INTEGRATING DIGITAL GAMES AND MODELING IN K-12 SCIENCE CLASSROOMS

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To my beautiful children, Kaitlyn and Ethan, for providing me with laughter, hugs, joy and

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CHAPTER 1

INTRODUCTION

Traditional science instruction often characterizes science as a body of proven facts, theories and laws (Driver, Leach, Millar, & Scott, 1996; Duschl, Schweingruber, & Shouse, 2007). However, expertise in science not only involves the development of scientific concepts in a domain, but also entails participation in a set of disciplinary practices used to generate and refine scientific knowledge (Duschl et al., 2007; Lehrer & Schauble, 2006b; Pickering, 1995). In recent years, the field of science education has called for classroom instruction to adopt a more practice-based perspective and incorporate practices such as modeling into the science classroom (Schweingruber, Keller, & Quinn, 2012). This movement is evident in the development of the recent *Next Generation Science Standards* (NGSS Lead States, 2013) where scientific practices and content knowledge are integrated into grade-level expectations. For example, standards for middle school physical science recommend that students be able to "develop and use a model to describe waves," as well as "plan an investigation to determine the relationship between" various forms of energy. However, there is often little guidance or support for teachers on *how* they should design activities to support this type of integration of concepts and practices in their classroom.

In these three papers, I adopt the view that modeling is the key epistemic and representational practice in the development of scientific expertise (Duschl et al., 2007; Giere, 1999; Lehrer & Schauble, 2006b; Nersessian, 1999) and that science instruction should be organized around models and modeling (Harrison & Treagust, 2000; Hestenes, 1987, 1992;

Lehrer & Schauble, 2006b; Schwarz & White, 2005; Wells, Hestenes, & Swackhamer, 1995; Windschitl, Thompson, & Braaten, 2008a). Research in science education shows that students make significant advances in their understanding of science by generating and revising explanatory models (Gravemeijer, Cobb, Bowers, & Whitenack, 2000; Hall & Stevens, 1994). However, model-based instruction in the classroom is often hindered by teachers' limited understanding of modeling and challenges arising from their lack of experience with modeling and model-based reasoning (Justi & Gilbert, 2002; Van Driel & Verloop, 1999; Windschitl & Thompson, 2006). One of the central goals of this work is to investigate one possible way to address these challenges by using educational technologies, such as digital games for learning and computational programming platforms, in the classroom that encourage students to make meaningful representations of phenomena and that are designed to engage students and teachers in modeling practices.

Modeling as a Central Scientific Practice

The three papers in this work are grounded in the Science as Practice perspective and take the view that the act of modeling and the development of scientific concepts are deeply intertwined (Lehrer & Schauble, 2006; Duschl et al, 2007; Pickering, 1995). Modeling is widely regarded as the language of science and the core disciplinary practice in the development of scientific expertise (Duschl et al, 2007; Giere, 1999; Nersessian, 1999). A scientific model is a representation of some aspect of the natural world that generally simplifies a system in order to highlight salient features about the system. Most models are explanatory in nature (Lehrer & Schauble, 2002) and describe relationships within the system so that predictions and explanations about a phenomenon can be generated. The general purpose of scientific modeling

is to test these predictions and explanations generated by the model against real-world observations in order to assess how well the model fits the natural phenomenon being described (Harrison & Treagust, 2000). Based on these evaluations, revisions to the model are made in order to accommodate new empirical data or theories. Conversely, scientific ideas and theories may also change as a result of efforts to validate models.

Since a fundamental objective of science is to construct models of natural objects and processes, science educators are increasingly calling for instruction to be organized around models and modeling (Harrison & Treagust, 2000; Hestenes, 1987, 1992; Lehrer & Schauble, 2006b; Schwarz & White, 2005; Wells, Hestenes, & Swackhamer, 1995; Windschitl, Thompson, & Braaten, 2008). However, challenges arise because model-based reasoning is a form of reasoning that does not come naturally and is challenging for beginners to grasp (Lehrer & Schauble, 2010). It entails constructing and studying a simplified representation of a phenomenon instead of directly studying the phenomenon itself. It is crucial to involve students in the *construction* of models, rather than working with models already provided to them (Lehrer & Schauble, 2006a; Schwarz, 2009; Windschitl, Thompson, & Braaten, 2008b). However, when scientific modeling is done in classrooms, the process of constructing and evaluating models are the least typical modeling practices used (Schwarz, 2009).

One reason that instruction organized around modeling can be challenging is because teachers often have a limited understanding of model-based reasoning. Many teachers view models primarily as helpful visualizations that aid students in understanding unproblematic scientific ideas instead of as tools to make and test predictions about a phenomenon (Windschitl et al., 2008b). Engaging students in scientific modeling in the classroom places a high demand on teachers, and many in-service teachers do not possess the knowledge and skills necessary to

build models themselves and to support students in this endeavor (Justi & Gilbert, 2002; Van Driel & Verloop, 1999, 2002). Direct instruction to pre-service teachers on doing model-based inquiry activities have met with limited success (Crawford & Cullin, 2004; Windschitl & Thompson, 2006). Only after experiencing a highly-scaffolded learning environment do pre-service teachers show a more expert-like understanding of models (Windschitl et al, 2008a). But even with extensive scaffolding, teachers find it challenging to generate their own theoretical models to ground their empirical investigations or demonstrate use of model-based reasoning to interpret their results. This is due, in part, to their own prior experiences with school-based science which often inadvertently create a simplistic view of the "scientific method" with an emphasis on confirmatory lab exercises (Windschitl et al., 2008b). When teachers do model-based inquiries in their classrooms, they often reduce the activity down to a variation of the scientific method, since they often do not see any real distinction between this classic method and modeling. For these reasons, it is challenging to implement model-based inquiries into the science classroom, and many science teachers need support in order to effectively engage their students in these practices.

Using non-traditional representations of natural phenomena in physics as tools for modeling may be a productive way to integrate modeling practices into the science classroom, and this is a hypothesis I examine in Chapter 2. I take traditional representations in a domain to be representational forms that tend to universally recognized and understood by experts in that domain. In the domain of physics, these representations can include such things as force diagrams, dot traces, motion graphs, and mathematical equations. They can be referred to as canonical representations and are usually common in physics textbooks. Non-traditional representations, therefore, could include non-canonical representations of physics such as a video

of a physical event in a non-representational space (i.e. without common inscriptions or representational systems visible in the video). These representations of a real-world event could then be used by teachers in a variety of ways to teach and model numerous physics concepts. Non-traditional representations could also include representations that use aspects of canonical representations but in an informal environment. For example, a video game whose design incorporates physics principles into core game mechanics could also have aspects of canonical physics representations integrated into game play, such as vector diagrams and dot traces, but in a less formal environment than is typically found in traditional science classrooms. I examine the relationship between teachers' canonical physics knowledge and their explanations of pedagogical use of such non-traditional representations in Chapter 2.

Digital Games as a Productive Medium for Scientific Modeling

Digital games, when designed to support science learning, can be a productive medium to develop a deeper conceptual understanding of scientific phenomena while also supporting the use of scientific practices, such as modeling. Digital games have the potential to increase student motivation, support conceptual change, and foster the practices of argumentation and discourse (Clark, Nelson, Sengupta, & D'Angelo, 2009; Hilton & Honey, 2011). The game environment enables players to see and manipulate representations of the phenomenon being investigated, and students can investigate aspects of the phenomenon that are typically unobservable in the course of their everyday lives. These game-play experiences and interactions with representations can serve as a bridge between students' naive understandings and more formal, expert-like understandings of concepts and representations (Clark et al., 2009; Gee, 2003).

A digital game can be thought of as a model where users make choices that alter the state of that model. When models and modeling are used as key interactive features within the game, students can build their own models by modifying or constructing central game elements to design game solutions. In this view, gameplay is an iterative process of model exploration and modeling, with users making predictions about their game play choices, observing the results and then revising their predictions based on continuing experimentation (Holland, Jenkins, & Squire, 2003). The practice of modeling can be further supported in game play through the use of increasingly complex, domain-appropriate, symbolic representations as core game elements. These disciplinarily-integrated games (Clark, Sengupta, Brady, Martinez-Garza, & Killingsworth, 2015) maintain a focus on conceptual relationships while creating opportunities for students to mathematize phenomena and symbolize salient aspects of motion and related concepts. This symbolization is integrated as an essential component of game play and offers a chance for students to supplement their intuitive understandings with more formal, domain-specific terminology and representations (Clark et al, 2015). Since digital games for learning have the potential to offer powerful pedagogical affordances for scientific modeling, a central focus of this work is integrating digital games for learning science into K-12 curricula.

Overview of this work

In these three papers, I investigate the use of non-traditional representations, such as digital games and real-world videos, to promote the development of the epistemic and representational practice of modeling in middle and high school physics curricula.

Chapter 2. A key characteristic of games is that they make learning "fun," and games for learning often involve interesting and engaging activities that utilize non-canonical

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representations of phenomenon that are not necessarily found in classroom textbooks. Since games are increasingly being incorporated into K-12 curricula, it is important to understand how teachers make sense of and use non-canonical representations in their curriculum and if they are able to use these types of representations for scientific practices such as modeling. The first paper in this work addresses this issue by exploring how high-school physics teachers reason about non-canonical representations of physics phenomena through videos of ill-defined, real-world events and how teachers may use these representations in their classroom instruction for modeling purposes.

This study examined the nature of expertise in high school physics teachers when they were presented with both canonical and non-canonical representations of physics problems in the domain of Newtonian mechanics. In the study design, physics teachers watched two videos that were situated in a non-representational space, meaning they were not obviously identified as "physics videos" through use of canonical representational systems (i.e. vector diagrams, dot traces, motion graphs, mathematical equations) or other inscriptions embedded in the video. Thus, these representations were considered to be non-canonical representations of physical phenomena. This study focused on the nature of the teachers' explanations of the underlying canonical physics ideas, as well as their explanations of how they would use non-canonical representations of physics problems in their classrooms. We found that teachers who view non-canonical representations of physical phenomena as either models or contexts for modeling were more likely to adapt these representations in their classroom instruction in a manner that supports the development of authentic scientific practices in students such as modeling. We identified two facets of such model-based reasoning demonstrated by the teachers. Our analysis also suggested

incongruence between assessments of canonical physics knowledge (e.g., Chi et al., 1981) and teachers' model-based reasoning in physics.

Chapter 3. Although learning involves both conceptual change and the development of epistemic practices, research on games for learning has generally focused on investigating the overall effectiveness of games rather than analyzing the specific processes of conceptual change through which students learn (Clark, Tanner-Smith, & Killingsworth, 2015). There is little to no research on how conceptual change occurs in physics during game play. The second paper investigates the process of conceptual change in students while playing a digital game for learning physics and how representational systems within the game can support conceptual development in students.

In this work, we showed how conceptually-integrated games can be analyzed using a conceptual change framework and postulated how conceptual change happens in a conceptually-integrated game designed to support learning about Newtonian mechanics. This study used a Knowledge-in-Pieces perspective (diSessa, 1993) as a lens to investigate how students without any formal background in physics used their intuitive knowledge to develop a progressively-refined intuitive understanding of motion, specifically *deflections*, a phenomenon that has been previously identified as challenging to understand for novice physics learners (diSessa, 1993). We demonstrated how one student's developing understanding of deflections involved iterative refinement of conceptual understanding through a process known as distributed encoding (diSessa, 1993) and examined how students learned to reason about deflection by modeling trajectories in a game. Additionally, we found that the design and sequencing of levels in the game played a key role in the conceptual change process. Game levels were designed to highlight the contextual boundaries within which their naïve conceptual resources were

productive and unproductive, and they were also sequenced in such a way that solving them successfully increased the cueing priority of the relevant resources.

Chapter 4. Since modeling is a core disciplinary practice in science, games for learning can be enhanced by integrating this practice into game play. Additionally, designing multiple modeling experiences for the same phenomenon can provide opportunities for the learners to engage in model evaluation through comparison of competing models (Lehrer & Schauble, 2010; Lesh & Doerr, 2003). In the final paper, we examine how the integration of disciplinarily-integrated games (Clark, Sengupta, et al., 2015) with complementary modeling activities can support the development of scientific modeling in K-12 classrooms. We also investigate some of the challenges associated with this pedagogical approach and identify ways in which these types of modeling activities can enrich students' conceptual development.

The third paper builds from the work in the second paper and leverages disciplinarily-integrated games that engage students in modeling through interpretation and translation across multiple representations of phenomena in the game environment to progressively deepen their conceptual understanding (Clark, Sengupta, et al., 2015; Sengupta & Clark, (in press)). In this study, we investigated two pedagogical approaches where students created models for phenomena outside of the game environment in order to reason about similar phenomena within the game. These model-based inquiries involved a material integration of virtual game play through a physical modeling activity in the classroom, and use of a complementary inscriptional tool involving an agent-based computational programming platform. This study highlights the significance of designing multiple complementary representations of the same phenomenon as a core element of game play and related modeling activities.

As a set, this work contributes to the agenda of engaging and supporting students and teachers in the representational practice of scientific modeling though use of non-traditional representations such as digital games for learning and real-world videos. They explore how teachers make sense of and use such representations as tools to engage students in modeling through their instruction. They illustrate how conceptual change can occur during through an iterative process of model development, evaluation, and revision during game play and how representational design within the game environment can play a key role in the conceptual change process. Finally, they offer insights into the design of multiple complementary modeling activities, and their accompanying representational tools, that support productive student learning.

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CHAPTER II

RETHINKING EXPERTISE IN TEACHING PHYSICS[1]

Introduction

Several scholars have argued for the connection between scientists' everyday knowledge and the development of scientific theories. Studies of scientists by cognitive scientists, historians, philosophers of science and ethnographers have shown that core aspects of scientific expertise such as problem choice, generative analogies, and novel problem solutions stem from, or are interleaved with, mundane aspects of everyday experience. This is evident in Fox-Keller's (1983) analysis of Barbara McClintock's research in biology, John-Steiner's (1997) biographies of creative insight in the arts and sciences, and Kuhn's (1979) analysis of Einstein's "thought experiments". Science educators have also argued for a constructivist approach in science education, in which students' repertoire of everyday knowledge can serve as productive resources for the development of scientific expertise (diSessa, 1993; diSessa & Sherin, 1998; Gupta, Hammer, & Redish, 2010; Sengupta & Wilensky, 2009; Smith, diSessa, & Roschelle, 1993).

It is therefore not surprising that science educators have argued for integrating real-world phenomena that are connected to students' everyday experiences in K12 science classroom instruction in various forms (Duschl, Schweingruber, & Shouse, 2007; Fortus, Dershimer, Krajcik, Marx, & Mamlok-Naaman, 2004; Heller, Keith, & Anderson, 1992; Krajcik, Blumenfeld, Marx, Bass, & Fredricks, 1998; Linn, Clark, & Slotta, 2003; Reif & Heller, 1982;

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[1] This chapter is under review in *Science Education.* The citation can be found in the references (Krinks & Sengupta, submitted).

Reiser, Krajcik, Moje, & Marx, 2003). The experience of students in physics classrooms is mediated through symbolic representations, such as equations that express physical laws, and other forms of canonical representations, such as laboratory experiments, all of which decidedly are "models" that can explain our experiences in the real world (Hestenes, 1992). For example, in a high school physics lab, a commonly used experiment to investigate Newton's laws involving frictionless surfaces and motion detectors is also an example of real-world phenomena, because this setup uses several elements that are familiar. But the pre-determined choice of the instruments and the physical setup, as well as the prescribed nature of the laboratory activity, stand in sharp contrast to a teacher introducing a video of a snowboarder jumping and landing, and asking students to analyze the video and build a model of the underlying physics. It is the second form of representation – the video of an activity happening "in the wild" – that we would consider an authentic representation of a real-world phenomenon.

A key difference between these two forms of representations is that lab experiments are designed to make explicit (to the learner) only those aspects of the putative phenomenon that are relevant for conducting the inquiry, and typically, in high school labs, such activities are limited to the verification of a physical law. In contrast, the phenomenon depicted in the video might represent complex forms of motion, and analysis might require the application of multiple physical laws and/or concepts, as well as further editing, or even re-shooting the video. Furthermore, because these videos were not initially shot with the purpose of being used for scientific work (and/or or classroom teaching), they may not make explicit all the necessary information needed for problem solving. Thus, the key characteristic of this second type of representations is that they are *ill-defined.* Fortus, Dershimer, Krajcik, Marx, & Mamlok-Naaman (2004) characterized "ill-defined" representations in the form of word problems which

require more complex reasoning to understand (in terms of the relevant canonical physics concepts and relationships) than well-defined problems typically used in physics textbooks. In addition to greater conceptual complexity, we posit that that a key characteristic of ill-defined problems is that they involve more complex representational work (compared to well-defined textbook problems) in order to develop a deep conceptual understanding of the underlying physics. Modeling the motion of an object in such an ill-defined context is a much more complex endeavor compared to learning how to verify an equation of motion in a well-defined context because it involves more elements of modeling (e.g., model invention and revision, in addition to verification), whereas the latter typically focuses on model verification. This will become clear in our analysis.

For the purposes of this paper, we define *canonical representations* as physics problems that are typically found in physics textbooks, and *non-canonical representations* as representations of physical phenomena that are not commonly used in physics textbooks or in traditional lab activities. Examples of non-canonical representations that we use in this paper are videos of everyday physical activity such as tire swings or snowboarding. Our goal is to investigate and understand the nature of thinking and reasoning that can be helpful for high school physics teachers in order to integrate non-canonical representations of physical phenomena in their classroom instruction in a manner that supports the development of students' authentic scientific inquiry practices.

Research Question

We ask the following research question: what is the nature of expertise in high school physics teachers when they are presented with both canonical and non-canonical representations

of physics problems in the domain of Newtonian mechanics (i.e., commonly used textbook problems in physics, and videos of real-world phenomena). More specifically, we investigate the nature of the teachers' explanations of the physics underlying canonical and non-canonical representations of physical phenomena, as well as their explanations of how they would use the non-canonical representations in their classroom instruction.

Background

Scientific Inquiry as Modeling

For the purposes of this article, following Schwarz & White (2005), Rapp & Sengupta (2012) and Lehrer & Schauble (2006), we broadly define a scientific *model* as a set of representations, rules, and reasoning structures that can be used to generate predictions and explanations of a target (or observed) phenomenon. Examples of models, as Schwarz & White (2005) have pointed out, may be as varied as scale models of the solar system, computer simulations, quantitative laws such as F = ma, or qualitative principles. Following Lehrer & Schauble (2000) and Duschl et al. (2007), we believe that the act of modeling and the development of concepts are deeply intertwined with one another. We therefore use the term *model-based reasoning* to indicate broadly the process of development of scientific models, as well as the use of models as scientific explanations.

Scientific inquiry can take many forms, such as observational, comparative, or theoretical, and it can be conducted in many contexts, such as physics laboratories, astronomical observatories, or biological field stations. Regardless of this variability, there are particular practices that are integral to the core work of science, with this core being organized around the development of evidence-based explanations of the way the natural world works (Longino,

1990). This in turn involves the development of hypotheses from theories or models and testing these against evidence derived from observation and experiment (Darden, 1991; Duschl & Grandy, 2008; Giere, 1988; Longino, 1990; Nersessian, 2005; Windschitl, Thompson, & Braaten, 2008). Modeling (i.e., the collective action of developing, testing and refining models) has been described as the core epistemic and representational practice in the sciences (Duschl et al., 2007; Lehrer & Schauble, 2006; Nersessian, 1992, 2008). The general aim of modeling is to test an idea—which is represented as a system of related processes, events, or structures— against observations in the real world and to assess the adequacy of the representation (i.e., model) against standards of evidence (Hestenes, 1992; Lehrer & Schauble, 2006; Lesh, Hoover, Hole, Kelly, & Post, 2000; Metcalf, Krajcik, & Soloway, 2000; Schwarz & White, 2005; Stewart, Hafner, Johnson, & Finkel, 1992; Stewart, Passmore, Cartier, Rudolph, & Donovan, 2005).

