Clark, D. B., & Martinez-Garza, M. (in press). Prediction and explanation as design mechanics in conceptually-integrated digital games to help players articulate the tacit understandings they build through gameplay. C. Steinkuhler, K. Squire, & S. Barab (Eds.), *Games, learning, and society: Learning and meaning in the digital age.* Cambridge: Cambridge University Press.

Prediction and Explanation As Design Mechanics In Conceptually-Integrated Digital Games To Help Players Articulate The Tacit Understandings They Build Through Gameplay

Douglas B. Clark & Mario Martinez-Garza
Vanderbilt University

Abstract. Several games have been developed in recent years with a focus on engaging players in inquiry. Most of these games have focused on inquiry as an explicit part of the gameplay where the player moves through the world to locations where the player can then engage in inquiry activities. These games have proven successful in helping players learn about inquiry and the science concepts involved. A few games, by contrast, have focused on integrating the science learning directly into movement and navigation through the game itself (e.g., Supercharged, SURGE). A significant challenge in these games, particularly those focused on Newtonian motion and mechanics, is that the learning tends to remain at a very tacit embodied level. This paper discusses the potential of harnessing prediction and explanation as design mechanic in digital games to help players articulate the tacit understandings they are building through gameplay.

Introduction

Well-designed digital games are exceptionally successful at helping learners build accurate intuitive understandings of the concepts and processes at the heart of the games due to the situated and enacted nature of good game play (e.g., Gee, 2003; 2007). Most commercial games fall short as platforms for learning because they do not help people articulate and connect their evolving intuitive understandings to more explicit formalized structures that would support transfer of knowledge to other contexts. Games hold the potential, however, to support learners in integrating their tacit spontaneous concepts with instructed concepts, thus preparing learners for future learning through a flexible and powerful foundation of conceptual understanding and skills (Clark, Nelson, Sengupta, & D'Angelo, 2009). The integration of prediction and explanation mechanics into gameplay potentially provides tools for supporting this extension from tacit to explicit by helping players articulate and explore the connections between the science-based dynamics present the game and the formalized scientific principles they instantiate. This chapter explores those possibilities and proposes an example how this might be accomplished in a physics-based game.

Background: Digital Games for Science Learning

This perspective that games provide significant potential affordances for science learning is not idiosyncratic. In 2006, the Federation of American Scientists issued a widely publicized report stating their belief that games offer a powerful new tool to support education and encouraging governmental and private organizational support for expanded funded research into the application of complex gaming environments for learning. In 2009, a special issue of *Science* (Hines, Jasny, & Mervis, 2009) echoes and expands this call. Later in 2009, the National Research Council convened a committee and workshop to explore this potential of Games and Simulations for Science Learning in greater depth.

Clark, Nelson, Sengupta, and D'Angelo (2009) wrote the first of the five topic papers for this workshop, focusing on the evidence for the value of simulations and games for science learning. That review discusses several studies providing evidence for the potential of digital games to support science proficiency. These studies, for example, demonstrate potential in terms of conceptual understanding and process skills to operate on that understanding (e.g., Annetta, et al., 2009; Barab, Sadler, et al., 2007; Clark et al., 2009; Dieterle, 2009; Hickey et al., 2009; Holbert & Wilensky, 2010; Kafai et al., in press; Ketelhut et al., 2006; Klopfer et al., 2009; Moreno & Mayer, 2000, 2004; Steinkuehler & Duncan, 2009). These studies also show that games can support players' epistemological understanding of nature and development of science knowledge (e.g., Barab, Zuiker, et al., 2007; Clarke & Dede, 2005; Neulight et al., 2007; Squire & Jan, 2007; Squire & Klopfer, 2007) and players' attitudes, identity, and habits of mind in terms of their willingness to engage and participate productively in scientific practices and discourse (e.g., Anderson, 2009, in press; Barab et al., in press; Barab et al., 2009; Dede & Ketelhut, 2003; Galas, 2006; McQuiggan, Rowe, & Lester, 2008).

Several of these games cast players as scientists or investigators (e.g., *Quest Atlantis*, *River City*, *Operation: Resilient Planet*). In these games, the player learns science by moving through the game world to specific locations and engaging in explicit inquiry activities at these locations. This chapter will refer to this genre of games as "conceptually-embedded" games where science processes are embedded within the game world. This approach has the advantage of directly making the science learning and processes explicit. Furthermore, these types of games have the potential to be very transformative in terms of the players' identities. The players can view the world as a scientist, using their tools, seeing how and why it's interesting, and using science to have a direct impact on the world (Gee, 2007; Squire, this volume).

Another, smaller, set of games focuses on the science learning directly within the motion and mechanics of the game world itself, such as *Supercharged* (Squire, Barnett, Grant, Higginbotham, 2004; Anderson and Barnett, in press; Barnett, Squire, Higginbotham, & Grant, 2004), *SURGE* (Clark, Nelson, D'Angelo, Slack, & Martinez-Garza, 2010, submitted; Clark, Nelson, D'Angelo, Slack, & Menekse, 2009; D'Angelo & Clark, in preparation; D'Angelo, Clark, Nelson, Slack, & Menekse, 2009), and *FormulaT Racing* (Holbert & Wilensky, 2010). This chapter will refer to this genre of games as "conceptually-integrated" games[1] where the science concepts of focus are integrated directly into the core mechanics that operate in the game environment. These games have the potential advantage of engaging the player with the science ideas targeted in the game a higher percentage of the play time (potentially the vast majority of play time) whereas conceptually-embedded games involve other interactions while moving and exploring the world between specific inquiry locations and activities, or as backdrop for those activities. The disadvantage of integrating the science learning goals directly within the motion and mechanics of the game world, however, is that while the players may spend the vast majority of gameplay time interacting with the core ideas as a means of navigating through the world,

---

[1] In making this distinction between "conceptually-embedded" and "conceptually-integrated" games, we certainly are not diminishing the power of conceptually-embedded games. Our purposes is simply to highlight differences in affordances and challenges for "conceptually-integrated" games, which generally have received less focus in games for learning research.

making the core ideas and relationships explicit rather than tacit is a much bigger challenge than in the conceptually-embedded approach.

Essentially, even though playing a conceptually-integrated game engages the player constantly in the targeted relationships, the player may never articulate or even identify those relationships. For example, in a study on *Enigmo*, researchers found that while players of this commercial physics-based projectile motion game developed some tacit understanding that led to higher performance on an immediate post test in terms of predicting trajectories, they didn't demonstrate gains on other aspects of Newtonian mechanics on the immediate posttest, and showed no gains compared to a control group after subsequent traditional instruction (Masson, Bub, & Lalonde, 2010). Thus, while *Enigmo* provides students with a strong intuitive 'feel' for physics concepts, it doesn't appear to help students make the leap from tacit understanding to more formalized knowledge. Specifically, Masson, Bub, and Lalonde found that students "improved their ability to generate realistic trajectories" (p. 1). However, the game did not help them learn more from a direct instruction "tutorial" when compared to a control group. These findings suggest that simply having players engage with physics-based games is not sufficient to help them learn physics. This result is not overly surprising; few people would suggest that playing soccer, for example, will teach people physics even though soccer is clearly a physics-based game in many ways. *Enigmo* was developed as a commercial recreational game rather than as a learning experience, and thus unsurprisingly follows along this path. Soccer and *Engimo*, however, could potentially be re-envisioned or redesigned in a manner that would support explicit articulation and exploration of the core physics implicit in their game experience.

Paralleling these findings, *Super-Charged* research has emphasized the importance of supports for metacognition (Squire, Barnett, Grant, Higginbotham, 2004; Anderson & Barnett, in press; Barnett, Squire, Higginbotham, & Grant, 2004). Squire et al., for example, report that the teacher collaborating in their research created activity structures outside of the game to engage students in predicting and explaining what was happening in the game and reflecting on connections. Similarly, research with *SURGE* has demonstrated some learning gains on questions based on or drawn from the Force Concept Inventory, but that further supports to help players explicitly articulate and explore the core relationships would be of significant pedagogical value (Clark, Nelson, D'Angelo, Slack, Martinez-Garza, & Menekse, 2010; Clark, Nelson, D'Angelo, Slack, & Menekse, 2009; D'Angelo, 2010; D'Angelo, Clark, Nelson, Slack, & Menekse, 2009). SURGE research further suggests that the players' learning was heavily related to their embodied experience in the game, and raised the possibility that whatever learning gains the players were making remained inchoate and contextually rooted in the game experience (Clark, Nelson, D'Angelo, Slack, & Martinez-Garza, 2010, submitted).

