectivity and our design efforts failed to foster a mutual willingness to re-examine particular epistemic stances in light of unfolding game dynamics. We find these tensions interesting in light of Bourdieu's ideas about the effects of a community on the beliefs, dispositions, and practices of its members, as reflected in the notion of epistemic reflexivity (Bourdieu & Wacquant, 1992).

Epistemic reflexivity considers the tensions associated with the inherent perspectivity of meaning making, as detailed above in our theoretical framework. In one sense, the challenge of epistemic reflexivity is to address the problems we never knew we had. In the context of this study, we organized serious play, dialogic activity cycles, and the notion of guided participation to create opportunities for individuals, groups, and the teacher to illuminate a range of such unknown problems along a trajectory towards shared understandings. The whole class debate about stopping particle motion that we showcased in our analysis exemplifies epistemic reflexivity at a group level. Nevertheless, it largely hinged on the teacher's skillful facilitation and remained a paradigmatic case rather than a representative instance. As we continue to design for the interplay between play and learning, we contend that a principled approach to leveraging serious games across cycles of dialogic activity requires a deliberate effort to design not only for discussion and debate but for the translation of such talk back into the game space. In this way, the concrete features of the game mechanics can not only be refashioned into ideas and beliefs that surface through dialogic cycles but also can, in turn, be used to fashion subsequent experiences of the game, potentially illuminating the problems learners didn't know they had.

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