Modeling can be understood to be the mode of inquiry that scientists undertake during a scientific investigation. Our argument here is also supported by Dewey's theoretical analysis of scientific inquiry and its relationship to everyday knowledge, as argued by Hall (1996). According to Dewey, much of our routine experience passes without the need for explicitly representing aspects of the situations in which we live. These situations are suitably structured and our experience of them is sufficiently unproblematic that we simply live through the experience without deliberate problem solving. This state of affairs breaks down when an experience is unsettled, disturbed, or indeterminate with respect to its outcome (Dewey, 1938). One can resolve an indeterminate situation through an active process of inquiry: "Inquiry is the controlled or directed transformation of an indeterminate situation into one that is so determinate in its constituent distinctions and relations as to convert the elements of the original situation into

a unified whole" (Dewey, 1938b, pp. 104-105). Inquiry proceeds by a reflective interplay between selecting conditions in a situation that frame a problem and conceiving of related activities that will bring about a solution. According to Dewey, these conditions and related activities must be represented if inquiry is to move forward. We posit that scientific modeling is the collective act of representing these conditions of inquiry - struggling with posing questions, arranging conditions for seeing, developing measures, structuring data, and understanding the entailments of data - which transform a phenomenon into a model. Ill-defined problems, such as the videos we used in this study, are examples of contexts that can provide opportunities for students to engage in these acts of inquiry. Therefore, it is important for us, as science educators, to investigate conditions in which such forms of inquiry can be supported by teachers. We see this paper as an important step in that direction.

Expertise in Physics

Most studies of expertise in physics have focused on how experts and novices reason about canonical problems commonly used in physics textbooks or classroom instruction (Chi et al., 1981; Larkin, 1983; Trowbridge & McDermott, 1981). These studies show that experts' reasoning about such problems is based on canonical physics principles and laws, while novices attend to surface features of the problems. In contrast, other scholars have argued that novice and expert reasoning share many commonalities (e.g., they can both be intuitive in nature) and their differences are more nuanced and context dependent (Clement, 1994; diSessa, 1993; diSessa, Gillespie, & Esterly, 2004; Smith et al., 1993). In this perspective, a criticism of Chi's study is that the problems experts were asked to solve were strictly canonical and very familiar to experts (diSessa, Gillespie & Easterly, 2004). For example, a college physics professor can be expected

to solve such classic textbook physics problem in a predictable, formulaic manner, repeatedly, over many years. On the other hand, Clement (1994) showed that when an expert physicist (e.g., a noble prize winner in physics) is asked to solve an uncommon physics problem (e.g. a problem involving a complex and uncommon configuration of springs, *ibid* Clement 1994), then his reasoning looks similar to that of novices in terms of its intuitive nature and such reasoning is also less reliant on canonical domain principles as suggested by Chi et al (1981). Fortus (2009) further showed that graduate and postgraduate students in physics who have prior experience in solving real-world problems find it easier to solve non-canonical physics problems compared to experts who do not have such experience. Reasoning about informal or real-world physical phenomena, can therefore be regarded as different and more challenging than reasoning about canonical, textbook problems in physics.

Researchers also suggest that personal epistemological beliefs (i.e., beliefs about the nature of scientific knowledge) also affect how students and teachers reasoning about physical phenomena. For example, Lising & Elby (2005) showed that physics students (novices) sometimes demonstrate an epistemological "wall" between canonical reasoning and intuitive reasoning that can hinder their physics learning. Brickhouse (1994) showed that when teachers try to incorporate real-world phenomena into their classrooms, they often encounter "messy" situations that can reinforce an epistemological belief that formal classroom physics is incompatible with everyday physics outside of the classroom. However, the ability to reformulate a complex everyday situation in terms of disciplinary lenses, is indeed a significant characteristic of expertise in physics, and perhaps, of expertise in general (Goodwin, 1994).

Role of Everyday Knowledge in the Development of Theories in Physics

As mentioned earlier, the history of physics provides direct evidence of the connection between everyday knowledge and the development of scientific theories. James Clark Maxwell, who is largely credited with inventing modern electromagnetic theory, proposed mechanical models of electrodynamic behaviors (such as generation of induced currents) by modeling these behaviors in terms of simple, hypothetical mechanical models. For example, he modeled the electric field using a set of hypothetical, diagrammatic representations known as "field lines" (Maxwell, 1890). He further explained the mechanism underlying the actions and effects of these field lines in terms of aggregations of local actions of many hypothetical, but familiar concrete objects such as "idle wheels" and "ball bearings" (Maxwell, 1890; Nersessian, 2002). Similarly, as Smith, diSessa & Roschelle (1994) pointed out, the origins of Newton's particulate theories of light can be involved analogical reasoning about the motion of tennis balls.

In these examples, theory development required selecting appropriate pieces of everyday knowledge, i.e., a non-canonical representation, and its reformulation as scientific explanation, (i.e., a canonical representation). It is indeed true that reformulation and further development changed the systematic features of the initial concept by embedding it in a formal theory, but that still does not change the fact that the refined, canonical concept began as an everyday, non-canonical idea (Smith, diSessa & Rochelle, 1994).

Teacher Professional Knowledge & Model-based Reasoning

According to Shulman (1987), pedagogical content knowledge or PCK includes the "most useful forms of representation of these ideas, the most powerful analogies, illustrations, examples, explanations, and demonstrations-in a word, the ways of representing and formulating

the subject that make it comprehensible to others" (Shulman, 1987, p. 9). In this view, PCK includes "an understanding of how particular topics, problems, or issues are organized, presented, and adapted to the diverse interests and abilities of learners, and presented for instruction" (Shulman, 1987, p. 8). Furthermore, the key to distinguishing the knowledge base of teaching lies at the intersection of content and pedagogy and in the capacity of a teacher to transform the content knowledge he or she possesses into forms that are pedagogically powerful and yet adaptive to the variations in ability and background presented by the students (Shulman, 1987, p. 15).

In the domain of science education, PCK refers to teachers' interpretations and transformations of several different types of knowledge, including orientations toward science teaching, and their knowledge and beliefs about the following: the nature of science, instructional strategies, science curricula being used, and assessments in science (Lederman, Gess-Newsome, & Latz, 1994; Magnusson, Krajcik, & Borko, 1999; Wilson, Shulman, & Richert, 1987). Some researchers consider PCK to be an under-researched area in science education (van Driel, Verloop, & Vos, 1998). However, researchers have shown that PCK develops over time with extensive teaching experience and professional development (Lederman, et al., 1994; van Driel, et al., 1998), and early career teachers often use "recipe-like" classroom instruction, that focuses on teaching students algorithmic procedures for solving canonical textbook problems (Barnett & Hodson, 2001).

The relationship between teachers' model-based reasoning, modeling-based pedagogy and PCK has recently begun to receive attention in science (in particular, physics) education. Teacher educators have found that pre-service teachers find model-based reasoning, as well as a modeling-based pedagogy challenging to develop. Van Driel & Verloop (1999) and Crawford &

Cullin (2004) found that science teachers' preconceived ideas about the nature and function of scientific models are often "inaccurate" or "incomplete". An example of such an idea, found by Crawford & Cullin (2004), is that the primary functions of models are to serve as visual aids or as demonstrations of how things work. They may recognize the value of modeling activities and the benefits that students gain by doing those activities, but they tend not to use models in their own classes (Justi & Gilbert, 2002).

As Schwarz (2009) pointed out, most teachers have a limited experience and knowledge about scientific modeling or modeling-centered inquiry (Van Driel & Verloop, 1999, 2002; Windschitl & Thompson, 2006). Some researchers have found that teachers often view models as useful for teaching information about curricular scientific content, rather than as using viewing modeling an authentic scientific practice that can help learners understand the nature of science (Crawford & Cullin, 2004; Henze, van Driel, & Verloop, 2007; Justi & Gilbert, 2002) or as thinking tools that can advance students' model-based reasoning (Harrison & Treagust, 2000; Henze et al., 2007). Furthermore, when teachers do engage their own students in modeling, there is much variation of use (Harrison & Treagust, 2000) and limitations on the epistemological richness of the pedagogy (Justi & Gilbert, 2002) such as simplifying model-based inquiry to a variation of the "scientific method" (Windschitl & Thompson, 2006). Both Schwarz (2009) and Windschitl et al. (2008) show that through sustained engagement in pre-service teacher education courses that require teachers themselves to engage in learning science through modeling, pre-service teachers were able to improve their understanding of model-based reasoning, as well as were able to design inquiry-based science lessons that emphasized the development model-based reasoning in students.

Method

Participants

Ten high school physics teachers with varying levels of teaching experience and educational backgrounds participated in this study. All of the teachers taught physics at either a public or private school in a large mid-southern city in the United States. Participants were identified either through prior relationships with the first author or through email solicitation based on information gained from schools' public websites.

For the purposes of this study, six teachers were identified as *experienced* and four teachers were identified as *beginners* based on their teaching experience and background in physics (see Table 1). All of the experienced teachers had taught physics at the high school level for 5 years or more, had taken more than 5 college-level physics courses, and were certified to teach physics by the state in which they taught. In contrast, the four beginning teachers had taught physics for 3 years or less at the high school level. Three of them had taken only two undergraduate physics courses. Only two of these teachers held a state certification to teach physics.

Table 1. Teaching Experience and Physics Background of Participants

Participant	Years of Experience Teaching Physics	Number of Undergraduate Physics Courses	State Certification to Teach Physics
E1	5	6	Yes
E2	5	5	Yes
E3	15	6	Yes
E4	7	6	Yes
E5	6	7	Yes
E6	12	10	Yes
B1	1	2	Yes
B2	3	2	No
B3	3	2	No
B4	3	10	Yes

Procedure

We conducted semi-clinical, semi-structured interviews with each participating teacher after school hours in his or her respective classroom. Each interview lasted approximately one hour and consisted of three segments where the participants were asked to think aloud during each segment. During the first two segments, participants watched two video segments depicting physical phenomena in real-world contexts. In the third segment, in order to investigate the participants' reasoning and explanations about canonical problems, we adopted a task design similar to Chi, et al. (1981). We describe both of these types of tasks below.

Videos of Real-World Phenomena. The first video portrayed a man pushing a child on a tire swing (Figure 1), and the second one showed a slow-motion snowboard jump with aerial rotations (Figure 2). These videos were chosen as non-canonical representations of physical phenomena because a) they are minimally altered representations of real-world events that we experience outside school or classroom settings, and b) they are not typically used in text books as examples of physical laws. This stands in contrast to traditional textbook problems that are typically idealized, simplified formal representations of a more complex real-world event or phenomenon. However, we also considered that, for the purposes of our study, the non-canonical representations needed to represent phenomena that could be explained or analyzed from the perspective of canonical physics principles and theories that are taught at the high school level, such as projectile motion, rotational motion and energy conservation.

Two different video segments were chosen to represent varying degrees of complexity in terms of the physics involved. The tire swing video (Figure 1) depicted a pendulum-like, damped, simple harmonic motion. Primary physics principles that were illustrated in the video included simple harmonic motion (period, frequency, length of pendulum), as well as forces

involved in motion such as gravity, tension in the rope, the applied force of the father pushing

the tire swing, frictional force between the rope/tree, and air resistance on the swinging child/tire.

The video also depicted the classic canonical physics concept of energy conservation through

transformation of potential energy to kinetic energy and vice versa, with energy loss to the

surrounding environment creating a damped oscillation that is offset by regular pushes from the

adult in the video.

Figure 1. Screenshot of the Tire Swing Video

Figure 2. Screenshot of the Snowboarding Video

The snowboard video (Figure 2) was relatively more complex in that an analysis of the

events depicted in this video could involve a variety of physics topics such as projectile motion,

energy transformation, rotational motion and impulse (O'Shea, 2004). Projectile motion was an obvious physics topic that could easily be observed in the video through the snowboarder's initial velocity, distance traveled, and time elapsed. Also, we hypothesized that the snowboarder's landing may help our participants think about the ideas of impulse and change in momentum, as well as the effects of friction on the snowboard upon landing. Other relevant ideas included moment of inertia (i.e., loosely speaking, reasoning about rotational motion relative to the the center of mass of the snowboarder-snowboard system), and energy transformations (i.e., conversion of kinetic, potential and rotational energy into one another during the motion).

After showing each video, we asked each participant the following question: "As a physics teacher, what do you think when you see this video?" Follow-up questions attempted to further elicit the following: a) their conceptual understanding of the relevant canonical physical laws (e.g., Newton's laws) and concepts (e.g., momentum) they identified in the videos, and b) their explanations of pedagogical use of the videos in the classroom.

Problem-Sorting Task. This task was adapted from the problem-sorting task reported by Chi et al., (1981). Chi and her colleagues asked PhD students in physics to categorize 24 problems selected from Halliday and Resnick's (1974) Fundamentals of Physics, beginning with Chapter 5 (Particle Dynamics), and ending with Chapter 12 (Equilibrium of Bodies). Three problems were selected from each chapter, and they were individually typed on index cards. Chi and her colleagues instructed the participants to sort the 24 problems into groups based on similarities of solution; but the participants were not allowed to use pencil and paper and, thus, could not actually solve the problems in order to sort them.

Note that Halliday and Resnick (1974) was the most popular textbook for introductory physics at the time of the study conducted by Chi et al (1981). For our study, we selected some of the problems from problems from Halliday & Resnick (1974), as well as some from a well-known physics textbook that is currently used by major US universities for their freshman physics courses (Walker, 2002), and Advanced Placement tests on kinematics. We asked teachers to sort a total of 16 textbook physics problems in Newtonian mechanics. Our decision to reduce the number of problems was primarily based on time constraints for our study, given that none of our participants agreed to be interviewed for more than an hour.

We identified four major areas of Newtonian mechanics typically found in introductory college physics textbooks: Force, Energy, Momentum and Rotational Mechanics (Table 2). Each category had three or more problems. The force and energy categories each had four unique problems and two that could be solved with either force equations or energy methods and therefore could be classified in either of the two categories. It was important to ensure that selected problems represented a variety of surface features (i.e. pulleys, strings, inclined planes) so that we could differentiate between sorting tasks based on underlying physics principles and sorting tasks that relied on the surface features of the problem. It order to accomplish this diversity, additional problems were selected for the force and energy categories since these groups typically include a wider range of problems in textbooks than do the other two categories. We also posited that the order of presentation of the problems might itself act as a prompt for reasoning about the relevant physical laws for some teachers, especially for those who are more familiar with standard physics textbooks. For example, in most textbooks, chapters on speed and acceleration usually precede chapters concerning work and energy. To minimize chances of this

confound, the problem cards were thoroughly shuffled before each sorting task so that the problems appeared in random order.

Similar to Chi et al. (1981), we presented the problems in text-only format with no diagrams, and each problem was printed on a separate index card. Teachers were asked to sort the problems according to the similarities of their solutions and to think aloud during this process. There were not allowed to actually solve the problem. Where necessary, the interviewer asked further questions in order to clarify relevant aspects of their explanations. Upon completion of the sorting task, teachers were asked to identify the categories they created and explain why they put the problems into these groups.

Table 2. Categorization of Physics Problems used in Card-Sort Activity

Group Category	Problem #'s	Justification for similarity
Force/Newton's Laws	2*, 3, 5, 8, 10*, 11	All problems were solved using Newton's 2nd Law ($F_{net} = ma$)
Energy	1, 2*, 4, 10*, 14, 15	All problems were solved using conservation of mechanical energy (i.e. gravitational potential energy, elastic potential energy, kinetic energy and work done by nonconservative forces).
Momentum	6, 7, 16	Problems were solved using either conservation of linear momentum or change in momentum (impulse) equations
Rotational Mechanics	9, 12, 13	Problems involved use of rotational kinematics equations (torque, angular momentum, moment of inertia)

Some problems could be solved in multiple ways and appeared in more than one category.

Identifying and Coding Facets of Model-based Reasoning

We began our analysis by transcribing all of the interview videos. We then conducted thematic analysis (Braun & Clarke, 2006; Miles & Huberman, 1994) of the interview data. A theme captures aspects of the data that are important in relation to the research question, and

represents a patterned response (or meaning) within the data set (Braun & Clarke, 2004; Miles & Huberman, 1994). In our case, each theme represents a form of explanation, which we have termed a *facet* of model-based reasoning. Hunt & Minstrell (1994) defined a facet as "a convenient unit of thought, an understanding or reasoning, a piece of content knowledge or a strategy" (p 52) used by in making sense of a particular situation. Following Minstrell and his colleagues, our facet descriptions paraphrase the language used by the participating teachers in order to provide explanations or justifications. In our paper, a *facet* represents *a convenient unit of model-based reasoning*.

Note that in our discussion of the relationship between model-based reasoning and inquiry in science, we established that model-based reasoning includes both reasoning about the development of models, as well as the use of models in scientific explanations. However, given that we are investigating model-based reasoning in the domain of physics teaching, it is imperative that we also consider teachers' ideas and explanations about the *pedagogical* use of models and modeling in their instruction. The facets we have identified therefore demonstrate two types of understandings or explanations*:* a) an understanding of the video as a representation of a physical phenomenon, and b) explanations of how students would learn using the video through conducting modeling activities.

The two facets that we found in the teachers' explanations are explained below. For each facet, we first provide an operational definition, and then provide the different instantiations of the facet as evident in teachers' statements. The operational definition and the instantiations are hierarchical in nature (i.e., while the instantiations are direct, slightly paraphrased representations of teachers' utterances, the operational definition is comparatively more interpretive in nature).

Each operational definition can be understood as a statement of the intended meaning that is implied in the different instantiations of the same facet.

1. The "Video as a Representation" Facet Cluster:

    a. *Operational Definition:* The video is a representation of the phenomena and can only capture certain, but not all, aspects of a phenomenon.

    We found that this facet was instantiated by participants in the form of the following types of explanations:

        i. *Instantiation 1:* Video needs to be edited or changed in order to highlight particular aspects of the relevant physical processes.

        ii. *Instantiation 2:* Different viewing angles highlight different aspects of the relevant physical processes.

        iii. *Instantiation 3:* The video needs to be pared down significantly in order to reduce the complexity of the phenomenon captured.

2. The "Modeling with the Video" Facet Cluster:

    a. *Operational Definition:* The video can be used to design student activities that involve modeling, including data modeling.

    We found that this facet was instantiated by participants in the form of the following types of explanations:

        i. *Instantiation 1:* Students can conduct data modeling activities using the video.

ii. *Instantiation 2:* Students can themselves redesign (or re-shoot) the video so that it can be better used for data modeling.

In addition to thematic analysis of the interview data, we also coded the data for teachers' use of physics variables and analogical phenomena during the interviews. Each teacher's interview transcript was coded for any mention by the teacher of physics variables (i.e. velocity, momentum, acceleration, tension) and analogical phenomena (i.e. air resistance and free fall) when discussing the videos during the interview. These variables were listed by teacher and aggregated by experienced/beginner groups. For each variable mentioned, a note was also made as to whether the teacher's description of the physics principle was accurate.

Reliability

We used the double coding method (also known as the check coding method) described by Miles and Huberman (1994) to analyze the interview protocols in order to identify the facets. In this method, two or more researchers independently code data and then clarify their differences until consensus is reached. For this particular study, during the first three months after the completion of data collection, both the authors independently analyzed the videotaped interviews and transcripts and identified a list of salient themes. Over the next four months, the researchers then met periodically several times to compare and negotiate the themes each of them identified and iteratively refined the themes until consensus was reached. The emergent findings were then presented in front of a small audience of researchers in science education at Vanderbilt University, and feedback from this presentation led to further refinement of the codes. During this process of refinement, the authors conducted another round of analysis of the data, in which they independently used the refined codes to re-analyze the entire dataset. In the resultant

analysis, which we have presented in this paper, the authors agreed 96% of the times (Cohen's Kappa = 0.95).