Essentially, the findings across these studies suggest that simply having players engage with physics-based games is not sufficient to help them learn physics. This should not be overly surprising. Few people would suggest that playing soccer, for example, will teach people physics even though soccer is clearly a physics-based game in many ways. *Enigmo* was developed as a commercial recreational game rather than as a learning experience, and thus unsurprisingly follows along this path. Soccer and *Engimo*, however, could potentially be re-envisioned or redesigned in a manner that would support explicit articulation and exploration of the core physics. What needs to happen to support an explicit articulation and exploration of the relationships in a physics-based game?

Framing the Challenge: Learning Occurs But Remains At An Intuitive Level

We propose that the learning challenge conceptually-integrated game mechanics can be framed in terms of the distinction that Parnafes and diSessa (2004) make between model-based reasoning and constraint-based reasoning. Parnafes and diSessa explored players' thinking in a game-like simulation called *NumberSpeed*. In *NumberSpeed*, players designate the position, velocity, and acceleration for two different turtles to solve a series of challenges (e.g., get Turtle A to a distance of 20 first while getting Turtle B to a distance of 40 first). Parnafes and diSessa observed that players sometimes engaged in thinking very locally through simple processes of co-variation (constraint-based reasoning) and sometimes engaged in thinking more deeply about the underlying relationships and components to make more principled or model-based accounts of the challenge and what needed to happen to solve the challenge (model-based reasoning).

Essentially, constraint-based reasoning involves "using a set of heuristics to meet the problem constraints, usually using simple co-variation" (Parnafes & diSessa, 2004. p. 265). It involves means-ends strategies focusing on local comparisons, simple motion principles, or pure co-variation focusing on a small number of the problem constraints or parameters at a time. Model-based reasoning, however, involves "creating a mental a mental model of the whole scenario of motion, and mentally running the model to reason about the motion situation" (p. 268). It involves examining plans and modifying or considering alternative plans in pursuit of an integrated qualitative solution based on complex motion principles and multiple parameters.

From the perspective of science learning, constraint-based thinking is fine asif it ultimately supports the development of model-based thinking about phenomena, ultimatelythe latter type of thinking being necessary for lasting understanding. In a game for example, if players never progress beyond reactively adjusting their avatar's motion through the gamespace in a constraint-based manner (e.g., just a bit more to the right or a bit more to the left), it would seem surprising if those players exhibited understanding deeper than that level of reflexive compensation on transfer or assessment tasks subsequent to the game. Thus we might expect the player to be able to predict how a specific minor action component (e.g., clicking the "left arrow" key) might affect the trajectory of an object, for example, but more global understandings would seem unlikely . This is because more global understandings would involve model-based thinking about the relationships in the game rather than simple constraint satisfaction, which might even reside primarily at an even lower unarticulated tacit or instinctive level "in the thumbs" of the player.

We can characterize the differences in learning in terms of elemental perspectives on conceptual change (e.g., Clark, 2006; Clark, D'Angelo, & Schleigh, in press; diSessa, 1993; diSessa, Gillespie, & Esterly, 2004; Parnafes, 2007; Wagner, 2006). These perspectives hypothesize that students' conceptual ecologies include a wide range of elements such as sub-conceptual p-prims[2], beliefs, facts, facets[3], and mental models, among others. These elements are cued by context and interact with one another in a network of positive and negative connections. These core mechanisms and interactions result in the potential for conflicts between ideas, sensitivity to contexts, differential weighting of ideas, and the systematicities created by the interaction of prominent elements. Learning according to these perspectives occurs as people sort through and revise their ideas as they build and revise connections between the ideas. The ultimate goal is that the learners will hopefully develop a more parsimonious and coherent understanding of normative theory-like character over time through these process. The goal for education then is to facilitate these processes of revision and reorganization.

The challenge for games with conceptually-integrated core mechanics is that if the games only demand constraint-based reasoning of the player, very little substantial reorganization and revision of the player's ideas is required. People's understanding of physics situations is often not an articulated level (e.g, disessa's (1993) discussion of phenomenological primitives or Clark's (2006) account of students' thinking about heat and temperature). Gameplay that allows or incentivizes players to simply react through constraint-based reasoning, or for gameplay to remain in the player's "thumbs," neither pushes players to articulate the components of their thinking (e.g., p-prims) nor the overarching relationships and connections between the multiple relevant components relevant to the phenomenon at hand. Turkle argues this in terms of learning in SimCity, for example, focuses on learning simple heuristics (Turkle, 1997). Squire (in press) argues that this kind of shallow understanding transforms into model-based reasoning as people become more expert. The focus of this chapter is on how we might design gameplay that specifically incentivizes this model-based thinking at a higher level of conceptual awareness and articulation (e.g., mental models rather than p-prims) that involves closer consideration of the nature of the components and the overarching relationships between them.

Possible Solutions: Prediction and Explanation Mechanics

If encouraging model-based reasoning is the goal, how can we incentivize it? In simulations and hands-on science labs, students often use trial-and-error as opposed to mindful strategies (Chang & Tsai, 2010). Parnafes and diSessa argue that certain representations provide more ready affordances for one form of reasoning or the other. Research has shown that contexts can be structured or queued in a manner that the students are more likely to view their goals in an epistemological manner encouraging pursuit of explanatory coherence (e.g., Ranney & Schank, 1998; Rosenberg, Hammer, & Phelan, 2006; Thagard, 1989, 2007; Thagard & Verbeurgt, 1998). Research also suggests that coupling highly interactive visualizations with meta-level learning activities, such as self- or peer-evaluation (Chang, Quintana & Krajcik, 2010; Moreno and Valdez, 2005) or critique (Chang, 2009; Chang and Linn, in preparation) can help students reflect on and refine ideas (Chang, Chiu, McElhaney, & Linn, in preparation).

---

[2] P-Prims (or "Phenomenological Primitives") are inarticulate explanatory primitives in a student's conceptual ecology that provide the basis for many of that student's explanations about science phenomena (e.g., diSessa, 1993).
[3] Facets are independent explanatory facts or "rules of thumb" that students use to understand and explain situations and phenomena (e.g., Hunt & Minstrell, 1994).

A further challenge for conceptually-integrated games involves building in these exterior supports while preserving the immersive and engaging properties of the game itself. We propose that engaging players in prediction through the navigation interface and explanation through their dialog with the game's non-player characters or entities can provide metacognitive supports for model-based reasoning.

A growing body of research and scholarship on games and cognition emphasizes cycles of prediction, observation, and refinement as being a core mechanic of game play processes (Squire, Jenkins, Holland, Miller, O'Driscoll, Tan, & Todd, 2003; Salen & Zimmerman, 2004, Wright, 2006). We propose to leverage these ideas with research from psychology on self-explanation and research from science education on prediction and explanation to operationalize and refine the potential of prediction and explanation mechanics in conceptually-integrated games to support science learning. Even if players do engage in reflective cycles of hypothesis formation and revision, few games provide structures for externalizing and reflecting on these cycles. More often, such articulation and reflection occurs *outside* the game, through discussion among players or participation in online forums (Gee, 2007; Squire, 2005; Steinkuehler & Duncan, 2009). Developing methods to integrate such articulation and reflection into the game experience and extending them so as to promote broader application is a challenge for contemporary educational design.

The focus on prediction and explanation are central to many curricular focuses in science education. The Predict-Observe-Explain model developed by Champagne, Klopfer and Anderson (1980), for example, has seen wide practical application as pedagogical practice in science classrooms and school laboratories. Broadly described, Predict-Observe-Explain is a classroom or laboratory activity with three distinct stages. In the 'prediction stage', students are shown a situation or system at rest in which a given science principle applies, and students are prompted to predict the outcome of setting the situation or system into motion. In the 'observation stage', students see the phenomenon unfold (or perform the experiment themselves) and are asked to describe the outcome. Finally, in the 'explanation stage', students are asked to compare their observations with their predictions and explain their agreement or disagreement. The Predict-Observe-Explain process has long been recommended by science educators (e.g., Mazur, 1996; Grant, Johnson & Sanders, 1990; reviewed more generally in Scott, Asoko & Driver, 1991) as a classroom activity that is epistemologically similar to real-world scientific inquiry. Many studies show Predict-Observe-Explain to be effective at promoting learning and reflection on concepts of science (e.g., Palmer, 1995; Shepardson, Moje & Kennard-McClellan, 1994; Cosgrove & Osborne, 1985; Baird & Mitchell, 1986; Borges, Tecnico & Gilbert, 1998; Rickey & Stacy 2000) and also as a useful tool for probing and diagnosing students' conceptions of science facts as well as monitoring conceptual change (Liew & Treagust, 1995, 1998; Searle & Gunstone, 1990; White & Gunstone, 1992).