Findings

Analysis of the Problem-Sorting Task

Table 3 shows the problem categorization for the six experienced teachers. The first column identifies the category labels created by the teachers, the second column shows how many teachers used a certain category label (N = 6 teachers), the third column reports the average number of problems represented by that category (N = 16 problems), and the fourth column relates the number of problems that were sorted into that category by all experienced teachers (N = 96 problems sorted in the study). The final column represents the total percentage of problems that were sorted into the category for each group of participants. We found that each of the experienced teachers used at least four major categories that were directly based on canonical physics principles, similar to Chi et al., (1981). These categories include conservation of energy, force/Newton's Laws, momentum and rotational mechanics. Together, these four categories represented 86% of the problems that were sorted and classified by the experienced teachers. The remaining 14% of problems were spread across more narrow categories, such as work and friction. In accordance with Chi et al. (1981), these six experienced teachers can be considered expert-like in their physics reasoning.

The contrast between beginning and experienced teachers is evident in the responses of the beginning teachers. Table 4 shows the category labels created by the beginning teachers. Out of the four categories that were used by all six of the experienced teachers, the beginning teachers used only three categories: conservation of energy, momentum and rotational motion. None of the four beginning teachers used the Newton's Law category; only one teacher used the

conservation of energy category, while two teachers mentioned the rotational mechanics

category and three used the momentum category. The two largest categories for experienced

teachers were Newton's Laws and Conservation of Energy – together they accounted for 51% of

the total problems classified. In contrast, these two categories accounted for only 3.1% of the

total number of problems classified by the beginning teachers.

Table 3. Problem Categorization by Experienced Teachers,
with the four major categories highlighted

Category Labels	# of people using category labels (N = 6)	Avg. size of category (N=16)	# of problems accounted for (N = 96)	% of problems accounted for
Conservation of Energy	6	4.2	25	26.0%
Force/Newton's Laws	6	4.0	24	25.0%
Momentum	6	3.0	18	18.8%
Rotational Mechanics	6	2.7	16	16.7%
Springs	2	2.0	4	4.2%
Work	1	3.0	3	3.1%
Force Vectors	1	2.0	2	2.1%
Angular Momentum	1	2.0	2	2.1%
Hooke's Law	1	1.0	1	1.0%
Friction	1	1.0	1	1.0%

Together, the four major canonical categories - conservation of energy, rotational

mechanics, Newton's second law, and conservation of momentum - accounted for only 18.8% of

the total number of problems that were sorted by all the beginning teachers. All four beginning

teachers grouped problems based on "surface features" (Chi et al., 1981) described in the

problems. That is, several of the categories mentioned by these teachers were based on either key

terms or phrases in the problem description (e.g., tension, speed), or physical objects that were

described in the problem (e.g., pulleys, springs). For instance, one participant (B2) formed 9

groups, based on rationales such as "these are both round things," "these two were pulley

problems," etc. We also found that one teacher included in the study did atypical problem

classifications. When given the instructions to sort the problems according to the similarity of

their solutions, B1 interpreted the task in such a way that he sorted the problems into the ease of

their solutions. He then created 3 categories: (1) easy, one-concept problems, (2) harder

problems involving multiple concepts and (3) difficult problems that contain only variables.

However, the absence of physics principles in his sorting logic may indicate a novice-like type of

physics reasoning.

Table 4. Problem Categorization by Beginning Teachers,
with four major categories highlighted

Category Labels	# of people using category labels (N = 4)	Avg. size of category (N=16)	# of problems accounted for (N = 64)	% of problems accounted for
Conservation of Energy	1	2.0	2	3.1%
Force/Newton's Laws	0	0	0	0
Momentum	3	2.0	6	9.4%
Rotational Mechanics	2	2.0	4	6.3%
Springs	3	3.0	9	14.1%
Pulleys/Mechanical Advantage	3	2.3	7	10.9%
Tension	2	1.5	3	4.7%
Speed	2	1.0	2	3.1%
Work	1	1.5	3	1.6%
Straightforward, single-concept problem	1	8.0	8	12.5%
Complex, multi-concept problem	1	5.0	5	7.8%
Forces and Impulses	1	5.0	5	7.8%
Friction	1	3.0	3	4.7%
Angular Speed	1	2.0	2	3.1%
Coefficient of friction on incline	1	2.0	2	3.1%
Variable-only problem, no numeric answer	1	2.0	2	3.1%
Kinematics	1	1.0	1	1.6%
Impact	1	1.0	1	1.6%
Answer is zero (obvious answer)	1	1.0	1	1.6%

Thus, based on the participants' responses, according to the classification scheme in Chi et al (1981), B1, B2, B3, and B4 can be considered physics novices while E1, E2, E3, E4, E5 and E6 can be considered comparatively more expert-like in terms of their understanding of the physical principles. We find these results to be consistent with Chi et al. (1981), as these results suggest that a longer experience in taking formal physics courses (as well as a longer experience in teaching physics, in the particular context of this study) is correlated with participants' ability to group physics problems based on the deep structure of the problems (i.e, the underlying canonical concepts, relationships between these concepts, and physical laws).

Analysis of the Video Tasks

Table 5 shows the facets of model-based reasoning demonstrated by each teacher. As mentioned earlier, each teacher's response for each video was coded separately, and each facet, if demonstrated, was only recorded once per response. That is, we did not count multiple instantiations of the same facet for a teacher's response to the tire swing video. Therefore, according to our coding rubric, each participant could demonstrate a maximum number of two facets per video, and a total of four facets for both of the videos.

Table 5. Facets of Model-Based Reasoning Demonstrated by Each Teacher

	"Video as a Representation" *Tire Swing Video*	"Modeling with Video" *Tire Swing Video*	"Video as a Representation" *Snowboard Video*	"Modeling with Video" *Snowboard Video*	Total # of Facets
E1	1	1	1	1	**4**
E2	1	0	0	0	**1**
E3	0	1	0	0	**1**
E4	0	1	1	1	**3**
E5	1	1	1	1	**4**
E6	0	0	1	0	**1**
B1	0	0	0	0	**0**
B2	0	0	0	0	**0**
B3	0	1	0	0	**1**
B4	0	0	0	0	**0**

Once each teacher's responses had been coded for the facets of model-based reasoning, we ranked those teachers in terms of the total number of facets demonstrated. This is shown in Table 6. We noticed a distinct separation among the six experienced teachers, with three of them demonstrating multiple facets of model-based reasoning and three of them demonstrating only one facet of model-based reasoning. To facilitate ease of discussion, we separated the experienced teachers into two groups based on this distinction: Group 1 (E1, E4, and E5) and Group 2 (E2, E3, and E6). This is based on our observation that, while all of the experienced teachers showed strong evidence of *canonical* expertise (as discussed in the previous section), there was variability in their responses pertaining to facets of model-based reasoning. For both the videos, we found that teachers in Group 1 (E1, E4 and E5) demonstrated both the "Video as a representation" and the "Modeling with the Video" facets in the context of reasoning. All three teachers in this group mentioned that they had observed that their students struggle to connect real-world phenomena to textbook-like physics, and their students saw a real disconnect between what they were taught in class and what they experienced in the real world. But rather than using the video to simply highlight the canonical equations, they all indicated that they would use the video, or a modified form of the video, to design learning activities that would engage students in experimentation, data collection and modeling, and measurement activities. Responses of the three "experienced" teachers in Group 2 were more variable. In contrast, responses of the beginning teachers were relatively more similar, both in terms of reasoning about the canonical physical laws and principles, as well as model-based reasoning. Therefore, we will discuss all of the beginning teachers together as one group (Group 3). The subsequent analysis is presented in terms of these three groupings, with responses from each group as supporting evidence.

Table 6. Total Facets Demonstrated by Individual Teachers

Group	Teacher ID	# of Facets per Teacher	Analysis
Group 1	E1	4	- Showed *canonical expertise* in sorting task
	E5	4	- Demonstrated multiple facets of model-based
	E4	3	reasoning
Group 2	E2	1	- Showed *canonical expertise* in sorting task
	E3	1	- Demonstrated very few facets of model-based
	E6	1	reasoning
Group 3	B3	1	- *NO canonical expertise* in sorting task
	B1	0	- Demonstrated few or no facets of model-based
	B2	0	reasoning
	B4	0	

Tire Swing Video Analysis

Illustrative Case for Group 1: E1. In Group 1, two of the teachers (E1 and E5)

demonstrated the "Video as a Representation" facet, and all of the teachers (E1, E4, and E5)

demonstrated the "Modeling with Video" facet. In this section, we will use E1 as a representative

example of Group 1 and will first consider the "Video as a Representation" facet. As discussed

previously, this facet became explicit in these teachers' explanations when they stated that the

videos were representations of real phenomena, and therefore, could only highlight and/or

capture certain types of information. Both these teachers also suggested modifications they,

along with their students in some cases, would like to make to the video in order to use the video

in class for teaching simple harmonic motion.

Excerpt 1

1	Interviewer:	As a physics teacher, what do you think when you see this video?
2	E1:	It's pretty obvious that it's a pendulum (laughing).
3	Interviewer:	Yes (laughing).
4	E1:	That's the first place I go. I start thinking should I time the interval
5		and the period. Clearly we're going to model this as a pendulum.
6	Interviewer:	um-hm
7	E1:	You're adding energy at every time so the period's not going to be

8		ideal. But if we just took one cycle, it could make a good
9		demonstration for my physics class. I could totally put that on my
10		projector and use that. I'd like that camera angle to be more of a
11		right-angle.
12	Interviewer:	Tell me a little bit more about how you would use that in your
13		classroom.
14	E1:	In the classroom, we have a problem with relevancy to students'
15		lives. They want to know what they need to know for the test. You
16		have to make it relevant. Let me pose a problem. I'm going to show
17		the video and you have to sprint across before the tire swing hits
18		you. You get to pick how long the rope is …[pauses for a few
19		seconds] You try to make it something that they can find mental
20		stimulation in. For you and me, I thought the kids were cute too.
21		So I think it's cool to watch little kids having fun. But the other
22		part of my brain sees a pendulum, but that's because I know it
23		already. I hang a coke bottle full of water from the big thing and
24		swing it around [gestures back to a large wooden structure in the
25		room used for various demonstrations]. The visual of me talking
26		about pendulums with an actual pendulum, they at least focus.
27		They pay attention to it and get a gestalt sense of "Oh wait, that did
28		make it shorter." A physical visual seems to help. And video is
29		cool for the things that you can't squeeze in your classroom, so I
30		would totally go with a video.

Upon seeing the tire swing video, as Excerpt 1 shows, E1 immediately stated that the

video reminded him of a pendulum, and began thinking of ways in which he would use the video

for teaching in class. The first part of this excerpt shows that E1 recognized the video as a non-

ideal representation of the physics of pendulum swings. In lines 4 - 5, he explicitly stateed that

he would measure the "interval and the period" (line 4), which in turn led him to state that he

would model the video as a pendulum ("Clearly we're going to model this as a pendulum", line

5). In line 7, he further recognizes that the father pushing the child on the tire swing adds energy

to the system at each cycle. This infusion of energy into the system makes it *non-ideal.* In other

words, from the perspective of canonical physics, a simple pendulum (also known as an *ideal*

pendulum) exhibiting simple harmonic motion does not lose or gain energy during its motion, when friction and air-resistance are ignored. Thus, this participant clearly identified the underlying cause of divergence of the tire-swing scenario represented in the video from the canonical representation of a simple pendulum. In order to deal with this imperfect situation, in lines 8 - 11, he also elaborated on how he would address this issue, by highlighting the representational nature of the video. This is evident in the two proposals that he put forward to make changes to the video. First, he proposed paring down the phenomena to "just one cycle" (Line 8). Although he did not elaborate more on this, it is likely this would involve shortening the length of video. He further explained that he would prefer a different viewing angle. In lines 10 and 11, he stated that he would prefer if the camera were positioned orthogonal to the path of the swing to facilitate comparatively more accurate measurements of time. Again, he did not elaborate on this, but it is important to note that by placing the camera at a right angle, the video would be shot from the same visual perspective that is typically used for drawing simple pendulums in physics textbooks. Given that both his proposals for editing or changing the video were intended to create a representation of the same phenomenon that could be better used to support pedagogical activities, we believe that his explanation provides evidence of the Video as a Representation facet.

As the interview progressed, upon the interviewer's prompting, E1 transitioned to explaining the pedagogical affordances of the video as a representation. In lines 14 – 30, he identified three such affordances: a) that the video was "cool" or engaging, because it showed a baby being pushed in the swing and students would find it "cute"; b) the video, when accompanied by a live demonstration (he referred to this as a "physical visual" in line 28) could enable learners to use their "gestalt" in noticing relevant aspects of pendulum motion; and c) the

video as a representation, enabled him to bring in "things that you can't fit into the classroom" (lines 28 and 29), such as the tire swing.

During this part of the interview, in lines 16 – 18, he also suggested an activity that the students would conduct using the video. He said: *"They want to know what they need to know for the test. You have to make it relevant. Let me pose a problem. I'm going to show the video and you have to sprint across before the tire swing hits you. You get to pick how long the rope is…"* (Lines 16 – 18, Excerpt 1). This quote made explicit that he would engage his students in a modeling activity where his students would have to figure out the time period of the tire swing shown in the video by selecting a rope of the required length. In doing so, students would engage in using the equation for calculating the time period of a simple harmonic oscillator where the time period is directly proportional to the square root of the length of the oscillator (in this case, the length of the rope). However, this task was design-based. Instead of rote memorization of physics formula, this activity involved students engaging in generating a phenomenon by enacting a scenario using their bodies as objects in motion, collecting data and conducting analysis based on the formal relationships between relevant physics variables. In this way, the activity involved both model development and deployment. Students would develop an understanding of the equation by designing a physical setup (e.g., a pendulum with a rope and a coke bottle) to satisfy real-world constraints (e.g., the time period of the tire swing from the video; time takes to sprint across the room). We consider this as evidence for a particular instantiation of the "Modeling with the Video" facet: *students can conduct modeling activities that involve designing measures and physical setups for experimentation using the video.* In lines 23 – 26, E1 further stated that he conducted a similar activity with his students by hanging a coke

bottle from the top of the ceiling of his class indicating a history of such activities as part of his usual pedagogy.

As the interview progressed, E1 proposed additional data modeling activities that he would conduct with his students using the video, and also identified potential modifications to the video that would support students' data modeling activities. Consider for example, the following excerpt (Excerpt 2):

Excerpt 2

1	Interviewer:	Would you do any energy analysis or force analysis?
2	E1:	I don't like showing long movies, but a 2 - 5 minute video clip, if
3		it's done right, can really be persuasive. Personally, if I were
4		making this video for my physics class, I would have meter sticks
5		taped to the rope, and maybe a giant clock hand with seconds so
6		we could actually pull some data literally from it and THEN it
7		would get to be really cool. Which you're making me think now
8		that I need to make one of these videos. You can freeze-frame and
9		catch things that you couldn't catch otherwise. So you've got
10		simple harmonic motion, conservation of energy, you have gravity
11		and its effect on the pendulum. At least 3 times in a year you
12		would want to use this to cross-connect things.

E1 began this excerpt by suggesting that if he were to prepare a video for this class, he would modify the video in certain ways. In lines 4 – 6 in Excerpt 2, he stated that he would likely use a set of tools in the video, such as "a meter stick" and "a giant clock hand with seconds," so that he and his students could "pull some data directly" from the video. That is, E1 wanted to create a revised version of this video that would include taping meter sticks to the rope and placing a clock within the field of view of the camera to support data modeling activities of the students. This quote provides additional evidence for the "Modeling with the Video" facet. Furthermore, in lines 8 – 9 (Excerpt 2), he identified an affordance of the video as a representation of the phenomenon – the ability to "freeze-frame" – which in turn could help

students notice aspects of the phenomenon that they might not otherwise notice. This excerpt provides evidence for another instantiation of the "Video as a Representation" facet: *The video only represents particular aspects of the physical phenomenon, and it needs to be modified in order to highlight particular aspects of the relevant physical processes.*

Illustrative Case for Group 2: E2. Only one of the experienced teachers in Group 2 (E2) demonstrated the "Video as a Representation" facet, although his expression of this facet was considerably more pessimistic than the experienced teachers in Group 1, as seen in Excerpt 3.

Excerpt 3

1	Interviewer:	What do you think this shows about a pendulum?
2	E2:	Well, it's not the greatest for because what you'd want to show
3		typically is that the time it takes for the tire to go back and forth
4		doesn't depend on the strength of the push or the displacement.
5		And also the tire could have been exceeding 15 degrees on either
6		side which would mean that it's no longer simple harmonic
7		motion.
8	Interviewer:	What would that mean?
9	E2:	That would mean that the restoring force was no longer
10		proportional to the displacement, which is what defines something
11		as simple harmonic motion. You can't use all the simplified
12		formulas that we teach people in physics to solve this problem.
…		
13	Interviewer:	Would you use something like this in your classroom?
14	E2:	I'd rather have [the video] somewhat 'artificialized', maybe
15		showing the father pushing the baby from the side to see the
16		arc…I'd like a different camera angle and a different kind of
17		scripting—not just a father having fun with his kids. It could be a
18		father having fun with his kids, but a physics lesson intended.

Similar to the teachers in Group 1, E2 also wanted to transform the video in a different manner. Lines 14 - 16 provide clear evidence of the "Video as Representation" facet: "I'd rather

have [the video] somewhat 'artificialized'…I'd like a different camera angle and a different kind

of scripting." This statement shows that E2 recognized that the video could be modified to

highlight different aspects of the phenomenon by changing the camera angle, or show a different

phenomenon by changing the scripting. For E2, the central learning objective of using the video

as a classroom activity was to show that "the time it takes for the tire to go back and forth does

not depend on the strength or push of the displacement" (Lines 3 – 4 in Excerpt 3). This

particular relationship is an instantiation of a more general phenomenon: in a pendulum

exhibiting simple harmonic motion, the time-period is independent of the amount of force

applied on the pendulum or the value of its periodic displacement, for small angles of swing.

This is known as the small-angle approximation. Mathematically, in the *small-angle*

approximation, the motion of a simple pendulum is approximated by simple harmonic motion.

The period (T) of a mass attached to a pendulum of length *L* with gravitational acceleration *g* can

be expressed as:

$$T = 2\pi \sqrt{\frac{L}{g}}$$

Note that this excerpt provides evidence of his awareness that a key axiomatic

assumption of the ideal pendulum model—that simple harmonic motion is only valid for small

angle displacements of approximately 15° or less—may be violated in the tire swing example.

He recognized that the real-world enactment introduced more complicated, "messy" ideas and

calculations into the problem. But E2 sought to modify the video in a reductive manner such that

the represented phenomenon closely represents the canonical representations of the ideal

pendulum model taught in class (i.e., he wished to create a canonical representation that would

obey the small angle approximation limit.) The "Video as a Representation" facet, as evident in

his explanation, can therefore be stated as: *the video needs to be pared down in order to represent relevant aspects of the phenomenon, but in a manner that closely corresponds to canonical representations of simple harmonic motion.*

Illustrative Case for Group 3: B1. None of the beginning teachers indicated the "Video as a Representation" facet in their responses to the tire swing video and only one demonstrated a "Modeling with the Video" facet. All four teachers explicitly identified that the video could serve as an example or a context in which students can talk or think about physics in everyday life, and they also stated that they would use it as an introductory demonstration. We will consider the illustrative case of B1, as shown in Excerpt 4:

Excerpt 4

1	Interviewer:	So you would primarily focus on forces and energy at the concepts
2		you would introduce in the classroom. What ways do you see
3		yourself using this in your classroom?
4	B1:	I would use it in 2 different ways: (1) an intro video in terms of
5		talking about how physics is in everyday life. It's a normal,
6		everyday event. There's so much you don't ever think about and it's
7		all physics. Talking about how there is energy and an intro to what
8		energy is and what forms of energy there is kinetic energy and
9		potential energy and using that as a springboard to reference back
10		to when we're actually having lecture. (2) Using it later in an
11		energy/mechanics unit and having it be a tool that students use to
12		express their knowledge of what they've already learned. I've
13		showed you the video, now I want you to explain in words all the
14		physics knowledge that you have so far in mechanics and energy
15		that's going on in that picture. Include free-body diagrams and
16		maybe just make it as open-ended as I wanted or as close-ended as
17		I want it--just tell me where the highest potential energy is and
18		where the highest kinetic energy is.
19	Interviewer:	So that would be a kind of assessment or just an activity?
20	B1:	It could be both. A good activity for them to do on their own and
21		see what other people got. Share with the class. And then add to
22		their own as we add things as a class. It will also give me a good
23		idea of what things they were able to come up with. And if they

24		didn't come up with friction on the tire, then maybe that's
25		something I need to go over again.
26	Interviewer:	Have you used anything like this in your classroom before? Real-
27		world examples?
28	B1:	I've used a few, but not a whole lot. I've used mostly those physics
29		demos on that website I mentioned earlier. And they have mostly
30		kind of visual representations of certain concepts rather than just
31		real-world kind of things and applying it to physics. No I don't do a
32		whole lot with them.

In lines 4 – 18 in Excerpt 4, B1 stated that he would use the video in two forms: a) in order to talk about energy (kinetic and potential energy) in a "normal everyday event"; and b) to use it as a prompt for articulation for students in order to "express their knowledge of what they've already learned." Specifically, B1 identified that the video would provide students a real-world context for thinking about potential and kinetic energy. As the first part of his explanation shows, B1 clearly understood that the video could be used to bridge canonical physics knowledge and everyday phenomena; however, it is important to note that both of these forms of use would occur in course of lectures.

In line 13, the interviewer asked B1 for further clarification of how he would use this activity (i.e., whether he would use this as an assessment or an activity). In response, B1 stated that he would use this as "both". In lines 19 – 20, he stated that students could engage in this activity by themselves by identifying the relevant physics variables on their own, and then share with the class. At this point, the interviewer was curious about what this activity might look like; but instead of asking this question directly, the interviewer asked B1 if he had done similar activities in the past with his class (lines 26 – 27). In response, B1 stated that he had only used such examples a few times before. However, he used mostly representations of certain concepts rather than "just real-world kind of things" (lines 28 – 32). Finally, he stated that he does not "do

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a whole lot" with such videos. Given his previous statements in this excerpt, this phrase most likely indicates that the use of these artifacts in his teaching had been limited to demonstrational and discussion purposes.

Overall, B1's explanation stands in sharp contrast with both E1 and E2's responses. First, it is clear that both E1 and E2 have prior instructional histories of using non-canonical representations in their classrooms. In contrast, B1 clearly stated that he never used "just real world kind of things" in the classroom, rather only demonstrations to accompany his lecture. Furthermore, the visual demonstrations he typically used were specially designed to instantiate particular physical concepts, in contrast to the tire swing video. Second, it is also evident that the learning activities that E1 would design with the videos necessitate their students to engage in modeling and measurement, with an emphasis the generation or design of measures. These points provide evidence for the claim that B1 did not show any evidence of "Modeling with the Video" facet. In contrast, B1 wanted to use the video a conversational prompt, and a lecture demonstrational aid. Finally, in contrast to B1, both E1 and E2 stated that they would like to edit the video so that the video can better highlight particular aspects of the relevant physics. This provides evidence for the claim that B1 did not show any evidence for "Video as a representation" facet.

Discussion of Canonical Physics During Response to Tire Swing Video

In addition to the differences in modeling facets, one of the major differences observed in the experienced and beginning teachers during their verbal response to the tire swing video was their identification and explanation of relevant physics concepts observed in the video. As mentioned earlier, the primary canonical physics concepts depicted in the tire swing video

include simple harmonic motion, energy transformations, and forces (including force diagrams). While all of the experienced teachers in both Groups 1 and 2 mentioned a variety of physics concepts when describing the tire swing video, they focused on two in particular. Each experienced teacher identified the concept of simple harmonic motion, as well as energy conservation, as two primary physics concepts that they saw in the video. Each teacher in both groups discussed at length how the video demonstrated principles of periodic motion by using terminology such as period, frequency and simple harmonic motion. They also focused extensively on the analysis of energy transformations within the dynamic system as energy was converted into different forms during the swing's motion. In addition to these two common concepts mentioned by all experienced teachers, other concepts mentioned by one or more of these teachers included forces, tension, friction, and rotational motion. All experienced teachers in Groups 1 and 2 were accurate in their descriptions of the physics phenomenon. When prompted by the interviewer to go into greater detail on a certain concept, all experienced teachers easily delved into deeper explanations, maintaining an accurate interpretation of the physical phenomena.

The four beginning teachers in Group 3, however, either omitted some of these key concepts or only mentioned them very briefly. For example, B1 did not mention simple harmonic motion, period or frequency at all in his response to the tire swing video—a topic discussed extensively among the experienced teachers. B2 and B4 mentioned simple harmonic motion briefly but did not elaborate in any way. B3 referenced simple harmonic motion in a vague sense, but, when prompted by the interviewer for details, admitted that she wasn't sure how to calculate the period of a pendulum. Other teachers from Group 3 had similar difficulties when prompted by the interviewer to elaborate on physics concepts they had mentioned. B1 stumbled to identify

all the forces acting on the pendulum during its motion and struggled to account for the energy that was dissipated in the system. B2 mentions tension as a concept that she sees in the video, but then admits that she doesn't know how to calculate the tension in the rope of a dynamic system. In general, the beginning teachers were somewhat accurate in their descriptions of physics concepts, and some struggled to provide deeper physics explanations when pressed by the interviewer.

To illustrate the difference in complexity of responses between experienced teachers and beginning teachers, each teacher's responses was analyzed for evidence of the teacher's mental model of simple harmonic motion (SHM). This concept was chosen as an illustrative example because it was mentioned by all of the experienced teachers and identified by these teachers as a primary physics concept demonstrated by the tire swing video. Additionally, three of the four beginning teachers also mentioned the principle of SHM. For each teacher, verbal statements related to SHM were analyzed, and a visual network map was created that showed concepts related to SHM and the relationships between these concepts. For instance, the network map listed variables that participants identified as relevant to the topic of SHM, as well as other relationships and limitations associated with SHM. The experienced teachers listed more relevant variables than beginning teachers did (Table 7), with the experienced teachers identifying between 3-6 variables relevant to SHM and the beginning teachers identifying 0 – 2 variables. Almost all experienced and beginning teachers who mentioned SHM as a physics concept depicted in the video identified period and frequency as two important variables related to SHM. However, the experienced teachers went on to discuss other variables such as length of the pendulum, mass and amplitude. The additional variables mentioned by the experienced teachers could reflect a more robust and complex mental model of the principle of simple harmonic

motion. While three of the beginning teachers also identified SHM as a relevant physics principle depicted in the tire swing video, the depth at which they discussed the concept is noticeably less than that of the experienced teachers, possibly reflecting a less-developed mental model than that of the experienced teacher. Also one teacher (B3) demonstrated confusion when discussing SHM. She identifies period and frequency as two relevant variables and then says, "Hmm, harmonic motion, what [else] do we need? Um, length of arm? I'm not sure!"

Table 7. Variables associated with Simple Harmonic Motion
identified by teachers during video response

	E1	E2	E3	E4	E5	E6	B1	B2	B3	B4
Frequency	✓	✓	✓	✓		✓		✓	✓	✓
Period	✓	✓	✓		✓	✓			✓	✓
Length	✓			✓	✓			✓		
Displacement		✓	✓							
Mass		✓		✓	✓	✓				
Amplitude		✓				✓				
Applied Force		✓	✓	✓						
# of Variables Mentioned	3	6	4	4	3	4	0	2	2	2
Limitations Mentioned	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No

Another interesting difference was a recognition of the limitations and non-ideal conditions that the tire swing video showed. Five of the six experienced teachers mentioned how the tire swing video did not depict ideal simple harmonic motion because the father continued to push the child with an applied force in every swing. The experienced teachers discussed things such as dampening motion and approximations that must be made. Two of the experienced teachers (E1 and E2) specifically mentioned how the equation governing the period of SHM was only valid for small angles (angles approximately less than 15 degrees) and would perhaps not be valid in the case of the tire swing. No beginning teachers mentioned any types of limitations or

approximations when discussing SHM. Also, no beginning teachers noted that the tire swing video depicted non-ideal SHM because of the father's applied force for each swing.

These discussion results support the findings in the card sort task. When comparing teachers' identification of relevant physics topics in the tire swing video, there is effectively no canonical difference between Group 1 (experienced teachers that demonstrated modeling facets) and Group 2 (experienced teachers who demonstrated few or no modeling facets). Both groups identified the same primary topics of SHM and conservation of energy in each video, and each teacher demonstrated an accurate and deep understanding of the identified principle. This stands in contrast to the teachers in Group 3 who did not identify these common principles and/or did not demonstrate a deep or accurate understanding of the identified principles. The fact that Group 1 and Group 2 showed no difference in their use of physics variables depicted in the tire swing video underscores the idea that correctly understanding physics principles does not necessarily mean that one will necessarily see the pedagogical usefulness in the real-world video.

Snowboarding Video Analysis

  Illustrative Case for Group 1: E1. All three teachers in the Group 1 (E1, E4, and E5) demonstrated both the "Video as Representation" facet in the snowboarding video and the "Modeling with the Video" facet. As before, we will again use E1's explanations as representative of this group. Our analysis shows that this video proved to be a more challenging task for most teachers (both experienced and beginning) to analyze, as expected, due to the increased complexity of the physics depicted in the video. In spite of this difficulty, E1 again demonstrated use of the "Video as Representation" facet in his response to the snowboarding video by commenting on the angle of the camera shot and indicating that he would like to alter

the video by changing the camera angle in order to see the trajectory of the snowboarder more clearly. Consider, for example, the following excerpt (Excerpt 5). This excerpt begins immediately after E1 completed watching the two snowboarding videos, but without any prompting from the interviewer. In this excerpt, E1 explains why he prefers one of the snowboarding videos over the other one.

Excerpt 5

1	E1:	[referring to 2nd snowboard video clip] I like this one better (than the 1st
2		one) and the reason is in the other one you don't see him coming down the
3		slope and you don't get the potential energy factor involved. There's a
4		problem with real-world camera work. There's a reason we use drawn
5		pictures a lot more than actual pictures because it's really difficult to stage
6		the perfect picture that shows all the details you want, because I've tried!

E1's explanation in Lines 1 – 3 shows that he identified being able to see the snowboarder coming down the slope as important in terms of making explicit connections with the underlying physics concepts and, in particular, potential energy. As the snowboarder moved downhill, his potential energy decreased and was transformed to other types of energy such as rotational and kinetic energy. In the first video (Figure 3), the camera angle was positioned in such a way that the majority of the video was focused on the snowboarder while he was in the air; in contrast, in the second video (Figure 4), the camera was focused on the snowboarder travelling down the slope. In lines 3 – 6, E1 highlighted the "problem of real-world camera work", and explained why drawn pictures are more often used in instruction. He stated that it was "really difficult to stage the perfect picture that shows all the details you want" (lines 5 and 6). This excerpt therefore revealed that E1 clearly understood that the videos were representations of physical phenomena, rather than being the phenomena themselves. Furthermore, E1 also understood that different representations of the same phenomenon lent

themselves to different kinds of analysis. In other words, E1 realized that the video is a limited

representation of the phenomenon because it can only highlight or make explicit certain aspects

of a phenomenon. We therefore believe that this excerpt provides evidence of the "Video as a

representation" facet.

As the interview progressed, E1 was asked to explain how he would use these videos in

his classroom instruction. E1's response is shown in Excerpt 6.

Excerpt 6

1	E1:	If we had a perfect camera angle, we could measure the velocity and
2		distance. We could do actual distance and look for differences between
3		theoretical and actual and why there's a difference and enter a
4		conversation about drag. The faster you move through the air, the more
5		drag you get. Here's the parabola we thought we had and here's what we
6		ended up with. Why is there a difference? I think that would be an
7		excellent conversation too. I do spend a lot of time talking about the ideal
8		world and the real world and how you're trapped between the two. The
9		real world is really hard and complicated to calculate sometimes but that's
10		the way it's really going to be so we'll settle for a model that gets us
11		close.

Figure 3. First snowboard video focusing on snowboarder in air

Figure 4. Second snowboarding video focusing on the snowboarder on the slope

E1 explained that he envisioned students engaging in data modeling and measurement activities with this video. His statement in line 5 ("Here's the parabola we thought we had …") indicates that he was envisioning framing this activity as a projectile motion scenario, as the trajectory of the snowboarder's jump would be similar to launching a projectile (i.e., both trajectories would follow a parabolic arc). E1 envisioned that students would conduct prediction and explanation activities in which they would have to predict the trajectory of the snowboarder using theoretical tools (i.e., equations of motion), then compare the expected trajectory with the actual trajectory as shown in the video, and explain the reason behind the divergence. This is evidenced in his statements in lines 2 – 4 when he stated that "we could do actual distances and look for differences between theoretical and actual and why there's a difference and enter a conversation about drag." E1 also identified that the difference between the theoretical and the actual trajectories would be due to the air-resistance (or "drag"). He characterized a proportional relationship between the velocity of the snowboarder in the air and the force of air-resistance (it is actually proportional to the square of the velocity). This is evidenced in lines 4 – 5 when he states that "the faster you move through the air, the more drag you get."

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In this excerpt, E1 also stated that students would not ignore the complexities that are introduced to the "real-world" (line 8) nature of the video in this activity; rather, he framed the divergence between the "theoretical and the actual" (line 3) as a productive opportunity for learning. In lines 7 - 11, E1 stated that he spent a lot of time in his instruction talking about the differences between ideal world (i.e., the world according to theoretical physics) and the real world (line 7 – 8). He recognized that models are imperfect representations of reality, and this was made explicit in lines 9 – 11, where he stated that there would always be a divergence between theory and real world, and that the purpose of a model was to "[get] us close" to the real world. This excerpt therefore provides evidence for "Modeling with the Video" facet, because students would engage in three forms of modeling activities: data modeling, prediction and explanation. Furthermore, E1 also identified the *purpose* of the modeling activity as not to ignore, but rather, to understand the differences between the theoretical and real world.

Illustrative Case for Group 2: E2. E2 demonstrated a deep grasp of many of the concepts depicted in the snowboard video. However, he did not exhibit either the Video as a representation or Modeling with the Video facet. He indicated that the real-world scenario depicted in the video was complicated, and he identified some of the inconsistencies compared to canonical projectile motion and energy conservation problems. As Excerpt 7 below makes explicit, he stated that this would prohibit him from using this video in class because the rotational motion depicted in the video would not be easy to analyze for his students.

Excerpt 7

1	Interviewer:	Do you see yourself using this in a classroom?
2	E2:	I don't use many videos, but I do pictures and demonstrations. So
3		we had [a stool]. And I put people on them with weights out and
4		then they pull them in and that would be conservation of
5		momentum. I don't do so much with shock absorbers, not

6		demonstrations directly. We do impulse and change in momentum,
7		things like that. We do the egg drop also.
8	Interviewer:	So do you see any value in having this in class.
9	E2:	It could be valuable. I personally wouldn't choose to use this video
10		because there's too many distractors to me.
11	Interviewer:	Like what?
12	E2:	It's just such a cool jump.
13	Interviewer:	If you were to show this, do you think your students would have
14		difficulty with it? What do you think they would do with it?
15	E2:	I think they would get involved in the event rather than in the
16		physics of the event. I would try to use something simpler first or
17		something that's relevant to their own life--driving in a car, a car
18		crash.

E2 stated that he used pictures and demonstrations as part of his classroom instruction. In lines 2 - 7, he mentioned some examples of demonstrations that he used in order to demonstrate impulses, and change and conservation of momentum. However, upon being asked whether he saw any value of using these videos in classroom instruction, he replied that while it could be valuable, he personally would not choose to use these videos due to distractions (lines 9 – 10). Upon being prompted to explain his response further, he stated that the jump itself was "cool" and therefore distracting (line 12: "it's just such a cool jump"). In line 15, he explained that students would "get involved in the event", rather than focusing on the underlying physics. Instead, in lines 16 – 18, he proposed that he would use a "simpler" video - such as driving a car or a car crash.

E2's responses stand in sharp contrast to E1's explanation in Excerpt 6. A central difference is that E2 does not engage in analyzing the representational properties of the video, such as the camera angle, in terms of the relevant elements of the underlying physics that is or can be highlighted. E1, on the other hand, spent a significant amount of time comparing the two videos in terms of such affordances, and also made explicit how he would prefer to alter the

videos. Another important difference is that E2 treated the jump as a potential distraction for his

students. E1, in contrast, explicitly emphasized the value of focusing students' attention to

inconsistencies of real-world situations and events with theoretical predictions. On the other

hand, E2's suggestion was to pare down these inconsistencies, and instead of using the

snowboarding video, he suggested using a simpler video such as driving a car.'

Illustrative Case for Group 3: B1. None of the beginning teachers indicated the "Video

as a representation" or "Modeling with the Video" facets in their responses to the snowboarding

video. As before, we will consider the illustrative case of B1, as shown in Excerpt 8:

Excerpt 8

1	Interviewer:	As a physics teacher, what do you think when you see this video?
2	B1:	I'm looking at projectile motion, impact and momentum, velocity
3		and acceleration. Air resistance and free fall. Usually when you
4		talk about free fall, they're not actually in motion like that [gestures
5		in a parabolic path]. They're kind of just falling. So I don't know if
6		I'd use that for those concepts.
7	Interviewer:	Can you pick one and start talking about it?
8	B1:	It may be difficult—I'm thinking about using it as a lab activity to
9		calculate different things in projectile motion. So like if I could
10		give them the angle that the ramp is and show them the video and
11		have them tell me his range. If he's going at this speed at this
12		angle. Then what is the distance that he can, regardless of air
13		resistance to try and make it less complicated, what would be the
14		farthest that he could reach and how much air time could he get. A
15		lot of kids like sports and so you could relate it to snowboarding
16		being an Olympic sport and give them information about Olympic
17		snowboarders. I don't know if they have a competition for just
18		aerial acrobatics or not. Olympic record for air time on a
19		snowboard is this long. And say what kind of angle or what kind of
20		speed do you need to make to get that amount of air time. You
21		could do a lot of different calculations with projectile motion just
22		using the snowboard.
23	Interviewer:	I hear you saying that you would use the real video to have them
24		do the calculations from that.
25	B1:	Using the video would help them in their engagement and interest

26		in it. Instead of me just giving them a problem on paper, you have
27		a snowboarder that jumps off a ramp at this angle. I would use the
28		video and give them more information about it to sort of make a
29		problem out of it.
30	Interviewer:	So you would show the video and then they would solve a problem
31		based on the video, so they're not actually sitting there with
32		stopwatches calculating it.
33	B1:	[expressing agreement by nodding his head] I wasn't actually
34		thinking about that…

In this excerpt, B1 clearly identified the relevant physics variables, and explained how he planned to integrate the video with his instruction in the form of a lab activity. In lines 9 – 14 in Excerpt 8, B1 proposed an activity in which students would be provided with the angle of the ramp in the video, and he would have students calculate the range of the jump (i.e., the distance travelled by the skateboarder at the end of the jump). He stated, "So like if I could ***give them the angle that the ramp is* and show them the video and have them *tell me his range*.. if he's going at this speed at this angle.** Then what is the distance that he can, regardless of air resistance to try and make it less complicated, what would be the farthest that he could reach and how much air time could he get?" (Lines 9 – 14, Excerpt 8, bold and italics added for emphasis).