Along with general demonstrations and arguments in favor of the efficacy of Predict-Observe-Explain, several other lines of research have probed more deeply into the connections of POE to constructivist, conceptual change, and metacognition literatures. From a constructivist perspective (e.g., Liew & Treagust, 1998), the PEO teaching/learning sequence draws on the Piagetian concept of accommodation (Piaget 1964), whereby learners become aware of conflicts between their conceptions and physical reality. Thus, later works on POE (e.g. Kearney, 2004;

Kearney & Treagust, 2000) have highlighted the importance of the 'explanation stage' of POE as the being the moment where learning is most likely to occur. Some didactical approaches similar to POE (e.g. Ideational Confrontation, as described in Champagne, Gunstone & Klopfer, 1985) involve a more social dynamic, evocative of Vygotsky, by asking students in the 'explanation stage' of POE to convince each other of the validity of their ideas. Many of these constructivist perspectives fit well with the elemental perspectives on conceptual change that guide this research. Other lines of research have supported the POE sequence from a cognitive perspective by grounding it in metacognition (Champagne, Klopfer & Gunstone, 1982) and conceptual change (Tao & Gunstone, 1999). According to these perspectives, the process driving learning in POE is the 'prediction stage', where students must not only articulate their naive concepts but also marshal explicit support for these concepts, underscoring the importance of the monitoring and regulatory aspects of metacognition (White, 1988; White & Gunstone, 1992). Other work in science education has focused more broadly on the value of prompting reflection. Work by White and Frederickson (1998, 2000) demonstrates that value of asking students to reflect on their learning during inquiry with physics simulations, for example, and Lin and Lehman demonstrated similar high learning gains by prompting for reflection in a computer-based biology environment.

In addition to research in science education, work on self-explanation by Chi and others provides clarity into the value of explanation for learning (e.g., Chi, Bassok, Lewis, Reimann, & Glaser 1989; Roy & Chi, 2005; Chi & VanLehn, in press). That work began by demonstrating that students who explained their answers and work to themselves perform better on posttests. The work went on to demonstrate that students who are prompted to provide explanations of their answers perform better on posttests. A recent review of research on self-explanation by students reports that self-explanation results in average learning gains of 22% for learning from text, 44% for learning from diagrams, and 20% in learning from multimedia presentations (Roy & Chi, 2005). Encouragingly, research by Bielaczyc et al. (1995) showed that instruction that stresses generating explanations improves performance even after the prompts are discontinued.

In terms of implementation in game-like environments, Mayer and Johnson (2010) implemented a self-explanation condition utilizing an explanation selection format based on work by Hausmann and Chi (2002) showing that computer-based multimedia learning environment reduced self-explanation effects when learners are required to type rather than verbalize their thoughts. Similarily, work by Atkinson, Renkl, and Merrill (2003) showed that performance on computer-based worked-out examples improved when learners chose explanations for each step from a pull-down menu. Mayer and Johnson (2010) found significant gains on a transfer task following game play for participants in the self-explanation condition in comparison to the control condition. These results suggest the potential value of building this functionality into conceptually-integrated games.

The inclusion of prediction and explanation into game environments for learning is not a trivial challenge. Although already rich with interaction schema that support learning (Gee, 2007), video games do not regularly ask players to predict or explain in-game phenomena at the level of general principles. At a more localized level of interactivity, however, prediction and (self) explanation exist throughout game play, framed as internal responses to moments of choice

(Salen & Zimmerman, 2003). A central task of our research plan is to highlight these moments of choice for the player-learner and turn them into opportunities for reflection and learning.

Example: What Might Prediction and Explanation Look Like In A Conceptually-Integrated Physics Game?

In some game formats, integration of explicit prediction and explanation can be more easily envisioned. In a conceptually-embedded game, such as a roleplaying game where the player is cast explicitly as a scientist, the game could include prediction and explanation in a relatively straight-forward manner. Physics-based games, however, are potentially less obvious in this regard. To explore what this might look like in a Physics game, we now outline a game design to implement these into the game mechanics in a manner that might support the explicit articulation of model-based thinking in a conceptually-integrated physics game. We first describe a simple core game mechanic as a context and then describe how prediction and explanation might be integrated.

Game Description: Cup Racer

To provide a context for these proposed prediction and explanation mechanics, we first outline a hypothetical physics game context, which we will refer to as "*Cup Racer*." Essentially, players in *Cup Racer* need to navigate their avatar (a small but very intelligent gecko who has equipped a coffee mug with rocket engines) through the play area to pick up food and friends and deliver them to safe locations while avoiding obstacles and enemies. The player in *Cup Racer* uses the rocket engines to navigate through levels that correspond initially to areas of a kitchen filled with food, friends, and dangers. Levels in *Cup Racer* are very short and puzzle-like in nature. Levels involve executing a small number of navigation maneuvers to solve specific challenges. From a content perspective, *Cup Racer* focuses on Newton's second law (Force = Mass x Acceleration) and basic kinematics in terms of the relationships between distance, velocity, acceleration, and friction with some emphasis on how forces can change motion in a new direction.

Prediction

How might prediction be integrated into a physics game? We propose that the navigation interface provides an excellent opportunity for prediction. Essentially, while real-time and just-in-time navigation formats are common in games like *Cup Racer*, formats supporting prediction are also not uncommon and could be developed within the "magic circle" of the game without breaking the game aspects of *Cup Racer*. Furthermore, a game like *Cup Racer* provides excellent opportunities for research on the integration of prediction into games because of the range of interface formats afforded along a prediction/real-time format.

Essentially, real-time or just-in-time navigation formats engage the player in making decisions during the flow of the level often in a reflexive manner mirroring constraint-based thinking (e.g., the player continually micro-adjusts direction and velocity as it becomes apparent that adjustments are required). Examples of such interfaces might include:

- ***Real-Time Constant Velocity.*** Clicking and holding down the "arrow" keys on the keyboard to move the avatar at constant velocity in the direction of the arrow key. This is a standard navigation interface in many games ranging from casual "platform" style games to massively multiplayer online games. This interface requires no prediction in terms of result of pressing a key -- push the key and move in that direction at a fixed velocity no matter what motion you may have been involved in the moment before. This is the core control condition for our pilots.
- ***Real-Time Constant Acceleration.*** Clicking and holding down arrow keys to apply a constant acceleration in the direction of the arrow key. The classic arcade game *Asteroids* made this interface popular long ago. This interface requires a higher level of prediction and model-based thinking because it requires more planning in terms of what you will need to do to maneuver into a location or vector of motion because you are just adjusting your velocity in terms of speed and direction rather than directly mandating your velocity simultaneous with your keystrokes.
- ***Real-Time Tilting for Constant Velocity or Constant Acceleration.*** Tilting a controlling device, such as the controller of the Nintendo Wii game console, or the entire device in the case of a smaller digital device such as the iPad or Sony PSP portable game player, to recreate any of the interfaces formats described above. Such an approach could create a more embodied and physical connection to the navigation, and even more embodied options are becoming available, such as the upcoming Microsoft Natal system.
- ***Real-Time Key-Based Variable Magnitude Acceleration***. Clicking arrow keys multiple times to increase the magnitude of acceleration or magnitude of force being applied along an axis (up-down or side-to-side). A rocket burst could begin and end when increasing above 0 and returning to 0, or a rocket burst could be defined as beginning and ending with clicks on another key (e.g., the spacebar) for an interface version that counted or limited the number of rocket bursts. This is similar to the interface above, but involves more planning about longer-term navigation goals.
- ***Real-Time Mouse-Based Variable Magnitude Acceleration***. Moving the mouse across a vector representation to choose direction and magnitude of force or acceleration. The player might click mouse to begin and terminate a rocket burst, or they might click another key, such as the spacebar, to initiate and terminate a rocket burst. This would provide a more visual representation and connect map the player's navigation more directly onto a formal representation format from the physics discipline. The vector could be constrained to one of the four cardinal directions, or even just to single axis (e.g., up-down), depending on the level. Alternatively, the vector could be allowed to span the full 360 degree range of possible motions.

Some of these interface formats incentivize a higher degree of prediction and model-based thinking than others. In a predictive interface, the player needs to think ahead more systematically about what the outcomes will be for a possible action. The more aspects of mechanics the interface requires the player to consider in making a successful prediction for solving the challenge at hand, the more that interface would seem to require and incentivize model-based thinking versus constraint-based thinking, and the further we would align that type of interface along the prediction end of the spectrum.

In the interfaces outlined above, for example, the constant velocity interface requires the least prediction, while the constant acceleration requires a bit more. Similarly, the vector interfaces that only allow thrusts along the up-down and side-to-side axes require more prediction than the vector interfaces that allow free 360-degree manipulation of the direction. Adding fuel limits or other resource limits further pushes toward the prediction end while allowing unlimited resources moves the challenge and experience more toward the real-time end (e.g., allowing a limited number of rocket bursts incentivizes players to plan and think more carefully about the outcomes of each burst more carefully than an interface that allows unlimited bursts because in the latter interface the player can keep applying bursts to micro adjust navigation in pursuit of a burst rather than needing to get "the most" out of each one). The examples below highlight some possible interfaces further along the prediction end of the spectrum.