This part of B1's explanation indicated that he did not want students to invent measures. Rather, he wanted to provide students with the values for the different variables, and students would then use known equations to calculate relevant outcomes. B1's explanations indicated that he placed an emphasis on calculations in his teaching: "You could do a lot of different calculations with projectile motion just using the snowboard" (lines 20 – 22). So even when students would engage with the real phenomena, their mode of engagement would be using physics equations to calculate "what kind of angle or what kind of speed do you need to make to get that amount of air time." He also identified that videos would capture student's interests.

Discussion of Canonical Physics During Response to Snowboarding Video

Overall, the participants found it comparatively harder to reason about rotational motion. Five of the six teachers in Groups 1 and 2 were able to identify concepts related to rotational motion (see Table 8). E2 identified conservation of angular momentum, moment of inertia, and angular speed; E3 identified torque and angular acceleration; E4 identified moment of inertia and torque; E5 identified moment of inertia; and E6 identified conservation of angular momentum as relevant concepts. In Group 3, two teachers (B2 and B4) briefly identified moment of inertia. One teacher was able to identify torque as a related concept, but was unable to explain in any detail how that concept was relevant to the video. For example, even though B3 mentioned torque, when pressed to explain further, she declined to elaborate and said that "Torque is not my strong point!"

Table 8. Variables associated with linear and rotational motion
identified by teachers during video response

		E1	E2	E3	E4	E5	E6	B1	B2	B3	B4
Variables related to linear motion	*Force*	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Energy		✓		✓	✓					
	Projectile Motion	✓	✓	✓	✓	✓	✓	✓		✓	✓
Variables related to rotational motion	*Angular Momentum*		✓				✓				
	Moment of Inertia		✓	✓	✓	✓			✓		✓
	Angular Speed		✓								
	Torque			✓	✓					✓	
	Angular Acceleration			✓							

We found that all teachers in groups 1, 2 and 3 saw the video as a case of projectile motion. We further noticed that when we prompted the teachers in Groups 1 and 2 for further elaboration, they were more articulate in their explanations of how they would use the canonical

concepts of forces and projectile motion in their classrooms. In contrast, the explanations of teachers in Group 3 were much less detailed. Of the four teachers, B1 went into the greatest detail, mentioning appropriately relevant variables such as velocity, angle and time, related to projectile motion. B4 also makes a passing mention of the ramp angle and initial velocity, and experienced difficulty while explaining the role of impulse. B2 and B3 only touched very briefly on projectile motion and made no mention of any specific way in which the video could be used to demonstrate this idea.

Discussion

Summary of Findings

At the broadest level, our study demonstrates that experienced physics teachers are likely to adopt non-canonical representations such as "real-world" videos in their classrooms when they view these videos as contexts for modeling canonical physics. Irrespective of their background in physics, teachers who simply viewed these videos as instantiations of physical laws rather than contexts for modeling, were on the other hand less likely to use them in their pedagogy in any meaningful manner beyond demonstrative purposes.

We believe that the findings from our study bear significance beyond the specific context of the videos. As results from the card-sorting task show, teachers' prior experiences in taking courses in physics directly correspond to their ability to identify canonical physics ideas, and this result is in direct agreement with Chi et al.'s (1981) study. In addition, all the teachers in our study, expressed the view that their students would find non-canonical representations such as real-world videos interesting, because they find the use of familiar, real-world situations in physics classroom instruction to be engaging. That is, all the participants believed that their

students would learn more effectively when they are interested in the curriculum, and can relate the canonical ideas of physics through non-canonical, familiar experiences. However, only some of the experienced teachers who were able to identify appropriate canonical physics ideas in the card sorting task, demonstrated evidence of model-based reasoning in the way they would use the videos in their classroom. That is, our study indicates the use of complex, ill-structured problems and teachers who view such problems and representations as both representations and opportunities for modeling would better support the use of such representations in the physics classroom.

Implications for Teacher Education in Physics: The Experience of "Knowing" Physics

We believe that our study demonstrates an underlying epistemological facet that might explain the difference between teachers who do engage their students in modeling in their classrooms, and teachers who do not. The three teachers in our study who belong to the first category clearly adopted a representational stance – that is, they viewed the videos as *representations* of physical phenomena, rather than viewing the videos as the phenomena themselves. On the contrary, the others viewed these videos as *demonstrations* or *examples* of the phenomena, or in some cases, the phenomena themselves. Here, we will discuss two related explanations of this difference, and their significance for physics education. The first explanation adopts a practice-based stance: expertise involves viewing the *object* of knowing – in this case, the video and associated canonical laws, concepts etc. – as deeply intertwined with the epistemic and representational actions through which the discipline (in this case, physics) generates knowledge. These epistemic and representations actions are collectively known as "modeling" (Duschl et al., 2007; Giere, 1988; Lehrer & Schauble, 2009). Therefore, to know any "thing" as

physics is therefore to experience that "thing" through the *practice* of modeling. A physical law, as Hestenes (1992) argued, is nothing but a model. That is, it is not reality, but a plausible and reduced representation of reality that also serves as an explanation, which in turn was developed through a series of complex epistemic and representational actions (i.e., the disciplinary practice of modeling). We therefore believe that the more provocative element of Hestenes' argument, similar to our point here, is that to a physicist, there is a certain degree of inseparability between a phenomenon and representation writ large: "Knowing" physics cannot be separated from "modeling" physics. Our study highlights the pedagogical significance of adopting such a practice-based, "representational stance". As evidenced by explanations of the Group 1 teachers, such an epistemological approach may make it possible for teachers to design activities for their students that will create opportunities for modeling as the way of knowing physics.

Our second explanation, in fact, is deeply intertwined with the first one. The practice-based stance we proposed earlier is significant, because the foundational research that still dominates physics education research posits that knowing physics is synonymous with knowing principles and laws that govern physics (Chi et al., 1981; Trowbridge et al., 1981). In this perspective, the emphasis is on developing abstractions *away* from the world of experience. What this perspective misses is the deep connection between *experience, representation* and *canonical abstractions*. Our brief sojourn in the history of physics earlier in the paper points to this fact. Everyday experience has indeed played a major role in the development of abstractions with a case in point being Maxwell's electromagnetic theories. Representations of idle-wheels and ball bearings mediated his experience in the real world with mechanical devices on one hand, and a more refined, canonical representation of electric fields (field lines) on the other. Group 1 teachers' explanations of how they would use the videos are along these lines: by

encouraging the students to edit and in some cases, recreate the videos, they are proposing a Maxwellean move – that of creating mediational representations that will encourage them to develop canonical abstractions by grounding their experiences more deeply in reality, rather than moving them away from it.

So, one might then ask: how can pre-service physics teachers develop such a model-based epistemology? Studies have also shown that teacher education courses that use direct instruction about modeling in order to support the development of teachers' model-based reasoning, have only been met with limited success (Crawford & Cullin, 2004; Windschitl & Thompson, 2006). While such pedagogical approaches can help teachers develop deeper understandings of the nature and function of models and can promote increased usage of modeling activities in the classroom, even after significant scaffolding in an instructional setting, the majority of teachers still encounter difficulties when trying to *create* their own models, as well as teaching students how to create models (Windschitl & Thompson, 2006). The most successful instructional interventions directly address pre-service teachers' pre-existing conceptions of scientific inquiry and include numerous opportunities for teachers to engage in complex *modeling* activities as learners that go beyond the use of pre-built models. They are then more likely to adopt model-based inquiry as the pedagogical approach in their science classrooms (Windschitl, et al., 2008).

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LEARNING TO DEFLECT: CONCEPTUAL CHANGE IN PHYSICS DURING DIGITAL GAME PLAY[2]

Introduction

Well-designed games can scaffold student learning (Clark et al., 2011; Clark, Nelson, Sengupta, & D'Angelo, 2009; Clark, Tanner-Smith, & Killingsworth, 2015). Research on games for learning, however, has generally focused more on demonstrating overall effectiveness of games or designs rather than analyzing the specific processes of conceptual change through which students learn. The current study presents a microgenetic analysis and case study of one student's *processes* of knowledge construction as he plays a *conceptually-integrated* digital game (SURGE Next) designed to support learning about Newtonian mechanics. More specifically, we apply the knowledge in pieces (KiP) perspective (Clark, 2006; Clark et al., 2009; diSessa, 1993; Hammer, 1996) as a lens to investigate how a student, Jamal, used his intuitive knowledge without any formal background in physics to develop a progressively refined intuitive understanding of motion during game play in a conceptually-integrated game.

In this article, we first explain the key characteristics of SURGE Next that are responsible for conceptual integration. We then present a conceptual framework for the analysis of conceptual change in conceptually integrated games and discuss key methodological issues. We then present findings from a research study using microgenetic, semistructured, clinical interviews conducted in an eighth-grade classroom. Using video recordings and screen captures

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of Jamal's game play (actions) and interview explanations after each level (i.e., mission in the game), we (a) identify the specific conceptual resources used by Jamal during each level of game play and (b) demonstrate how these resources reassembled to begin to resemble expert-like reasoning about a particular type of physical phenomenon in Newtonian mechanics— deflections—as Jamal progressed through the game. We discuss the implications of the findings for the design of conceptually integrated games for learning as well as the implications of the research methodology for future research on games for science learning.

Conceptually Integrated Games

SURGE Next is an example of a conceptually integrated game (Clark & Martinez-Garza, 2012; Clark, Sengupta, Brady, Martinez-Garza, & Killingsworth, 2015). In a conceptually integrated game, domain-specific learning goals are integrated with the mechanics and narrative of a game. Games designed in this way can allow students to build upon intuitive understandings of complex physical phenomena due to the situated and enacted nature of the game environment (e.g. Gee, 2008; Clark et al., 2009). Examples of conceptually integrated games include Supercharged (Squire, Barnett, Grant, & Higginbotham, 2004), SURGE Classic (Clark, Nelson, Chang, D'Angelo, Slack, & Martinez-Garza, 2012), and FormulaT Racing (Holbert & Wilensky, 2010). In SURGE Next, popular game-play mechanics (e.g., deflections, collisions, use of impulsive forces for accelerating objects) from commercial games such as Portal, Marble Madness, Marble Blast, Orbz, Tiger Woods PGA, Switchball, and Mario Galaxy are overlaid with key formal physics representations including vector representations and dot traces (Clark et al., 2015). Each game level (i.e., mission in the game) involves specific challenges that are designed to engage learners in reasoning about key concepts in Newtonian mechanics. Players

navigate through the game by placing impulses on Surge's ship so that it reaches the desired target, often avoiding obstacles on its way.

Conceptual integration in SURGE Next can be understood more concretely in light of two key characteristics in the design of the game levels: (1) the representational format of dot-traces in each level, and (2) the sequencing of levels. Along the first dimension, SURGE Next uses dot traces to represent Surge's position in space. This means that changes in Surge's speed become visible to the learner in the form of gaps between successive dot-traces that represent Surge's position. That is, an increase in Surge's speed results in a greater gap between successive dots, while a decrease in speed results in dots placed closer to one another. As Paranafes (2007) showed, simulations that use dot-traces to represent motion effectively transform time-based representations, such as graphs of position vs. time and speed vs. time, into spatial representations that are more intuitive for learners to interpret and understand. Spatial representations of speed, such as dot-traces, have also been shown to be intuitive for physics learners as well as useful for developing a deeper understanding of change in speed as a process of continuous change (diSessa, 2000; Parnafes, 2007; Sengupta, Farris, & Wright, 2012; Sherin, diSessa, & Hammer, 1993). Furthermore, in SURGE Next, the placement of impulses and forces are *conceptually salient* actions—that is, placing an impulse at a particular location necessitates first predicting the trajectory of Surge's ship as a result of the previous impulses (if applicable) and the new impulse, which in turn necessitates reasoning about canonical ideas such as speed, change in speed, and the direction of motion.

Along the second dimension, it is noteworthy that our pedagogical approach bears deep similarities with, and builds upon previous research about learning Newtonian mechanics using *microworlds*, in particular, the Thinker Tools microworlds-based learning environment (White,

1984, 1993). Microworlds (e.g., Boxer, diSessa, 1991; Thinker Tools, White, 1984, 1993) are

interactive computational learning environments that allow learners to manipulate, modify and

create dynamic simulations (Edwards, 1995; Hoyles, Noss & Adamson, 2002). In the domain of

kinematics, microworlds typically allow the learner to control the behaviors (e.g., movement and

rotation) of computational agents that in turn simulate motion (Papert, 1980; White, 1984, 1993;

Thompson, 1994; Sherin et al., 1993; Roschelle, 1992). In this sense, when interacting with

microworlds, learners themselves are act simultaneously as users and designers (Edwards, 1995;

Hoyles, Noss & Adamson, 2002). In Thinker Tools, the objective is for students to construct a

series of increasingly sophisticated *causal* models for reasoning about how forces affect the

motion of objects, in a sequence of progressively more complex microworlds. The initial

microworld (Microworld 1) in Thinker Tools represented simple idealized situations (i.e., motion

in one dimension with no friction and with quantized impulses; forces that are only applied for a

really short duration of time, as the causal agents). Subsequent microworlds increased in

complexity as students solved challenges by applying impulses to maneuver an object through a

predesigned two-dimensional map (Microworld 2), and using continuous forces (i.e., forces that

are applied for an extended duration of time, Microworld 3). White (1993) showed that students

can gradually build on their prior knowledge (e.g., impulses cause changes in velocity) toward a

more sophisticated conception of force and motion (e.g., forces cause accelerations) by

experimenting within microworlds in Thinker Tools through these progressions. Similarly, in

SURGE Next, each level introduces the learner to progressively more complex challenges. The

progressive complexity is evident in the form of progression from 1D motion to 2D motion

(similar to the shift from Microworld 1 to Microworld 2 in Thinker Tools), as well as a

progression from using short-duration impulses to using forces that are applied for extended

durations of time (similar to the shift from Microworlds 1 and 2 to Microworld 3 in Thinker Tools).

Framework for Conceptual Change

Two prominent theoretical approaches have tried to account for mechanisms of conceptual change in humans—theory change (also known as the *coherence* view) and KiP (also known as the *fragmentation* view). As Amin (2009) pointed out, according to the coherence view, concepts are embedded in theories (i.e., cognitive structures that represent a range of phenomena and the causal principles that explain them; e.g., Carey, 1985; 1999; Carey & Spelke, 1994; Smith, Maclin, Grosslight, & Davis, 1997; Wiser, 1995). Whereas theory change can sometimes involve the gradual change in beliefs formulated in terms of the same concepts – Carey (1998) termed this kind of change *weak restructuring*—in other cases, concepts in successive theories may themselves differ, and this type of change is known as *strong restructuring* (Carey, 1988, 1992, 1999; Carey & Spelke, 1994). Carey and colleagues have argued that the later sort of change occurs in development, with prominent examples including differentiating weight and density (C. Smith et al., 1997), differentiating heat and temperature (Wiser, 1995), and developing the adult concept of alive (Carey, 1985, 1999). In the domain of science education, adoption of this theoretical perspective manifests itself in a *discontinuous* view of learning. One of the most influential papers by McCloskey (1983), grounded in this perspective, explicitly states that the core of naïve physics is a "remarkably well-articulated" theory (p. 299) that varies only a bit from individual to individual and that strongly resembles the impetus theory of medieval natural philosophers. More recently, researchers have argued that students often conceptualize force as *substance*, and such a conceptualization is at odds with an

expert-like conceptualization of force as *process.* These conceptualizations have been argued to be ontologically distinct (Reiner, Slotta, Chi, & Resnick, 2000). Naïve theories have also been contrasted with experts' solving familiar physics problems (Chi, Feltovich, & Glaser, 1981), which in turn has revealed that experts reason about multiple problems in Newtonian mechanics using *coherent* strategies (i.e., they can identify the deep structure underlying multiple and different problems in physics based on a few canonically valid principles). As diSessa and colleagues (diSessa, 1993; Smith, diSessa & Roschelle, 1993; Hammer, 1996) pointed out, the educational implications of this view of intuitive physics is that misconceptions can and should be confronted, overcome, and replaced by valid principles (e.g., McCloskey, 1983).

A complimentary perspective, called the Knowledge-In-Pieces (KiP) perspective, frames conceptual change as a gradual and continuous process that relies on *bootstrapping*, as opposed to discarding ideas that students bring in with them to the instructional setting (Clark, 2006; diSessa, 1988, 1993; Hammer 1996; Smith, diSessa, & Roschelle, 1993; diSessa & Sherin, 1998; Jeppsson, Haglund, Amin & Strömdahl, 2013; Sengupta & Wilensky, 2009, 2011; Gupta, Elby & Conlin, 2014). Knowledge analysis from the KiP perspective requires understanding students' *sense of mechanism* (diSessa, 1993). Sense of mechanism is acquired through "dealing with the physical world" (diSessa, 1993, p 106) and should provide students with the capability to (a) assess the likelihood of various events based on generalizations about what does and does not happen in the world, (b) provide explanations of what will happen on the basis of what is the case (i.e., predictions), (c) explain what must have been the case in order for the present circumstances to exist (i.e., "postdictions," diSessa, 1993, p 106), and (d) provide causal descriptions and explanations.

diSessa (1993) postulated that the building blocks of sense of mechanism are phenomenological primitives (p-prims). P-prims are small knowledge elements developed from repeated abstractions of familiar events. Cued upon recognition of contextual cues, p-prims are used to construct intuitive understandings of the physical world. diSessa (1993) argued that conceptual change occurs through a gradual development of coherence through the alteration of *structured priorities* (diSessa, 1993) in relation to relevant p-prims and other knowledge elements. Structured priorities are altered by adjusting the probabilities with which particular pieces of knowledge will be activated upon recognition of specific contextual cues. diSessa (1983) demonstrated that physics learners tend to make errors because they overgeneralize (i.e., they use certain p-prims to make sense of situations in a manner that leads to erroneous explanations of the underlying physical mechanisms). Through carefully designed instruction and experience, students begin to cue more productive p-prims for a specific context, thus modifying the structured priority of p-prim activation and building more expert-like understanding (diSessa, Gillespie, & Esterly, 2004).

In terms of analysis of learning, the coherence and fragmentation views of conceptual change thus entail starkly different bootstrapping accounts (Amin, 2009). While both acknowledge that the process of conceptual change takes time, the coherence view treats conceptual change as a gestalt shift with a great deal of consistency attributed to both the naïve and expert knowledge structures. Several scholars have directly argued against this view, arguing that expert and novice reasoning often and productively traverses ontological categories (Gupta, Redish & Hammer, 2010) and that learners' processes of conceptual change can be better explained as a process of gradual bootstrapping that is continuous with their preinstructional

ideas (Clark et al., 2009; Levy & Wilensky, 2008; Sengupta & Wilensky, 2009, 2011; Dickes & Sengupta, 2013).

Fragmentation views argue instead that naïve understanding is highly sensitive to context, and that predictions and explanations depend in subtle ways on which particular knowledge elements happen to be triggered in particular situations. diSessa (1993) argues that according to the KiP perspective, conceptual change involves a gradual increase in coherence of understanding, and also suggests a cognitive mechanism through which coherence can emerge. Recent work by Chi, Roscoe, Slotta, Roy, and Chase (2012) has also shifted away from an incompatibility stance to a more continuous one, similar to diSessa (1993), especially in the domain of mechanics. In their revised account of naïve misconceptions, Chi et al. (2012) argued that linear motion is a "sequential process" (Chi et al., 2012; pp 53) and that novices can develop a canonically correct conceptual understanding of sequential processes using their intuitive repertoire of direct schemas (p 9). Chi and colleagues defined direct schemas as intuitive explanations that involve direct causation by an agent (typically in the form of local intentional interactions of the agent with one or a few other agents or entities) and argued that sequential processes can be explained by additively "summing" or "chaining" these local events (pp 9 - 11). Furthermore, Chi et al. (2012) pointed out that these direct schemas are piecemeal in nature in the diSessean sense, given that there may be a variety of answers to a particular question (p 9). Vosniadou's perspectives (2013) are also evolving in a manner that can be interpreted as shifting away from an incompatibility stance toward a finer-grained and organic elemental account of conceptual change (Clark & Linn, 2013).