- ***Predictive Table-based Pause And Program.*** Pausing the game and programming direction of force, magnitude of force, and duration of force into a table for the next rocket burst and then pressing a key to initiate the burst. This process would then be repeated for each subsequent burst, allowing the player to consider and plan carefully the impact of each decision, which might be further incentivized by tying score or success to minimizing the number of bursts required to succeed. This programming approach for each "move" hearkens back to early projectile motion games, such as *Scorched Earth*, where the player programmed each cannon shot in a race with the opposing player. This interface format simply adds the duration of the rocket burst to the process and transforms the planning format into a sequence of rocket bursts rather than a series of independent projectile launches.
- ***Predictive Vector-based Pause And Program.*** Pausing the game and using a vector interface for the magnitude and direction of the next rocket burst, entering a duration, then pressing a key to initiate the launch, and then pausing the game for each sequential burst. This transforms the format above into a GUI interface, and is a standard approach in many current projectile motion games, such as *Gravitee 2* on Kongregate.com.
- ***Predictive Table-based Full Program.*** Programming the direction of force, magnitude of force, the starting time, and duration of force for each rocket burst in a planned sequence of rocket bursts in a data table using numbers and then pressing a key to launch the plan and put it into action. This interface format requires the most prediction and model-based thinking because it requires the player to project and predict the results of subsequent rocket bursts in a chain to achieve a goal rather than executing one burst and then engaging in planning the next to adjust toward the goal in a manner mirroring more constraint-based thinking or the simple hill-climbing approach toward problem solving.
- ***Predictive Vector-based Full Program.*** Programming visual or GUI approach mirroring the approach above but rather than using numbers in a data table, this GUI approach might place blocks to represent duration and magnitude of rocket bursts along timeline tracks representing the direction of the burst with distance along the track representing the timeline for when the bursts initiate. As above, the player would eventually press a key to initiate the program. This GUI version might prove easier for players to use in visualizing the nature of the program they are creating, facilitating model-based thinking and prediction. These more predictive interfaces, we would argue, should support a higher level of model-based thinking than constraint based thinking, as well as a higher percentage of explicit articulation of

thinking versus implicit intuitive thinking that might stay at the level of unaware application of p-prims.

Explanation Mechanisms

Explanation seems more tricky to integrate within the "magic circle" of the gameplay for single-player conceptually-integrated game, but the literature supporting the role of explanation in learning is so compelling that further exploration for games seems very promising. We see numerous examples of players working collaboratively outside and inside the game as part of collaborative raids (Thomas & Brown, 2009), guild membership debreifs (Steinkeuhler, 2007), forum discussions (Steinkuhler & Duncan, 2009), affinity groups (Gee, 2003), emergent universities (Squire, this volume), and such. Two challenges for integrating explanation into single-player conceptually-integrated games include (1) providing a format for the player to provide an explanation that is not cumbersome and stays within the gameplay and (2) doing so in a manner that allows the software within the game to assess and react to the explanation. Generally, most approaches to explanation would likely shift toward a conceptually-embedded approach, but could still complement and synergize with the core conceptually-integrated game mechanics.

One surface possibility for *Cup Racer* or other games could involve having the the player explain how to overcome a certain type of challenge to hypothetical Non-Player Character (NPC) in the game so that the NPC could theoretically engage in that activity successfully. Similarly, the NPC might actually need to try and accomplish the task and the player could see the result and adjust the explanation.

This latter mechanic is central to the *Betty's Brain* software (Biswas, Leelawong, Schwartz & Vye, 2005), where a student creates a concept map to teach "Betty" about the relationships between various factors in problem context. *Betty's Brain* then allows the player to give Betty a test to see what she actually knows. By adopting this concept map format for explanations, Betty's brain allows the player to provide explanations that the software can interpret and act on.

A simpler approach to explanations might involve adopting the standard conversation format from many roleplaying playing games where the player is given a list of possible responses and chooses one from that list. Rather than choosing "I'd like to hire you as a guide to show me where the hidden cavern is", the player might have choices like "when you double your mass, you halve your acceleration." The computer could then give feedback, such as "I have input your explanation into the computer's flight simulator, and it looks like we would still crash -- Do you have other suggestions we might try?" This roleplaying game convention is essentially just multiple choice, but it does allow the game to anticipate answers and provide targeted feedback to those explanations.

Another possibility involves integrating argumentation into the process so that players include explanations as well as evidence for their choices. *Operation: Resilient Planet*, for example, has players include icons representing pieces of evidence that they have collected in support of the multiple-choice claim. This approach to claims and evidence has been extended and enhanced in other games such as *Citizen Science*, *Phoenix Wright*, *Our Courts*, and *Policy World*. In these games evidence generally involves the completion of a specific activity or reading a specific piece of text. These pieces of evidence are generally attached to claims. *Citizen Science* and *Our Courts* move a step further by including other components of arguments. In Quest Atlantis, players upload scientific reports that are then reviewed and feedback provided by teachers often signing their critiques as in-game characters (Barab, Zuiker, et al., 2007). Or, as another form of reflection, players in Quest Atalntis are expected to interpret a water quality problem and implement an in-game solution, aftere which they are required to travel to the future and as a form of reflection, analyze the outcome of their solution.

All of these are excellent approaches for game settings where other artifacts and readings make sense within the context of the game (e.g., reading a policy brief in *Policy World* or checking the contents of a shark's stomach in *Operation: Resilient Planet*). In this section, we propose a structure that would allows the player to more flexibly create and choose claims, qualifiers, and evidence in direct connection to the mechanics of a physics game. We first outline an iconic explanation creator that could allow players to flexibly create explanations that the game might assess and act on. We then explain an approach for allowing players to flexibly identify evidence gathered through the game engine that the game could assess and act on. A game might include only the iconic explanation creator, or it might also include the evidence/argumentation component to extend the iconic explanations.

Iconic Explanation Creator
Figure 1 shows a possible interface for iconic explanation creator. Explanations are represented in a manner that can be read as text and symbolically to clarify the structure. Essentially, explanations involve an independent variable, a dependent variable, modifiers for each variable that define their relationship (e.g., "Increasing" for the independent variable and "Decreases" for the dependent variable in the figure below), and any relevant conditions that define or limit the domain across with the explanation applies. Conditions (also called "qualifiers" in the argumentation literature) are thus essentially modifications to the explanation about the range of the domain in which the explanation holds true. These conditions are stated in terms of ranges for specific variables. These ranges can be stated verbally for some general relationships (e.g., "Independent of..." or "For a Constant...") or as ranges of values (e.g, "If Velocity is greater than 80 m/s" or "If Velocity is between 80 m/s and 130 m/s").

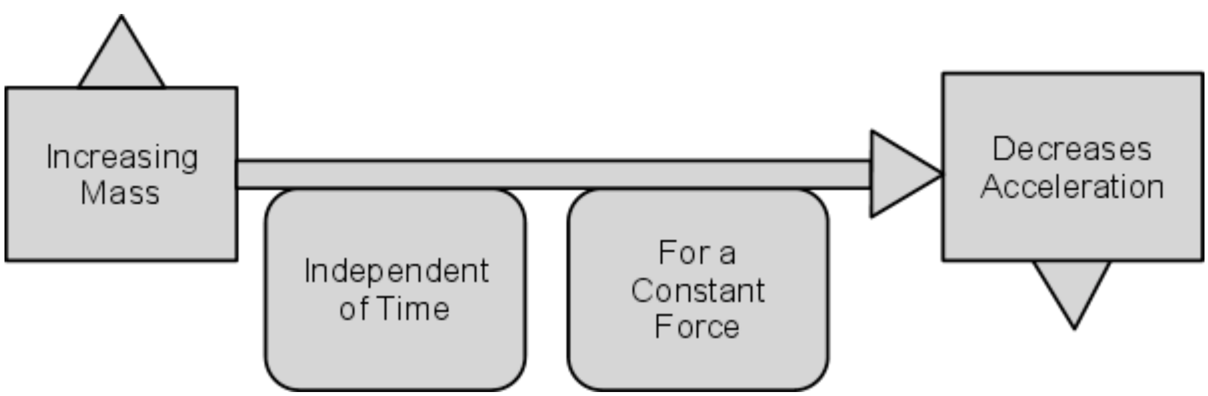

Figure 1. Iconic Explanation Creator provides students pull-down menus to select components of their explanations and displays the relationships in natural language and symbolically.

Players create explanations by clicking on boxes in the explanation which opens a set of pull down menus where the players choose the independent and dependent variables, modifiers for each, condition variables, and modifiers for each. Using this basic format, the game updates the player's explanation. If the player adds or deletes a condition, the game resizes the explanation appropriately. Available options in each pulldown menu would be increased from a small number of choices initially to larger numbers of choices as the game progressed. Examples of modifiers and explanations are included below.

- Modifiers for independent variables
  - increasing
  - decreasing
  - Doubling
  - Halving

- Modifiers for dependent variables
  - increases
  - decreases
  - doesn't affect
  - Doubles
  - Halves

- Modifiers for Qualifiers
  - for a constant....
  - independent of ...
  - if "Variable" is greater than, less than, between...

- Example Explanations
  - Increasing Time increases Velocity if Acceleration is greater than 0
  - Increasing Velocity increases Distance independent of Mass
  - Increasing Time doesn't affect Mass
  - Increasing Mass decreases Acceleration for a constant Force if Time is greater than 0

Players would use the iconic explanation creator to create explanations for various phenomena or situations in the game posed by an NPC. For example, between levels in *Cup Racer*, a friend of the gecko might show a short segment of play and ask why something happened the way it did (e.g, "Does the mass of the people you pick up in your cup affect your velocity?"). The player might then create an explanation in answer that the game might assess with the friend of the gecko responding (e.g., The friend might respond in the next frame by saying "I tried it myself and that works, thanks for explaining!" or "I tried using that explanation, but it doesn't seem to help me get the strawberry... Do you have any other ideas?").

The game could assess players' explanations using a causal map of the variables potentially involved in a scenario (which would be a matrix but which is displayed here visually for clarity). The links would specify the relationship between the variables. The figure below displays such a map that would address the relationship between all possible independent and dependent variables that the player might choose to include a complex projectile motion scenario late in the game (the player only chooses one independent and one dependent variable for an explanation, but the matrix needs to be able to account for all possible pairs). For simpler scenarios, a simpler matrix of pairs and relationships would suffice. In the map below, any dependent variable that is not "downstream" of the independent variable in the figure would be considered as "doesn't affect" from the modifier list (Figure 2). Conversely, any dependent variable that is downstream is affected although potentially only with qualifiers (e.g., increasing horizontal acceleration time increases horizontal velocity only if horizontal launch acceleration is greater than 0). The color codings in the map suggest possible relationships to consider as valuable to have the player explore from the perspective of the physics content.

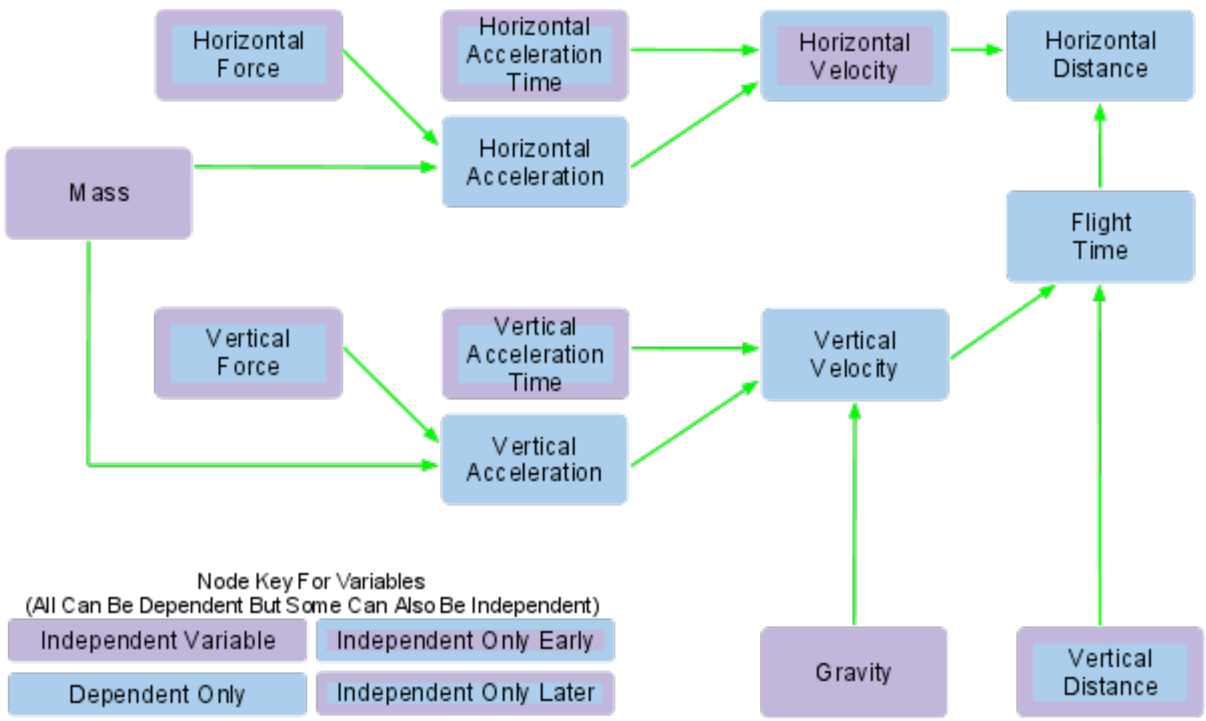

Figure 2. Flow chart showing logical relationships between variables for the Iconic Explanation Creator that would allow software to interpret both the accuracy and relevance of a student's explanation.

Evidence and Argumentation Components

The explanation system above could be woven into the story between play levels and players could earn additional points, unlock new levels, or gain other incentives, such as customization options for their appearance. A more elaborate, and potentially intrusive system, that would shift the player more into the player-as-scientist role, might engage the player in further argumentation around the explanation by incorporating evidence. The nature of conceptually-integrated game mechanics would actually allow the player to collect and identify evidence more fluidly and organically than is typical of argumentation-based games. Whereas evidence in most argumentation games tends to be predefined by the game authors, conceptually-integrated games might allow the player to identify and select evidence created through interaction with the game engine. In programming/prediction interface versions of *Cup Racer*, for example, the player experiments with different maneuvers or relationships in the game and then select sets of these trials as evidence for or against an explanation or parts of an explanation (Figure 3).

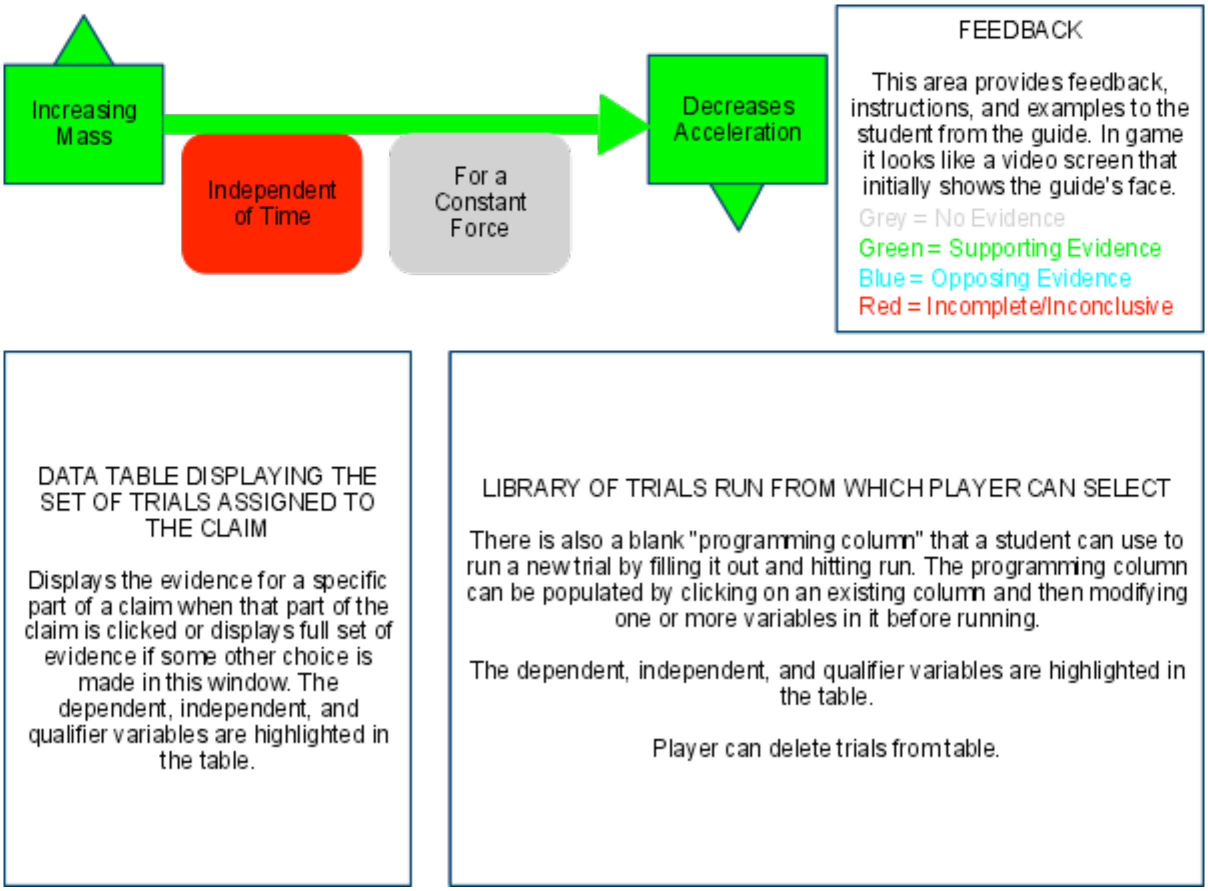

Figure 3. Integrating the Iconic Explanation Creator with data collection and selection to warrant or rebut explanations.