Our interest for the current study involves identifying the process or mechanism through which conceptual change occurs in conceptually-integrated games. To this end, coherence

perspectives would provide rather low-resolution accounts—replacement of incorrect ideas with correct ones. The KiP perspective provides a comparatively more mechanistic and fine-grained account (diSessa, 1993; Smith, diSessa & Roschelle, 1993; Hammer, 1996) that aligns with the evolving trends toward fine-grained and organic elemental accounts on conceptual change across research perspectives. Particularly relevant to our study, diSessa (1993) argues that as physics learners develop more canonical understandings of physical phenomena, p-prims may come to play smaller (i.e., more precise) and more local roles. That is, p-prims come to "serve as analyses that do their work only in contexts that are much more particular than the range of application of the general or universal laws of physics" (diSessa, 1993, p 115). diSessa (1993) terms this reuse and integration of intuitive knowledge structures into the functional encoding of expertise *distributed encoding*. The term *distributed encoding* is thus intended to imply that the sense of mechanism of, for example, a physical law, may be distributed over multiple intuitive knowledge resources, such as p-prims, each of which plays some small role in knowing the law (diSessa, 1993). The current study explores Jamal's developing understanding using the analytic lens of distributed encoding by highlighting how his sense of mechanism of motion and deflection becomes progressively more distributed across multiple relevant p-prims.

Analytical Approach

At the heart of the current study is a well-documented conceptual difficulty faced by physics learners. Students often posit that forces cause motion in the direction of the force *independent of prior velocity* (Halloun & Hestenes, 1985; diSessa, 1988, 1993; White, 1984). We explain this difficulty in terms of p-prims (diSessa, 1983, 1988, 1993), defined in the previous section. diSessa (1988, 1993) has shown that this form of incorrect explanation is a result of

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Force as Mover p-prim being cued in the learner's mind. diSessa (1983) pointed out that "the most commonplace situation involving forces, pushing on objects from rest, becomes abstracted as the highest priority p-prim that one will use to predict motion in general circumstances" (diSessa, 1983, p 30), overshadowing any developing understanding of the influences of prior velocity. The *Force as Mover* p-prim develops from repeated abstractions of commonplace situations involving pushing an object from rest (diSessa, 1983, p 30). As the application of this p-prim illustrates, the abstracted features in this case are object, push, and result. The feature that does *not* get abstracted from these situations is the *previous velocity* of the object in motion (diSessa, 1993). As a result, this p-prim, when activated, cannot account for situations such as deflection.

Moving an object from rest due to application of a force is one scenario in which the *Force as Mover* p-prim works well. diSessa (1993) clarifies that even experts use this p-prim to explain such situations (diSessa, 1993, pp. 129-130). However, the difference between novice and expert usage of this p-prim is that experts "know" much better when to, and when not to, apply this intuitive explanation (diSessa, 1993, p. 130). diSessa (1988) argued that development of a more expert understanding raises the priority of the competing *Force as Deflector* p-prim. diSessa explained the *Force as Deflector* p-prim as follows: "A force (e.g., shove) may act in concert with prior motion (momentum) to produce a compromise result, directionally between the two" (p. 218). From the perspective of canonical physics, whereas *Force as Mover* neglects the role of the momentum of an object, *Force as Deflector* takes momentum into consideration. *Force as Deflector* enables people to correctly predict and explain situations in which objects are already in motion or where multiple forces are applied to an object. *Force as Deflector* is

therefore critical to developing an understanding of relationships central to Newton's First Law.

Figure 1 schematizes both of these p-prims.
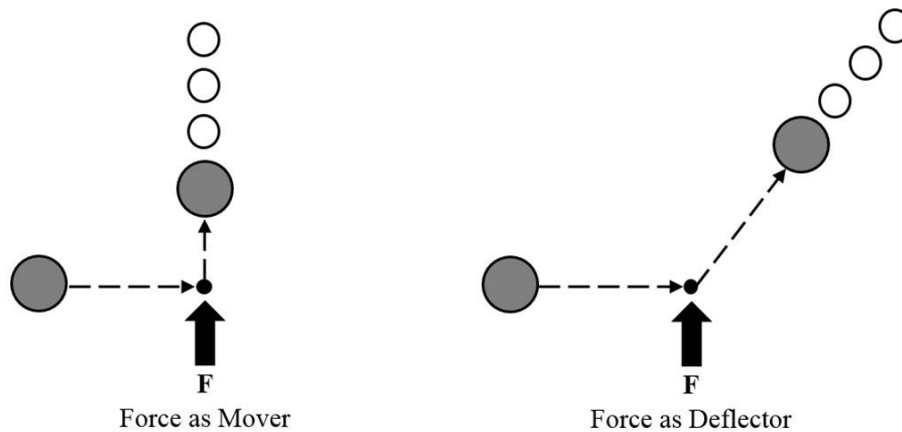
Figure 1. Schematization of the *Force as Mover* and *Force as Deflector* p-prims

Our goal is to investigate the process through which students develop progressively deeper understandings of deflection through game play. However, it is challenging for researchers to identify p-prims based on verbal explanations (diSessa, 1993, 2007). diSessa (1993) argued that p-prims belong "neither to the lowest, possibly 'hard-wired' and data-driven sensory elements, nor to the world of ideas, or named concepts and categories" (p. 112). Identifying p-prims therefore involves overcoming several challenges (see diSessa 1993, pp. 118- 120), which include the following: a) P-prims are fleeting in nature (i.e., they may be evident in verbal explanations only for a brief duration), b) p-prims may be self-evident to the learner in many cases, and c) p-prims may only indicate satisfaction or dissatisfaction with an explanation, and thus are generally hard to articulate.

For the purposes of identifying p-prims, data collection and analysis methodologies therefore require careful attention (diSessa, 1993, 2007). Although it has been argued that clinical interviews represent a form of mutual inquiry that "is developmentally derivative of

naturally occurring individual and mutual inquiry activities" (diSessa, 2007, p. 531), the analysis of such interviews, especially for the purposes of identifying the fragments of knowledge grounded in a KiP perspective, is interpretive to a certain degree (diSessa, 1993; diSessa, 2007; Galili & Hazan, 2000). Therefore, while our primary method of data collection focused on semi-structured clinical interviews conducted at the end of each game level, we also triangulated and corroborated our analysis of students' verbal explanations during the interviews with screen-captured videos of the students' actual game play during the level, changes in the students' written explanations in pre- and posttests, and researcher field notes. The pre- and posttest questions were representative of the focal learning goals (in particular, reasoning about deflections), and consisted of items that were adapted from the widely used Force Concept Inventory (Hestenes, Wells, & Swackhamer, 1992). These items, and the analysis of student responses, are discussed later in the paper (see "Analytical Summary: Distributed Encoding and the Development of an Expert-like Conceptualization of Deflection). Another advantage is that the analysis of students' responses to these out-of-game situations can also provide evidence of conceptual change in the form of *stabilization* of p-prims (i.e., even when provided with a new context, students are able to successfully explain the situation using the appropriate p-prims).

We describe the specific nature of the semi-structured clinical interviews we conducted in this study in the Methods section, but it is also important to mention here the key methodological tradeoffs involved in investigating students' thinking *in the context of game play*. As one of the reviewers pointed out, one could employ a think-aloud protocol where the student would be asked to verbalize his thoughts *during* game play. However, as Ericsson and Simon (1998) pointed out, there are two important challenges that interviewers must keep in mind while using the think-aloud protocol: (1) Think-aloud verbalizations often provide relatively incomplete

records of all the knowledge and complex cognitive processes that constitute performances of the relevant tasks, and (2) directing their full attention to the presented task while verbalizing their thoughts is typically challenging for participants, unless they are provided with several warm-up tasks for practice. We believed that the first challenge would present us with difficulties pertaining to making inferences about p-prims due to insufficient verbalization by the participants. Given the challenges in identifying p-prims that diSessa (1993) warns us about and discussed earlier, especially those pertaining to its "inarticulate" nature (diSessa, 1993, p. 119), we believe that the use of think-aloud protocol may present us with a significant methodological challenge. The second challenge would hinder participants' game play, by interrupting the *flow* (Csikszentmihalyi, 1991 2014; Rieber, 1996) of the game, which in turn is a *key* characteristic of game play. In addition, a third consideration is that conducting the interviews after each level provided us with the opportunity to triangulate the interviews with the videos of the actual game play and field notes rather than muddling all three by interjecting the think-aloud protocol within game play itself. However, we believe that in future work, it is important to conduct studies of game play comparing think-aloud and semi-clinical interviews in order to identify the challenges and difficulties associated with each method.

Research Questions

Our study investigates the process through which Jamal moved away from inappropriately applying *Force as Mover* and applied other context-appropriate p-prims more frequently, including *Force as Deflector,* in order to interpret and reason about situations involving deflections. Specifically, the current study investigates two questions as Jamal progresses through the sequence of levels in SURGE Next:

- What conceptual resources does Jamal use as he plays a digital game in the domain of physics, and how do these resources manifest in the game play?

- How does Jamal's use of these resources evolve as he progresses through the game?

Methods

Game Environment

The version of the game used in the current study was an early prototype of SURGE Next[3] (see Figure 2). This version of SURGE Next was divided into 10 short levels. Some of the basic levels only offered one possible solution, while others were more elaborate and open-ended with multiple possible solutions. Rather than employing a real-time interface (where pressing an arrow key results in the immediate application of a brief or continuous force), SURGE Next requires the player to spatially place all of the impulses (which vary in direction, magnitude, and duration) by dragging them from a pallet onto the map in advance. Once the students arrange all of the impulses and actions to their satisfaction, they launch their plan and watch to see whether Surge reaches the target and completes her mission. If the Surge character's trajectory crosses a point on the map where an impulse was placed, Surge's trajectory is modified by the application of that impulse based on its force, duration, and direction. In doing so, players direct Surge through and around different obstacles toward the target. Players must also contend with other challenges such as passing through velocity gates at certain speeds, changing the mass of the ship by picking up objects called *Fuzzies*, and depositing the Fuzzies at pre-placed "depots" along the way to "rescue" them.

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[3] Although the version of SURGE Next in the current study was a prototype, current versions of SURGE Next, other SURGE games, and information about the research projects are available at http://www.surgeuniverse.com

Because SURGE Next is a conceptually integrated game, learners' game play is deeply tied to the underlying concepts in physics. This means that the canonical concepts of force, speed, acceleration, and momentum are leveraged in an intuitive and qualitative manner during students' game play, both in the form of representational elements such as dot traces as well as conceptually salient actions such as placement of impulses. Application of an impulse along its trajectory (or Surge passing over an impulse already placed along its trajectory) affects the velocity of Surge, as does traveling on a friction pad (i.e., a small area within the game world with a nonzero frictional coefficient). The friction pad results in a continuous decrease in Surge's speed (until it comes to a stop), while application of an impulse results in Surge increasing or decreasing its speed instantaneously. As mentioned earlier, these changes in Surge's speed become visible over time in the form of gaps between successive dot traces that represent Surge's changing position. Furthermore, as our analysis shows, the progressive complexity of successive levels in SURGE requires the learner to reflect carefully on the lessons learned from previous levels.
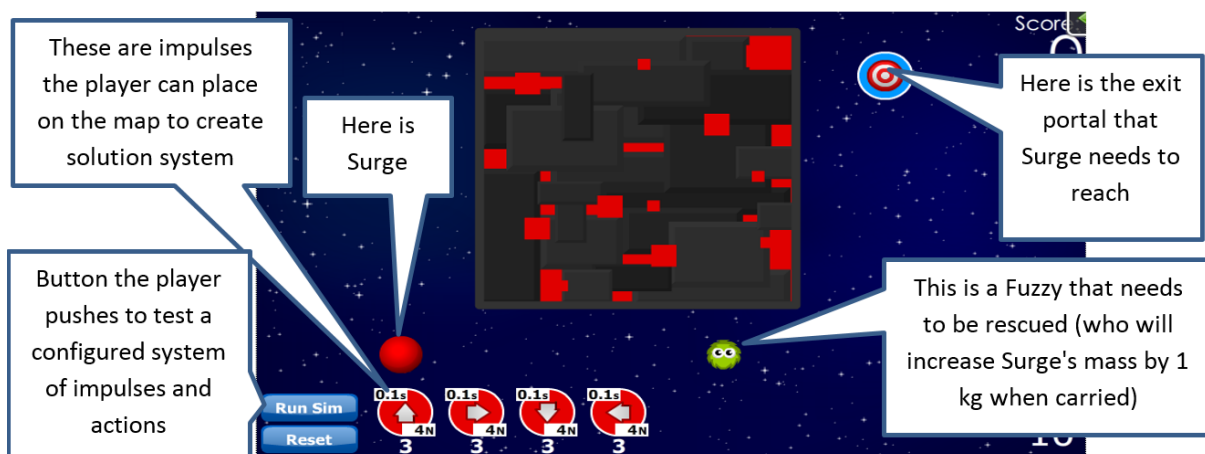

Figure 2. Sample *SURGE Next* Level with descriptive annotations

Students' predicted trajectories (as represented by the patterns of impulses they pre-place on a map) can be understood as models that make explicit their intuitive understanding of how instantaneous and continuous forces will affect the motion of an object. Once their hypothetical trajectories are laid out by arranging impulses, students deploy their models by launching their plan in real time. This offers players the opportunity to verify if Surge indeed follows the path that they predicted through their initial placement of impulses. As we discuss later in this article (in our analysis of student work), the dissonance between the predicted path and the actual path of Surge can lead to productive learning through iterative refinement of the placement of impulses. The nature of students' game play thus involves an iterative process of modeling. Hestenes (1993) argued that model development, deployment, and refinement are three key components of engaging in scientific inquiry in the domain of Newtonian mechanics. The process of game play and learning with SURGE Next outlined here includes each of these components. From a pedagogical perspective, we therefore believe, to paraphrase Hestenes (1993), that modeling indeed is "the name of the game" that students engage in while playing SURGE Next.

Research Context and Case Study Approach

The setting for this study was a 100% African American high-poverty public charter school located in a metropolitan school district in the southeast United States. The class consisted of nine eighth-grade students, all of whom participated in the larger research study. All the students were Title I students (i.e., they had been identified by the state educational body as failing, or being most at risk for failing, in science, math and reading). None of the students had taken any prior courses in physics or physical science. Using Taber's criteria of typicality and

representativeness for case selection, we present the case of a single student named Jamal (a pseudonym). Jamal's case was selected after we analyzed, coded, and compared data for all the students. *Representativeness* implies that the selected cases should aptly represent key aspects of the instructional process. Jamal's case is representative because Jamal was present every day and interviewed frequently, so his case provides an authentic representation of all the instructional activities. *Typicality* implies that Jamal's reasoning be similar to majority of the students in the classroom. Based on our comparisons of Jamal's game play and interview responses with others, his thinking appears to be typical of other students in the classroom. That is, the challenges he encountered during each level, and the conceptual resources he used during each level, were typical of the other students in the study. We present Jamal's case using an explanatory case study approach (Gomm, Hammersley, & Foster, 2000; Petri & Niedderer, 1998; Taber, 2008; Yin, 1994) to describe the processes of knowledge construction that occur during game play. Data analysis consisted of transcriptions of interviews, development of open coding schemes, application of codes to data to identify patterns, triangulation with other data sources (i.e., video, tests, and field notes) and selection of written and verbal excerpts to represent the data.

Data Collection

The study lasted for five consecutive days during which the students played SURGE Next for 1.5 hours per day. Data collection employed the microgenetic method (Siegler & Crowley, 1991) to study short-term conceptual change. The microgenetic method requires a high density of regular observations that span the entire duration of the learning activities and a qualitative analysis of the change (Siegler & Crowley, 1991; Kuhn, Schauble, & Garcia-Mila, 1992; Kuhn, 1995). In our study, these regular observations took the form of semi-structured

clinical interviews. We conducted these interviews with each student in the class immediately after he or she completed each level so that they were minimally invasive (i.e., we did not disrupt students' game play *during* each level). Instead, when a student completed a level, the student raised a hand and an interviewer came over to talk to the student about the level. In these interviews, we asked students to explain their actions during game play (e.g., why they placed the impulses at particular positions on the screen, why they combined two impulses at the same location). In cases where students used canonical physics terms such as *force* or *speed* in their verbal explanations, we also asked them for further clarifications so that we could understand what these terms meant to them. Each interview ranged from 1 minute to approximately 10 minutes, and each student was interviewed several times during each class.

It is important to note these interviews took place only after students had *successfully* completed each level. As explained earlier, we adopted this approach in order to minimize unintended scaffolding or interference with the game play *during* each level. Interview prompts intentionally did not introduce any formal terminology that was not expressed first by the student. In addition to the interviews, each student's computer ran screen-recording software (Camtasia) that recorded the entire screen during game play as well as the voice and face of the student. These recordings allowed the researchers to follow all of the students' interactions within the game, including initial failed attempts to solve levels and efforts by students to tweak placement of impulses in order to successfully solve the level. Finally, students were prompted at the end of each level to explain their game play in the form of written explanations. These questions appeared after each level and were related to physics concepts found within that level (i.e. "Does Surge always go in the direction of the last impulse placed on it? Why?" and "What happens to Surge when you pick up a Fuzzy?").

Coding for P-prims

We identified p-prims based on categorization of (a) students' actions as recorded during videos of game play and (b) utterances during their interviews in which they explained their actions. In order to categorize their actions and utterances, we used diSessa's schematic for identifying p-prims (diSessa, 1993, pp. 217 - 223). The most direct evidence of p-prims lay in students' placement of impulses along their predicted trajectory of Surge. Further evidence of p-prims arose through students' verbalizations (explanations) of their game play strategy. In some cases, these verbalizations were direct observations of the behavior of Surge. In some other cases, students' utterances had more explanatory power (i.e., their utterances explained the behavior that they observed).

We used the check coding method (Miles & Huberman, 1994) to analyze and code the interview and Camtasia data. In this method, two or more researchers independently code data and then clarify their differences until consensus is reached. This work was conducted in three phases. A first pass at data analysis was conducted jointly with four members of the research team. Each member was assigned two of the six students selected for analysis. We each watched the videos of our assigned students and noted segments that seemingly related to explanations of conceptual thinking. We recorded our initial observations in a shared online spreadsheet and discussed these as a group. These observations were mainly descriptive in nature and corresponded to what Miles and Huberman (1994) term *descriptive codes*. After this initial pass, transcriptions of all the interviews, as well as written responses, were generated for all six students who were selected for analysis. We then began open coding (Strauss & Corbin, 1990). During this phase of analysis, we carefully re-watched the interview videos and read the transcripts multiple times with the goal of generating analytic codes that Miles and Huberman

(1994) term *pattern codes*. A pattern code is inferential, a sort of meta-code, that pulls together the data labeled by descriptive codes into smaller and more meaningful units.

Descriptive codes in our study corresponded to discrete events that we identified in the Camtasia screen recordings and interview transcripts. Each event was comprised of a student's attempt (for Camtasia recordings) or their post-hoc explanations of their attempts (for interview transcripts) in order to attain a particular objective in their game play. Our descriptive codes for the p-prims are paraphrased versions of the key causal elements in students' actions and/or verbal explanations. For example, if the Camtasia video showed that a student reduced the number of impulses acting on Surge to make it move slower, the descriptive code for the conceptual resource was "fewer impulses make Surge move slower".

The pattern codes emerged during the second phase of coding. Pattern codes were identified through two steps. First, we compared the relevant episodes in the transcripts as indicated by the descriptive codes—including both Camtasia videos of their game play and interview transcripts—with the schematization of p-prims described by diSessa (1993, pp. 217-225). The first step in pattern coding involved identifying the *salient situational elements* evident in student's game-play actions, as well as their verbal descriptions and explanations of their game-play. We then identified the *qualitative relationships* between these salient situational elements. During this identification process, these codes were iteratively compared with diSessa's schematization of the relevant p-prim. The p-prims we identified, diSessa's schematizations of the p-prims, and our descriptive and pattern codes are described in the Appendix. Continuing with the example from the previous paragraph (i.e., "fewer impulses make Surge move slower"), the descriptive code was compared with diSessa's schematization of Ohm's P-prim: *increased effort or intensity of impetus leads to more result* (diSessa, 1993, p.

217). The salient situational entities evident in the student's actions are (a) impulses placed on Surge and (b) the resultant speed of Surge. An impulse corresponds to diSessa's schematization of an "impetus", while speed corresponds to diSessa's schematization of an "effect" of the impetus. The nature of the qualitative relationship between these entities is the *direct proportionality* between the magnitude of impulses acting on Surge and the resultant speed. The pattern code here therefore corresponds to diSessa's schematization of Ohm's P-prim: *increased effort or intensity of impetus leads to more result.*

Findings

In presenting our findings, we analyze Jamal's thinking during each game level in terms of the conceptual resources (p-prims) evidenced in his actions and explanations. The findings are presented in the chronological sequence of Jamal's progression through the game. For each game level, we identify the p-prims that were evident in Jamal's game play.

Initial Misapplication of *Force as Mover* and First Appearance of *Force as Deflector*

In Level 1, Jamal began his game play using *Force as Mover* and completed the level without any difficulty. Excerpt 1 is a transcription of a section of Jamal's interview conducted immediately after completing Level 1, and the bolded text indicates evidence of his use of *Force as Mover*.

Excerpt 1

1	Interviewer:	Which way did [Surge] move?
2	Jamal:	The target was on the right, so **when you put the impulse on him,**
3			**he moved to the right** toward the target.

As shown in Figure 3, Jamal placed a 4 Newton impulse with a duration of 0.1 seconds on Surge to move it to the right[4]. In lines 2-3, he indicated that Surge's rightward motion was a result of the impulse that he placed on Surge. Here the salient situational elements were the direction of the applied impulse and the direction of predicted motion. Jamal's statement and actions make it clear that he placed the impulse in the direction of the desired motion (i.e., toward the target). Based on the schematization in the Appendix, we therefore concluded that Jamal demonstrated the *Force as Mover* p-prim in his reasoning. Note that this episode is an example of the productive application of the *Force as Move*r p-prim.

Figure 3. Jamal's solution for Level 1

In Level 2, students needed to maneuver Surge in two dimensions in order to reach the target. When Jamal encountered this level, he initially cued only the *Force as Mover* p-prim, which had been productive in Level 1, but which is not productive in the Level 2. Jamal's

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[4] All game levels in this prototype progression focused on impulses with durations of 0.1 seconds.

interview response in Excerpt 2 illustrates his attempt to use *Force as Mover* to solve this level.

Jamal's initial strategy using *Force as Mover* can also be seen graphically in Figure 4.

Excerpt 2

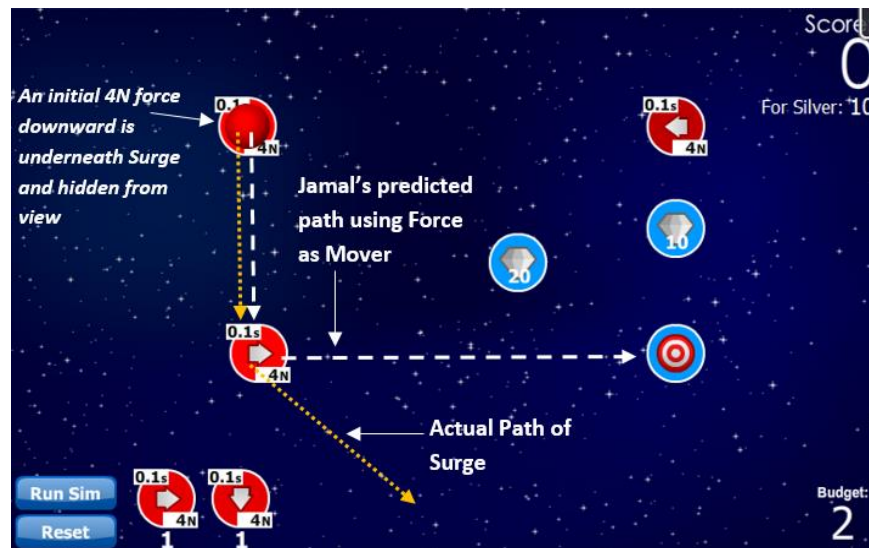| 1	Interviewer:	What did you do in this level?
2	Jamal:	My first attempt was to put the down impulse right here to make
3		him go down. Then I would **put this [right impulse] right**
4		**here to make him go across to the target**. But that really didn't
5		happen. It kind of slanted down and missed the target. So it went,
6		like, diagonal and went down.

Figure 4. Jamal's first attempt at Level 2

Jamal knew he needed to move Surge down and to the right in order to reach the target, so he initially placed a "down impulse" on Surge (i.e., an impulse pointing in the downward direction). In lines 3-4 in Excerpt 2, Jamal stated that he placed a right impulse in line with the target, anticipating that Surge would make a 90-degree turn and head toward the target. We believe that this statement demonstrates his use of the *Force as Mover* p-prim when reasoning about this level. These utterances (lines 3-4) indicate an assumption that Surge would

immediately stop moving in the original direction and begin moving in the direction of the new

force that acted on it. Jamal was surprised when, instead of turning by 90 degrees when the right

impulse was applied, Surge unexpectedly "slanted down and missed the target" (lines 4-5).

Upon noticing Surge's deflection (or "slant"), Jamal adopted an instrumental approach to

refine his strategy. That is, instead of explicitly reasoning about how deflection emerged, he

decided to *use* the deflection to design Surge's trajectory. This is evident in his explanation in

Except 3.

Excerpt 3

1	Jamal:	So what I thought was, since the sideways arrow would do that, I
2		would try a downward arrow to see if it would slant also and it did,
3		so I decided to **make Surge go to the right and THEN go down**
4		**so it can slant**. Then it hit the [target]."

During his interview, which took place immediately after he successfully completed this attempt,

Jamal explained that an object moving downward will begin to "slant" diagonally on a new

trajectory when a force is applied on it to the right (Excerpt 3, Lines 1-2). Using this discovery,

Jamal created a new trajectory for Surge, and his actions bear evidence that he used the *Force as*

Deflector p-prim to do so. He first used an impulse to move Surge to the right, and then placed a

downward impulse in Surge's path so that Surge would deflect, or "slant" (to use his word),

down to the target. This reasoning shows a marked change from his demonstrated reasoning in

the previous level (see Figure 4). In Excerpt 2, we saw that Jamal initially noticed the

phenomenon of "slanting" when he used a right impulse to alter the direction of a vertically

downward moving Surge. He then decided to try the combination of a right impulse to begin

Surge's motion and a downward impulse (see Excerpt 3, lines 3-4) to cause Surge to deflect (i.e.,

slant) and reach the target. This is also shown in Figure 5. We believe this is evidence of a successful application of the *Force as Deflector* p-prim.
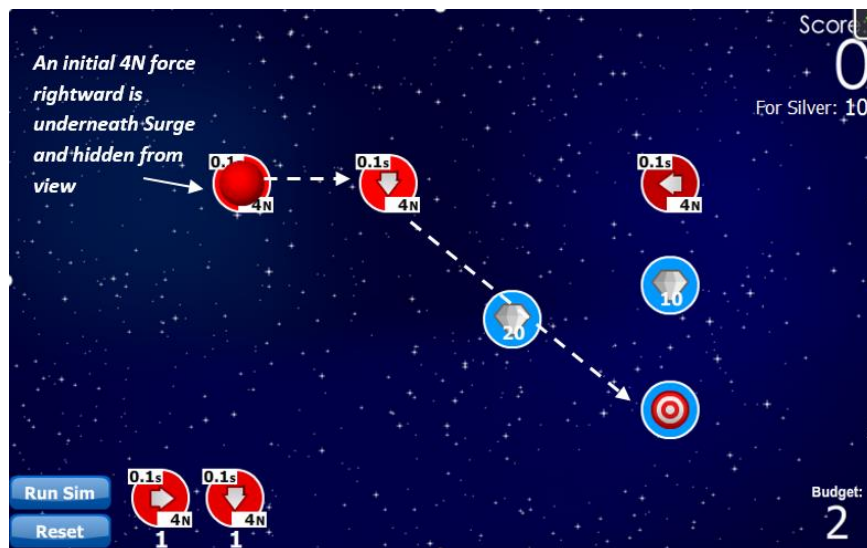

Figure 5. Jamal's successful solution for Level 2

Persistent Misapplication of *Force as Mover*

Despite Jamal's successful cuing and use of the *Force as Deflector* p-prim in Level 2, he initially unproductively cued the *Force as Mover* p-prim in Level 3. As shown in Figure 6, Jamal initially attempted to maneuver Surge along a right-angle path by placing a right impulse at the desired point of turning. Similar to his experience in Level 2, he was surprised when Surge did not move as he predicted. Lines 4-8 in Excerpt 4 indicate Jamal's unproductive application of *Force as Mover* within Level 3. This is evident in his expectation that the instantaneous force acting on Surge should alter the direction of its motion without taking into account its previous motion (lines 4 and 5). This expectation resulted in his action of placing a "right arrow", i.e., a rightward impulse, at the point where he wanted Surge to turn right by 90 degrees (lines 5 and 6).

Jamal failed to cue *Force as Deflector* even though the contextual cues in this level were quite similar to those in Level 2. This suggests that, at this point in the game, *Force as Deflector* still had a relatively lower cueing priority in Jamal's mind compared to *Force as a Mover*[5].

Excerpt 4

1	Interviewer:	Tell me what you did in this level.
2	Jamal:	Surge is right here [points to starting position] and you're trying to
3		get him between these two obstacles and go to the target. What I
4		did was, I decided to **take the up impulse and put it on Surge so**
5		**he could go up.** And **get a right arrow and put it right here**
6		**[points to the location where he placed the right impulse]**. My
7		first attempt was just to do this, **but it kind of went upward**
8		[gestures up and right in a diagonal path]."
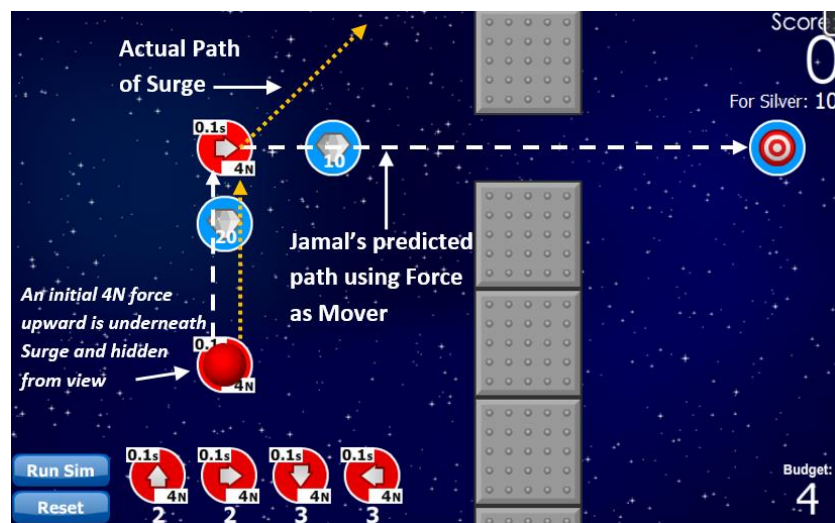
Figure 6. Jamal's 1st attempt at Level 3

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[5] A reviewer pointed out that one could also argue here that Jamal was simply attempting to "win" the level without reasoning explicitly about the outcome of placement of the "rightward" impulse. That is, Jamal's actions here could also indicate that he was trying to get SURGE to travel along the most direct path, hoping that SURGE would *somehow* make it through the narrow pathway. Note, however, that Jamal's explanation in Excerpt 5 provides evidence that his placement of the "Up" impulse was, in fact, based on his prediction about the expected direction of SURGE's movement as a result of the impulse.

Use of *Canceling* to Correct the Misapplication of *Force as Mover*

After his unsuccessful application of *Force as Mover* in Level 3, Jamal revised his

attempt using a downward impulse immediately before Surge encountered the right impulse.

This revised strategy led to cancelling the effects of the initial up impulse, thus enabling Surge to

turn right by 90 degrees when it encounters the right impulse (see Figure 7)[6]. As evident in lines

5 and 6 in Excerpt 5, Jamal maneuvered Surge exclusively in the rightward direction by

superimposing a down impulse on top of the right impulse (see Figure 7). The down impulse

canceled the up impulse, and the right impulse moved Surge to the target.

Excerpt 5

1	Jamal:	What I did was, I decided to take the up impulse and put it on
2		Surge so he could go up. And get a right arrow and put it right here
3		[in line with the gap]. My first attempt was just to do this, but it
4		kind of went upward [gestures up and right in a diagonal path]." So
5		I thought of the last one I did, **so I decided to put a down arrow**
6		**right here [on top of the right impulse] to see what it would do.**
7		It hit the target."

Jamal drew upon his actions in previous levels during his explanation of how he arrived

at the solution for Level 3. In lines 5 and 6 in Excerpt 5, he stated that he thought of the "last

one" (i.e., the previous level) and based his game play strategy on that experience. Jamal was

clearly reflective here – he remembered his experience with cancelling impulses in his previous

attempt (Excerpt 3) as a relevant experience. Jamal decides to experiment with a similar strategy

---

[6] The laptop that recorded Jamal's game play sequence for level 3 unexpectedly lost power, and we were unable to save the recorded screen-capture video data. However, Jamal re-enacted his game play strategies during his interview and described in detail his previous failed attempts to solve the level. Based on his explanations as well as video recordings of his re-constructive game play during the interview, we have recreated screenshots of both of his attempts at solving this level.

by placing a downward arrow to cancel the effect of the upward impulse. He then used a down

impulse of the same magnitude as the upward impulse to "see what it would do" (line 6).

It is important to note that Jamal's choice of the magnitude of the impulse was incidental,

or subconscious at best, in the sense that he did not explicitly reason about it. Although Jamal

was not certain about the outcome of his actions, his choice of a downward impulse clearly

suggests that his goal was to stop Surge's upward motion and prevent a deflection. Therefore, the

salient situational elements (the upward direction of motion of Surge and the downward direction

of the impulse) and their qualitative relationship (equal and opposite) suggests that Jamal's

reasoning was based on the *Canceling* p-prim. He then placed a rightward impulse to

successfully propel Surge in the direction of the target. Similar to our analyses in previous levels,

this evidences the successful application of the *Force as Mover* p-prim because the applied

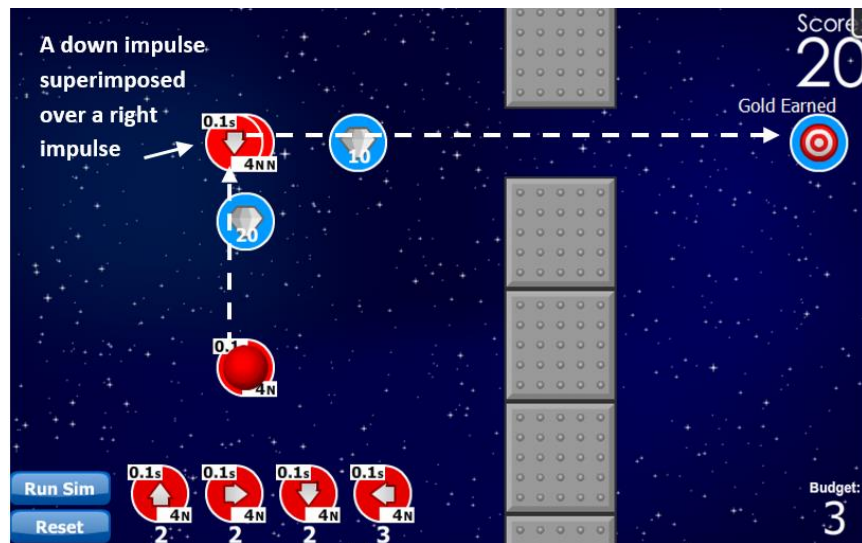impulse results in the predicted (and desired) change in the direction of motion.

Figure 7. Jamal's successful solution to Level 3 using *Canceling*

In the subsequent level, Level 4, Jamal encountered a similar situation that required deflecting Surge by 90 degrees. He solved this level iteratively on his third attempt. In his initial attempt, it appears that *Force as Mover* was still being cued with a higher cuing priority than *Force as Deflector* or *Canceling* p-prims (even though those latter resources would be more productive in the context of Level 4—just as they had proven more productive in Levels 2 and 3). In Excerpt 6, Jamal explains how he initially tried to solve Level 4.

Excerpt 6

1	Jamal:	Yesterday when I tried [Level 4], I was just putting it like this
2		[adds one up impulse at corner]. And when I hit Run Sim, it went a
3		different direction. It went that direction [diagonal up].

(a)   (b)   (c)
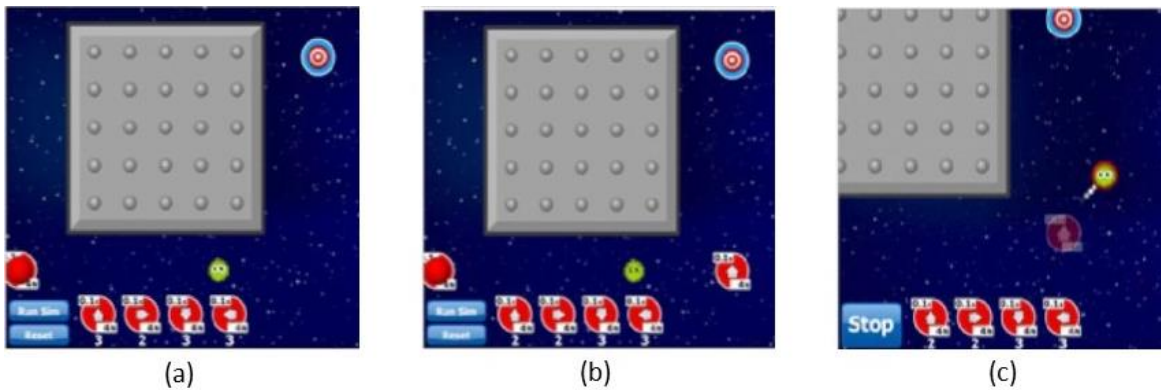
Figures 8a - 8c. Progression of screenshots of Jamal's first attempt at Level 4

Jamal initially placed a 4 N right impulse on Surge to start motion (see Figure 8a). Then Jamal placed one 4 N up impulse at the corner of the obstacle and ran the level (see Figure 8b). Surge deflected diagonally upward because Jamal did not use a left impulse to stop Surge's rightward motion (see Figure 8c). By using only one up impulse at the corner, as evident in his explanations in lines 1 – 3 in Excerpt 6, Jamal again demonstrated his intuition that Surge would

immediately stop moving right and will instead begin moving straight up to the target (see Figure 9). His explanation suggests that the *Force as Mover* p-prim was being cued here.
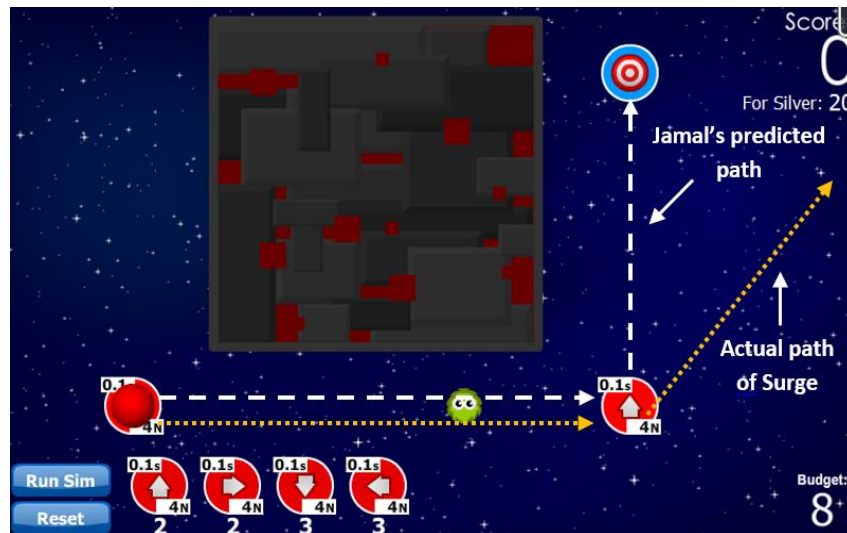
Figure 9. Jamal's initial solution to Level 4

Jamal then pursued a different approach similar to his final (successful) attempt for Level 3. This involved first counteracting the effect of the initial horizontal impulse by using an impulse in the opposite direction and then placing an additional impulse to make his ship move in the vertical direction. The Camtasia screenshots in Figure 10 show his use of an impulse to cancel Surge's horizontal motion. In this attempt, Jamal placed a 4N right impulse to start Surge's motion (see Figure 10a) and an additional 4N right impulse in Surge's path before the location of the fuzzy (see Figure 10b). He then placed a 4N up impulse and a 4N left impulse superimposed on each other (see Figures 10c and 10d). Jamal appeared to be using the *Canceling* p-prim because a left impulse is needed to stop Surge's motion in the rightward direction. Jamal has two 4N impulses to move Surge to the right, however and only one 4N left impulse to the

left. Jamal thus does not successfully cancel the rightward horizontal velocity, resulting in an

unexpected diagonal deflection (see Figure 10e).