In the figure, parts of the explanation can be clicked on to highlight the attached evidence in the data table and the option to click on the trials to see them run. For cases where the players are given an explanation by an NPC to critique, they would present both supporting and opposing evidence. For explanations the players create, the focus likely will be on supporting evidence because they would modify the model to adjust aspects of the arguments that they found evidence against (or they would add qualifications). The core relationship of of the argument as well as the individual qualifiers change color as evidence is connected to support or refute. All components start grey until evidence is attached, become red until a set of evidence is selected that supports of refutes the relationship or qualifier, then turn green if the evidence effectively supports or blue if it contradicts.

Players experiment to find a combination of trials that support or refute specific claims. The data table stores their trials and they select sets of trials from the table. Players can delete trials if they wish and possibly annotate trials. Clicking on a trial can rerun it in the environment. At the most basic level, the player can select two trials as supporting the claim. The software can then determine if the trials support the claim, refute it, or are neutral/not connected to the claim and provide this feedback to the player. Essentially, the software can check the trials to determine if the independent variable was varied, if the dependent variable responded in the manner indicated, if other variables were controlled, and if other stated conditions of the qualifiers were met. Potentially more feedback could be provided.

More complex arguments could require two or more claims and trials to support the combined claims. At the easiest level, two trials could be selected for each sub claim. There might be more complex relationships that could be chosen. The software could, for example, incorporate simple logical operators (e.g., AND, OR, IF) to allow the player to make more complex claims composed of separate subordinate claims. Similarly, a 2x2 experimental design could be implemented. Thus this approach to argumentation and experimentation could allow the player to flexibly and organically create and identify evidence in support or opposition of explanations provided by NPCs or explanations that they themselves had created regarding mechanics within the game, thus incentivizing model-based thinking and scaffolding the explicit articulation of this thinking.

Generalizability of Approach and Final Thoughts

These ideas about prediction and explanation mechanics would seem better suited to some domains and game formats than others. Generally speaking, games with extended levels might be less amenable than games with shorter focused levels. Similarly, games that focus on reflex speed (or "twitch" speed) are less amenable than games that are more strategic or puzzle based. Essentially, the challenge needs to be in deciding on a set of choices to make rather than on the dexterity or speed with which the player can implement those choices. That said, however, even in "twitch" games, specific levels might be added to focus on core mechanics within the game.

Along these lines, the game mechanics need to be amenable programming, pre-planning, or segmenting play in some way to capitalize on the prediction qualities of the plan. The explanation components, however, are more open for implementation because they simply ask the player to explain relationships within gameplay. It is relatively easy to imagine, for example, a first person immersive game that involves ongoing play where the player is asked to explain why sometimes their movement is slower than at other times (e.g., perhaps they might create an explanation about the relationship of mass to acceleration). Integrating evidence and argumentation components to their explanations, however, would also require some way of programming, pre-planning, or segmenting play so that trials could be identified as evidence.

The easiest explanations to address in the proposed evidence/argumentation functionality would seem to be ones of direct and indirect proportionality in systems that reach a final state in the model or a steady state. It would seem that systems that involve a very dynamic equilibrium process (such as ecology models) or where the issues of interest occur and fluctuate during the motion of the model would be difficult to handle this way, but phenomena where the equilibrium is more smoothly reached and is more constant, such as many gas law relationships, would work well (i.e., even though properties of the gaseous system are emergent properties of the independent individual interactions of the particles, a steady state equilibrium condition is smoothly arrived at with the end result being the object of interest more than any fluctuations observed in achieving that equilibrium).

The challenge is in finding game mechanics that include these characteristics. *Supercharged* involves very amenable characteristics in the domain of electrostatics and *Cup Racer* would fit well in the domain of mechanics. These domains are not, however, the only such domains for conceptually-integrated learning games, we now need to think inventively. Not so long ago, the wild popularity of matching pitch or rhythm to a visual analog in the music games *Dance Dance Revolution*, *Frequency*, and *Rock Band* was far from obvious. We now need to locate and leverage these opportunities for learning. Prediction and explanation mechanics seem to provide excellent opportunities for incentivizing model-based thinking and scaffolding players in explicitly articulating the intuitive understandings they develop about the underlying relationships in these conceptually-integrated learning games. Then, if a game is more than a simulation, we need to also ensure that the game play itself, especially with these extra layers of participation, remains fun.

References

Anderson, J. (2009). *Real Conversations in Virtual Worlds: The impact of student conversations on understanding science knowledge in elementary classrooms*. Paper presented at the American Educational Research Association Annual Meeting. April 13-17, 2009. San Diego, California.

Annetta, L. A., Minogue, J., Holmes, S. Y., & Cheng, M.-T. (2009). Investigating the impact of video games on high school students' engagement and learning about genetics. *Computers and Education, 53*(1), 74-85.

Atkinson, R. K., Renkl, A., & Merrill, M. M. (2003). Transitioning from studying examples to solving problems: Effects of self-explaining prompts and fading worked-out example steps. Journal of Educational Psychology, 95, 774-783.

Baird, J.R., and Mitchell, I.J. (Eds) (1986) Improving the quality of teaching and learning: An Australian case study — the PEEL project. Melbourne: Monash University Printery.

Barab, S. A., Gresalfi, M. S., & Ingram-Goble, A. (in press). Transformational play: Using games to position person, content, and context. To appear in *Educational Researcher*.

Barab, S. A., Gresalfi, M. S., & Arici, A. (2009). Transformational play: Why educators should care about games. *Educational Leadership, 67*(1), 76–80.

Barab, S. A., Sadler, T., Heiselt, C., Hickey, D., & Zuiker, S. (2007). Relating narrative, inquiry, and inscriptions: A framework for socio-scientific inquiry. *Journal of Science Education and Technology*, *16*(1), 59–82.

Barab, S. A., Scott, B., Siyahhan, S., Goldstone, R., Ingram-Goble, A., Zuiker, S., & Warrant, S. (2009). Transformational play as a curricular scaffold: Using videogames to support science education. *Journal of Science Education and Technology 18*, 305-320.

Barab, S. A., Zuiker, S., Warren, S., Hickey, D., Ingram-Goble, A., Kwon, E-J., et al. (2007). Situationally embodied curriculum: Relating formalisms and contexts. *Science Education*, *91*(5), 750–782.

Bielaczyc, K., Pirolli, P., & Brown, A. L. (1995). Training in self-explanation and self-regulation strategies: Investigating the effects of knowledge acquisition activities on problem solving. *Cognition and Instruction, 13*(2), 221-252.

Biswas, G., Leelawong, K., Schwartz, D., & Vye, N. (2005). Learning by teaching: A new agent paradigm for educational software. *Applied Artificial Intelligence, 19*, 363-392.

Borges, A. T., Tecnico, C., & Gilbert, J. K. (1998). Models of magnetism. *International Journal of Science Education*, *20*(3), 361.
Champagne, A. B., Klopfer, L. E., & Anderson, J. H. (1980). Factors influencing the learning of classical mechanics. *American Journal of Physics*, *48*(12), 1074-1079.

Champagne, A. B., Gunstone, R. F., & Klopfer, L. E. (1985). Effecting changes in cognitive structures among physics students. In L. H. T. West & A. L. Pines, Eds., Cognitive Structure and Conceptual Change. Orlando: Academic Press.

Champagne, A. B., Klopfer, L. E., & Gunstone, R. F. (1982). Cognitive research and the design of science instruction. *Educational Psychologist*, *17*(1), 31.

Chang, Chiu, McElhaney, & Linn (in preparation). Can dynamic visualizations improve science learning: A synthesis study.

Chang, H.-Y. (2009). Use of critique to enhance learning with an interactive molecular visualization of thermal conductivity. Poster presented at the annual meeting of National Association for Research in Science Teaching (NARST) 2009, Garden Grove, CA .

Chang, H.-Y., & Linn, M. C. (in preparation). Learning from a molecular visualization: Observe, interact or critique?

Chang, H.-Y., & Tsai, K. C. (2010, June). Investigating the role of physical and virtual experiments in developing integrated understanding of thermal conductivity and equilibrium. Presented in the symposium "Using visualization to link abstract science and everyday experience", the International Conference for the Learning Sciences 2010.

Chang, H.-Y., Quintana, C. & Krajcik, J. (2010). The impact of designing and evaluating molecular animations on how well middle school students understand the particulate nature of matter. Science Education, 94(1), 73-94.

Chi, M. T. H. (2000). Self-explaining expository texts: The dual processes of generating and repairing mental models. In R. Glaser (Ed.), Advances in instructional psychology (pp. 161-238). Mahwah, NJ: Erlbaum.

Chi, M. T. H., & VanLehn, K. A. (in press). The content of physics self-explanations. Journal of the Learning Sciences.

Clark, D. B. (2000). *Scaffolding knowledge integration through curricular depth*. Unpublished doctoral dissertation. University of California at Berkeley.

Clark, D. B. (2006). Longitudinal conceptual change in students' understanding of thermal equilibrium: An examination of the process of conceptual restructuring. *Cognition and Instruction, 24*(4), 467–563.

Clark, D. B., & Linn, M. C. (2003). Scaffolding knowledge integration through curricular depth. *Journal of Learning Sciences, 12*(4), 451-494.

Clark, D. B., D'Angelo, C. & Schleigh S. (in press). Multinational comparison of students' knowledge structure coherence. *Journal of the Learning Sciences*.

Clark, D. B., Nelson, B., D'Angelo, C. M., & Menekse, M., (2009). *Integrating critique to support learning about physics in video games.* Poster presented as part of a structured session at the National Association of Research in Science Teaching (NARST) 2009 meeting. Garden Grove, CA.

Clark, D. B., Nelson, B., D'Angelo, C. M., Slack, K. & Martinez-Garza, M., (2010). *SURGE: Integrating Vygotsky's Spontaneous and Instructed Concepts in a Digital Game.*

Proceedings of the Ninth International Conference of the Learning Sciences, 384-385. Chicago, IL.

Clark, D. B., Nelson, B., D'Angelo, C. M., Slack, K. & Martinez-Garza, M., (submitted). SURGE: Exploration and inquiry-related learning about mechanics in a digital game. Submitted to the *Journal of Research and Practice in Technology Enhanced Learning*.

Clark, D. B., Nelson, B., D'Angelo, C. M., Slack, K., Martinez-Garza, M., & Menekse, M. (2010). *SURGE: Assessing Students' Intuitive and Formalized Understandings About Kinematics and Newtonian Mechanics Through Immersive Game Play.* Paper presented as part of a structured poster session at the American Educational Research Association (AERA) 2010 meeting. Denver, CO.

Clark, D. B., Nelson, B., Sengupta, P., D'Angelo, C. M. (2009). Rethinking Science Learning Through Digital Games and Simulations: Genres, Examples, and Evidence. Invited Topic Paper in the Proceedings of The National Academies Board on Science Education Workshop on Learning Science: Computer Games, Simulations, and Education. Washington, D.C.

Clarke, J., & Dede, C. (2005). *Making learning meaningful: An exploratory study of using multi-user environments (MUVEs) in middle school science.* Paper presented at the American Educational Research Association Conference, Montreal, Canada.

Cosgrove, M. and Osborne, R. (1985) Lesson Frameworks for Changing Children's Ideas. In: Learning in Science: The implications of children's science, Osborne R. and Freyberg P. Heinemann

D'Angelo, C. M., & Clark, D. B. (in preparation). Scaffolding vector representations for student learning inside a physics game.

D'Angelo, C. M., Clark, D. B., Nelson, B. C., Slack, K., & Menekse, M. (2009). *The effect of vector representations on students' understanding of motion.* Poster presented at the Physics Education Research Conference (PERC)/American Association of Physics Teachers (AAPT) 2009 meeting. Ann Arbor, Michigan.

D'Angelo, C.M. (2010). Scaffolding vector representations for student learning inside a physics game. Unpublished doctoral dissertation. Arizona State University.

Dede, C., & Ketelhut, D. J. (2003). *Designing for motivation and usability in a museum-based multi-user virtual environment.* Paper presented at the American Educational Research Association Conference, Chicago, IL.

diSessa, A. A. (1983). Phenomenology and the evolution of intuition. In D. Gentner and A. Stevens (Eds.), *Mental Models* (pp. 15-33). Hillsdale, NJ: Lawrence Erlbaum Associates.

diSessa, A. A. (1988). Knowledge in pieces. In G. Forman & P. B. Pufall (Eds.), *Constructivism in the computer age* (pp. 49–70). Hillsdale, NJ: Lawrence Erlbaum Associates.

diSessa, A. A. (1993). Toward an epistemology of physics. *Cognition and Instruction, 10*(2 & 3), 105-225.

diSessa, A. A. (1996). What do "just plain folk" know about physics? In D. R. Olson and N. Torrance (Eds.), *The Handbook of Education and Human Development: New Models of Learning, Teaching, and Schooling*. Oxford, UK: Blackwell Publishers, Ltd., 709-730.

diSessa, A. A., Gillespie, N., & Esterly, J. (2004). Coherence versus fragmentation in the development of the concept of force. *Cognitive Science*, 28, 843-900.

Dufresne, R., Mestre, J., Thaden-Koch, T., Gerace, W., & Leonard, W. (2005). Knowledge representation and coordination in the transfer process. In J. Mestre (ed.), *Transfer of learning from a modern multi-disciplinary perspective* (pp. 155-215). Greenwich, CT: Information Age Publishing.

Galas, C. (2006). Why Whyville? *Learning and Leading with Technology, 34*(6), 30-33.

Gee, J. P. (2003/2007). What video games have to teach us about learning and literacy. New York: Palgrave Macmillan.

Grant, P., Johnson, L. and Sanders, Y. (1990).*Better links: Teaching Strategies in the Science Classroom*. STAV Publication, Australia.

Hammer, D., Elby, A., Scherr, R. E., & Redish, E. F. (2005). Resources, framing, and transfer. In J. P. Mestre (Ed.), *Transfer of learning from a multidisciplinary perspective* (pp. 89-119). Greenwich, Connecticut: Information Age Publishing.

Harrison, A. G., Grayson, D. J., & Treagust, D. F. (1999). Investigating a grade 11 student's evolving conceptions of heat and temperature. *Journal of Research in Science Teaching*, 36(1), 55-87.

Hausmann, R. G. M., & Chi, M. T. H. (2002). Can a computer interface support self- explaining? International Journal of Cognitive Technology, 7, 4-14.

Hines, P. J., Jasny, B. R., & Merris, J. (2009). Adding a T to the three R's. *Science, 323*, 53.

Holbert, N. R., & Wilensky, U. (2010). FormulaT Racing: Combining gaming culture and intuitive sense of mechanism for video game design. In Gomez, K., Lyons, L., & Radinsky, J. (Eds.) Learning in the Disciplines: Proceedings of the 9th International Conference of the Learning Sciences (ICLS 2010) - Volume 2, Short Papers, Symposia, and Selected Abstracts (pp. 268-269). Chicago, IL: International Society of the Learning Sciences.

Hunt, E., & Minstrell, J. (1994). A cognitive approach to the teaching of physics. In K. McGilly (Ed.), *Classroom lessons: Integrating cognitive theory and classroom practice* (pp. 51-74). Cambridge, MA: MIT Press.

Hunt, E., & Minstrell, J. (1994). A cognitive approach to the teaching of physics. In K. McGilly (Ed.), *Classroom lessons: Integrating cognitive theory and classroom practice* (pp. 51-74). Cambridge, MA: MIT Press.

Kearney, M. (2004). Classroom Use of Multimedia-Supported Predict–Observe–Explain Tasks in a Social Constructivist Learning Environment. *Research in Science Education*, *34*(4), 427-453.

Kearney, M., & Treagust, D. (2000). An investigation of the classroom use of prediction-observation-explanation computer tasks designed to elicit and promote discussion of students' conceptions of force and motion. Presented at the National Association for Research in Science Teaching, New Orleans, USA.

Kearney, M., Treagust, D. F., Yeo, S., & Zadnik, M. G. (2001). Student and Teacher Perceptions of the Use of Multimedia Supported Predict–Observe–Explain Tasks to Probe Understanding. *Research in Science Education*, *31*(4), 589-615.

Liew, C. W., & Treagust, D. F. (19 95). A Predict-Observe-Explain Teaching Sequence for Learning about Students' Understanding of Heat and Expansion Liquids. *Australian Science Teachers Journal*, *41*.

Liew, C., & Treagust, D. F. (1998). The Effectiveness of Predict-Observe-Explain Tasks in Diagnosing Students' Understanding of Science and in Identifying Their Levels of Achievement. Presented at the American Educational Research Association, San Diego, CA.

Lin, X.D., and Lehman, J. (1999). Supporting learning of variable control in a computer-based biology environment: Effects of prompting college students to re- flect on their own thinking. *Journal of Research in Science Teaching, 36*(7), 837- 858.

Linn, M. C. (2006). The knowledge integration perspective on learning and instruction. In K. Sawyer (ed.), *Cambridge handbook of the learning sciences* (pp. 243-264). Cambridge, UK: Cambridge University Press.

Linn, M. C., & Hsi, S. (2000). *Computers, teachers, peers: Science learning partners*. Mahwah, NJ:Lawrence Erlbaum Associates, Inc.

Linn, M. C., Eylon, B., & Davis, E. A. (2004). The Knowledge Integration Perspective on Learning. . In M. C. Linn, E. A. Davis & P. Bell (Eds.), *Internet Environments for Science Education*. Mahwah, NJ Lawrence Erlbaum Associates.

Masson, M. E. J., Bub, D. N., & Lalonde, C. E. (2010). Video-game training and naive reasoning about object motion. *Applied Cognitive Psychology*. Advance online publication. doi: 10.1002/acp.1658

Mayer, R. E., & Johnson, C. I. (2010). Adding instructional features that promote learning in a game-like environment. *Journal of Educational Computing Research, 42*(3), 241-265.

Mazur, E. (1996). *Peer Instruction: A User's Manual* (Pap/Dskt.). Benjamin Cummings.

McQuiggan, S., Rowe, J., & Lester, J. (2008). The Effects of Empathetic Virtual Characters on Presence in Narrative-Centered Learning Environments. In Proceedings of the 2008 SIGCHI Conference on Human Factors in Computing Systems, Florence, Italy, pp. 1511-1520.

Minstrell, J. (1982). Explaining the “at rest” condition of an object. *The Physics Teacher*, *20*, 10-14.

Minstrell, J. (1989). Teaching science for understanding. In L. Resnick, & L. Klopfer (Eds.), *Toward the thinking curriculum* (pp. 129-149). Alexandria, VA: Association for Supervision and Curriculum Development.

Minstrell, J., & Kraus, P. (2005). Guided Inquiry in the Science Classroom. In M. S. Donovan and J. D. Bransford (Eds.), *How Students Learn: History, Mathematics, and Science in the Classroom.* Washington DC: National Academies Press.

Moreno, R., & Valdez, A. (2005). Cognitive load and learning effects of having students organize pictures and words in multimedia environments: The role of student interactivity and feedback. *Educational Technology Research and Development, 53*(3), 35-45.

Neulight, N., Kafai, Y. B., Kao, L., Foley, B., and Galas, C. (2007). Children's participation in a virtual epidemic in the science classroom: Making connections to natural infectious diseases. *Journal of Science Education and Technology, 16*(1), 47-58.

Palmer, D. (1995). The POE in the primary school: An evaluation. *Research in Science Education*, *25*(3), 323-332.

Parnafes, O. (2007). What does "fast" mean? Understanding the physical world through computational representations. *Journal of the Learning Sciences, 16*(3) 415 -450.

Parnafes, O. & diSessa, A. A. (2004). Relations between types of reasoning and computational representations. *International Journal of Computers for Mathematical Learning, 9*, 251–280.

Piaget, J. (1964). Development and Learning. In R.E. Ripple & V. N. Rockcastle (Eds.), *Piaget Rediscovered* (pp. 7-20).

Ranney, M., & Schank, P. (1998). Toward an integration of the social and the scientific: Observing, modeling, and promoting the explanatory coherence of reasoning. In S. Read & L. Miller (Eds.), *Connectionist models of social reasoning and social behavior* (pp. 245–274). Mahwah, NJ: Lawrence Erlbaum Associates, Inc.

Rickey, D., & Stacy, A. M. (2000). The Role of Metacognition in Learning Chemistry. *Journal of Chemical Education*, *77*(7), 915.

Rosenberg, S., Hammer, D., & Phelan, J. (2006). Multiple epistemological coherences in an eighth-grade discussion of the rock cycle. *The Journal Of The Learning Sciences, 15(*2), 261–292.

Roy, M., & Chi, M. T. H. (2005). The self-explanation principle in multimedia learning. In R. E. Mayer (Ed.), The Cambridge handbook of multimedia learning (pp. 271-286). New York: Cambridge University Press.

Salen, K., & Zimmerman, E. (2003). Rules of Play: Game Design Fundamentals (illustrated edition.). The MIT Press.

Scott, P.H., Asoko, H.M., and Driver, R.H, (1991) Teaching for Conceptual Change: a Review of Strategies. In: Research in Physics Learning: Theoretical Issues and Empirical Studies. Proceedings of an International Workshop. R. Duit, F. Goldberg, H. Niederer (Editors) March 1991 IPN 131, ISBN 3-89088-062-2

Searle, P., & Gunstone, R. (1990). Conceptual Change and Physics Instruction: A Longitudinal Study. Presented at the American Educational Research Association, Boston, MA.

Shepardson, D. P., Moje, E. B., & Kennard-McClelland, A. M. (1994). The impact of a science demonstration on children's understandings of air pressure. *Journal of Research in Science Teaching*, *31*(3), 243-258.

Squire, K. (in press). *Video games and learning*. New York: Teachers College Press.

Squire, K. D. & Jan, M. (2007). Mad City Mystery: Developing scientific argumentation skills with a place-based augmented reality game on handheld computers. *Journal of Science Education and Technology, 16*(1) 5-29.

Squire, K., & Klopfer, E. (2007). Augmented reality simulations on handheld computers. Journal of the Learning Sciences, 16(3), 371 - 413.

Squire, K., Barnett, M., Grant, J. M., & Higginbotham, T. (2004). Electromagnetism supercharged!: learning physics with digital simulation games. In Y. B. Kafai, W. A. Sandoval, N. Enyedy, A. S. Nixon, & F. Herrera, (Eds.), Proceedings of the 6th International Conference on Learning Sciences (pp. 513–520). Los Angeles: UCLA Press.

Squire, K., Jenkins, H., Holland, W., Miller, H., O'Driscoll, A., Tan, K. P., & Todd, K. (2003). Design Principles of Next-Generation Digital Gaming for Education. Educational Technology, 43(5), 17-23.

Squire, K.D. (2005). Toward a theory of games literacy. *Telemedium 52*(1-2), 9-15.

Steinkuehler, C. (2007). Massively multiplayer online gaming as a constellation of literacy practices. *eLearning, 4*(3) 297-318.

Steinkuehler, C. & Duncan, S. (2009). Informal scientific reasoning in online virtual worlds. *Journal of Science Education & Technology*.

Tao, P., & Gunstone, R. F. (1999). The process of conceptual change in force and motion during computer-supported physics instruction. *Journal of Research in Science Teaching*, *36*(7), 859-882.

Thaden-Koch, T., Dufresne, R., & Mestre, J. (2006). Coordination of knowledge in judging animated motion. *Physics Education Research*, 2, 1-11.

Thagard, P. (1989). Explanatory coherence. *Behavioral and Brain Sciences, 12,* 435–466.

Thagard, P., & Verbeurgt, K. (1998). Coherence as constraint satisfaction. *Cognitive Science, 22,* 1–24.

Thomas, D. & Brown, J. S. (2009). Why virtual worlds can matter. *International Journal of Learning and Media, 1*(1), 37-49.

Turkle, S. (1997). Seeing Through Computers: Education in a Culture of Simulation. *The American Prospect, 31*(March-April), 76-82.

Wagner, J. F. (2006). Transfer in pieces. *Cognition and Instruction*, 24(1), 1-71.

White, B.C., and Frederiksen, J.R. (1998). Inquiry, modeling, and metacognition: Making science accessible to all students. *Cognition and Instruction. 16*(1), 3- 117.

White, B.C., and Frederiksen, J.R. (2000). Technological tools and instructional ap- proaches for making scientific inquiry accessible to all. In M.J. Jacobson and R.B. Kozma (Eds.), *Innovations in science and mathematics education* (pp. 321- 359). Mahwah, NJ: Lawrence Erlbaum Associates.

White, R. T. (1988). *Learning science*. Oxford: Basil Blackwell.

White, R. T., & Gunstone, R. F. (1992). *Probing understanding*. Routledge.

Wright, W. (2006). Dream machines. *Wired 14*(04). (http://www.wired.com/wired/archive/14.04/wright.html)

Zhou, G., Brouwer, W., Nocente, N., & Martin, B. (2005). Enhancing Conceptual Learning Through Computer-Based Applets: The Effectiveness and Implications. *Journal of Interactive Learning Research*, *16*(1), 31-49.