When Jamal launches his plan, the 4N leftward impulse at Point S is not sufficient to cancel his horizontal velocity because it is smaller in magnitude than the combined magnitude of the two previous rightward impulses. This imbalance of magnitudes results in the unexpected diagonal deflection.
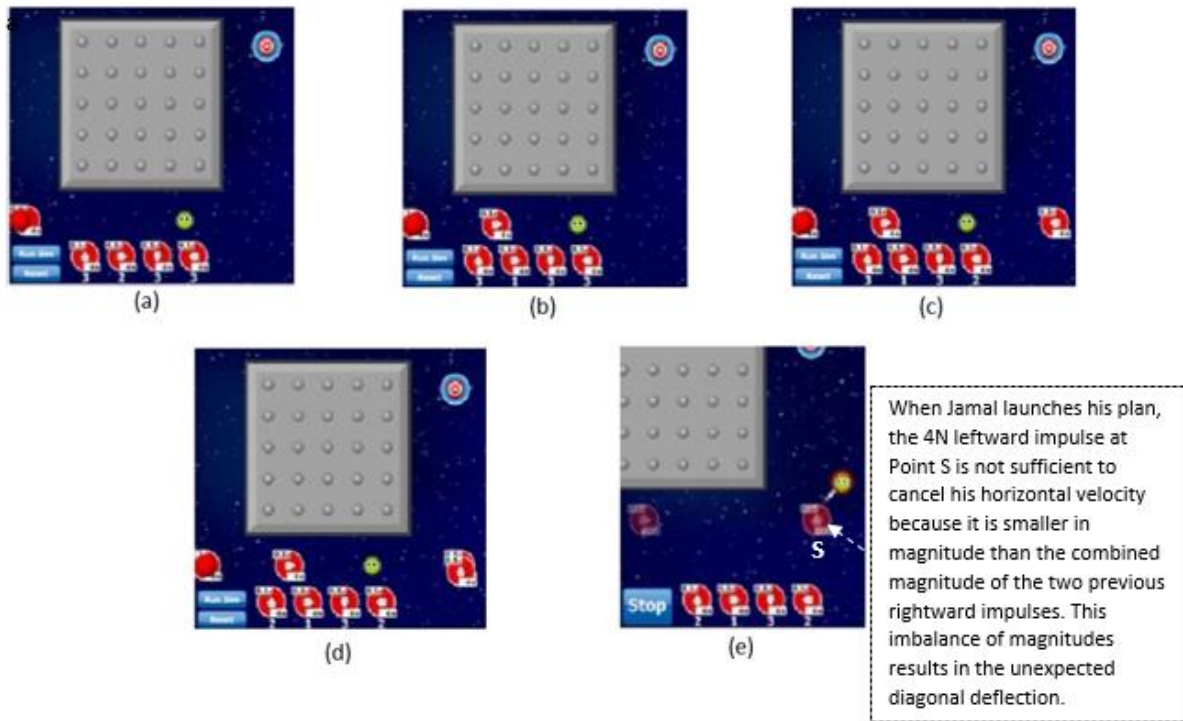
Figures 10a – 10e. Screenshots of Jamal's 2nd attempt at Level 4

In contrast to Level 3, Jamal's attempt here shows that (a) he has a canceling strategy in

mind but (b) his strategy of using the default magnitude of the cancelling impulse did not work.

This in turn created a situation that necessitated explicitly taking into account Surge's previous

velocity—both its direction and its magnitude. This is evident in his following attempt, which is

displayed in the sequence of Camtasia screenshots in Figure 11. His actions show that Jamal

recognizes that his plan needs to include the same amount of leftward force as rightward force so

that Surge will come to a complete stop in the horizontal direction at the position annotated as

Location S in Figure 10e. Toward this end, Jamal removed one of the 4N right impulses, leaving

a single 4N right impulse to begin Surge's motion (see Figure 11a) and the two impulses (4N left

and 4N up) at the corner (Point S) as shown in Figures 11b and 11c. Upon running the

simulation, Surge made a 90 degree turn and successfully hit the target (Figure 11d). These

actions show that Jamal was using *Ohm's P-prim* in order to figure out the appropriate

magnitude of the cancelling impulse. Following diSessa's schematization (see Appendix), the

situational elements salient in Jamal's actions are the magnitude of the cancelling impetus and

the effect of the impetus (i.e., the horizontal speed of Surge). Jamal's actions also made explicit

his conceptualization of the qualitative relationship between these elements; by reducing the

amount of right impetus acting on Surge, Jamal was reducing the effect of that impetus (i.e.,

Surge's horizontal speed toward the right).

(a)   (b)

(c)   (d)

When Jamal launches this plan at Point S, the 4N leftward impulse is sufficient to cancel his horizontal velocity because it is of the same magnitude as the initial rightward impulse. This balance of magnitudes results in the desired perpendicular deflection.
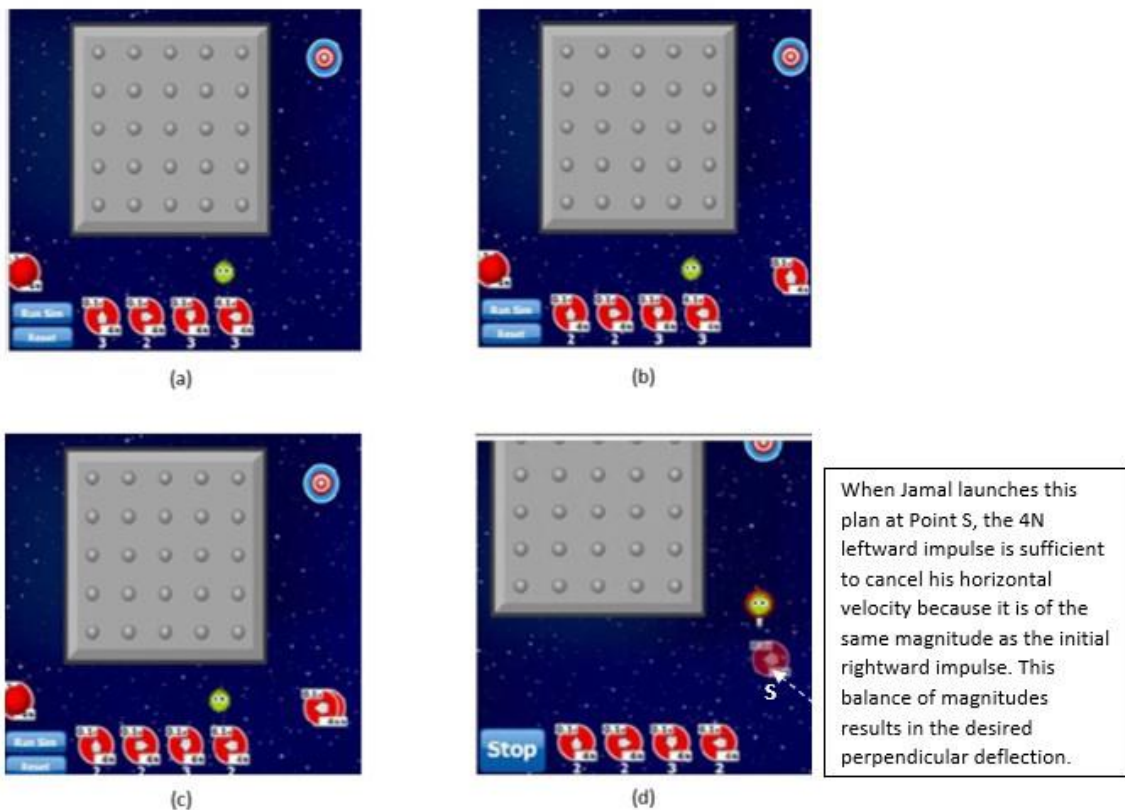
Figures 11a – 11d. Screenshots of Jamal's final (and successful) attempt on Level 4

In the interview that immediately followed (Excerpt 7), Jamal explained that the leftward impulse was responsible for stopping Surge from going right (lines 5-6 in Excerpt 7), thereby providing evidence of the *Cancelling* p-prim. He also explained that the upward impulse would then guide Surge vertically upward to its target (Line 7 in Excerpt 7), thereby providing evidence of the productive application of the *Force as Mover* p-prim.

Excerpt 7

1	Jamal:	So what I did was I put a right impulse on Surge. Then I put
2		an up arrow right here. On top of that, I put a left impulse right
3		here. Then I hit "Run Sim" and see how it goes. But when Surge
4		hits it [the fuzzy], it slows down because the fuzzy adds on more
5		weight which slows it down. Then it goes up to the target…**The**
6		**force of the left arrow will stop [Surge] from going [points to**
7		**right] and [the up arrow] will make it go straight up**.

Productive Stabilization of P-prims for Interpreting Deflection

In each of the subsequent levels, Camtasia recordings demonstrate that Jamal was able to successfully generate a 90 degree turn with no accidental deflection on his first attempt in each level. For example, on his first attempt in Level 5, Jamal correctly cued the combination of *Canceling* and *Force as Mover* p-prims to cause a perpendicular deflection in Surge's trajectory (similar to Level 4). Camtasia screen recordings of his first attempt at Level 5 (see Figure 12) show that Jamal placed a 4N right impulse on Surge to start motion (see Figure 12a), followed by a 4N left canceling impulse and a 4N down impulse superimposed on each other to turn Surge downward 90 degrees (see Figures 12b and 12c). Surge successfully made a downward 90 degree turn with no unexpected deflection (see Figure 12d).

Furthermore, in Level 6, Jamal designed a complex trajectory involving two different maneuvers. For the first maneuver, he executed a desired perpendicular deflection. He prevented

Surge from deflecting by applying the *Canceling* p-prim at the first corner, and he guided Surge

vertically with a productive application of the *Force as Mover* p-prim. For the second maneuver,

he executed a desired diagonal deflection (similar to Level 3) in order to reach the target.
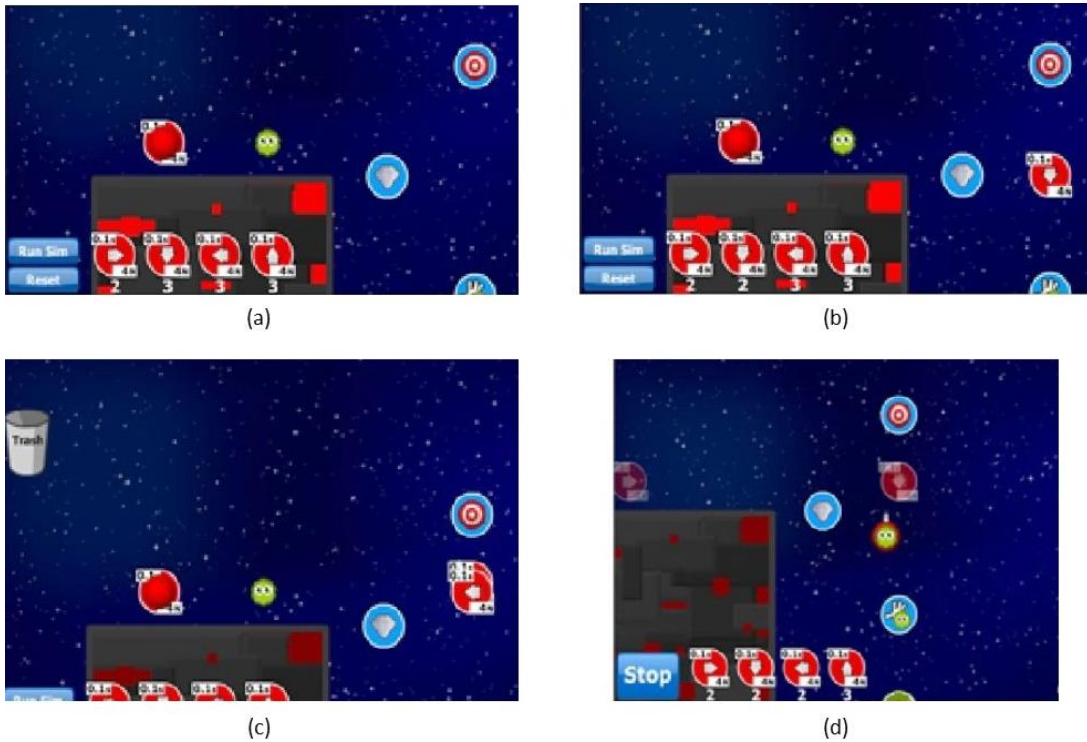
Figure 12a – 12d. Jamal's successful solution to Level 5 on his first attempt

Analytical Summary: Distributed Encoding and the Development of an

Expert-like Conceptualization of Deflection

Table 1 shows Jamal's learning trajectory in a graphical form, in terms of the p-prims he

cued during his attempts on each level. Resources cued inappropriately are identified with a

square icon. Resources cued appropriately are indicated with a circular shape. This table shows

that Jamal's difficulties with interpreting situations involving deflection continued through Level

Table 1. P-prims in Jamal's Reasoning

Resource	Level 1		Level 2		Level 3		Level 4		Level 5		Level 6	
	Beginning	End	Beginning	End	Beginning	End	Beginning	End	Beginning	End	Beginning	End
Force as Mover	●		■		■			●			●	
Force as Deflector				●		●	■		●		●	
Canceling						●	■	●	●		●	
Ohm's								●			●	

Note: ■ = incorrect reasoning; ● = correct reasoning

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4, but that Jamal was able to refine his reasoning in each of these levels iteratively by appropriately using alternative intuitive conceptual resources. As this table and our analyses show, however, Jamal reliably and appropriately cued *Force as Deflector, Ohm's P-prim, Canceling* and *Force as Mover* in his initial attempts on Levels 5, 6, and 7 to correctly predict, explain, and control the motion of Surge in situations that involve diagonal deflections and 90 degree turns. We posit that the development of reliability in the cuing of appropriate p-prims in these later levels can be explained in terms of what diSessa (1993) termed "distributed encoding".

According to diSessa, the mechanism of conceptual change involves *distributed encoding*, a process in which learning to "see" (i.e., interpret) a phenomenon through canonical lenses (e.g., a physical law) involves "many intuitive contributors that each play some small role in 'knowing the law'" (diSessa, 1993, p. 115). In Jamal's case, distributed encoding is evident in (a) Jamal's learning to differentiate between situations involving perpendicular and diagonal deflections and (b) Jamal's development of a progressively sophisticated sense of mechanism for dealing with perpendicular deflections. We explain both of these dimensions of distributed encoding in the following paragraphs.

Along the first dimension, Jamal learned to see deflection in terms of two different senses of mechanism for two different forms of deflection. He cued *Force as Deflector* to interpret a diagonal deflection in Level 2, and he cued combinations of *Canceling* and *Force as Mover* in order to interpret perpendicular deflections in Level 3 and Level 4. In each of these levels, Jamal's initial (inaccurate) sense of mechanism involved a problematic application of the *Force as Mover* p-prim. Through his iterative attempts to solve these levels, however, Jamal developed a more nuanced sense of mechanism for dealing with deflections within the game.

Along the second dimension, comparisons of Jamal's game play in Level 3 and Level 4 reveal further evidence of distributed encoding for dealing with the specific situation of perpendicular deflections. Note that although his solutions to Levels 3 and 4 involved using approximately the same sense of mechanism for interpreting and causing 90-degree deflections, Jamal needed to explicitly take into consideration the magnitude of Surge's velocity in his revised attempts of Level 4. More specifically, whereas Jamal's use of *Canceling* was intuitive (or coincidental) in Level 3, Jamal's approach to stopping Surge's horizontal motion in Level 4 required more deliberate reasoning about deflection. Jamal needed to cue an additional p-prim, *Ohm's p-prim*, to predict and correctly adjust the magnitude of the applied impulses on Surge so that the magnitude of the leftward impulse equaled the magnitude of the rightward impulse. Thereafter, from Level 5 onward, Jamal applied this more nuanced sense of mechanism without difficulty, thereby suggesting that his experience in Level 4 may have been instrumental in stabilizing this nuanced sense of mechanism (at least for rest of his game play).

The stable application of distributed encoding is perhaps best evident in Level 6, where Jamal encountered two different types of deflection. Jamal appropriately employed different senses of mechanism for each type on his first attempt. In situations involving diagonal turns, Jamal appropriately used *Force as Deflector* (similar to his successful final attempt in Level 2). In situations that required Surge to turn by 90 degrees (i.e., a perpendicular deflection), he was also able to use *Cancelling* and *Ohm's P-prim* to cancel Surge's initial velocity along his initial dimension of travel in tandem with *Force as Mover* to appropriately complete the perpendicular deflection (similar to his successful strategy in Level 4). This demonstrates that, by Level 6, Jamal came to appropriately conceptualize deflection with multiple sets of conceptual resources rather than relying on only one conceptual resource to understand and explain deflection in any

situation. This in turn enabled Jamal to take into consideration the previous velocity of Surge in a manner appropriate to the situation at hand—a clear move toward an expert-like conceptualization.

We found further evidence of stabilization in Jamal's reconceptualization of deflection in his responses to relevant questions on the post-test compared to the pre-test. A comparison between Jamal's pre and post-test responses indicated that he improved his reasoning on questions involving canonical representations of the focal concepts (deflection and relationship between force and speed) as portrayed in the Force Concept Inventory. Jamal displayed a counterproductive application of the *Force as Mover* p-prim on a pre-test question that asked students to select the path of a hockey puck after it is hit in a direction perpendicular to the direction of its original motion (Option A in Figure 13). In the post-test, Jamal's response (Option B) indicated use of the *Force as Deflector* p-prim. This suggests that after playing the game, Jamal was able to identify the effect of previous motion on the new direction of motion of the object. Similarly, in another post-test question, Jamal correctly identified that an object moving at constant speed experiences no net-force (i.e., the force with which a woman is pushing a box to keep it moving at constant speed is the same as the frictional force experienced by the box). In contrast, Jamal's response on the pre-test indicated that the force with which the woman is pushing the box is greater than the frictional force.
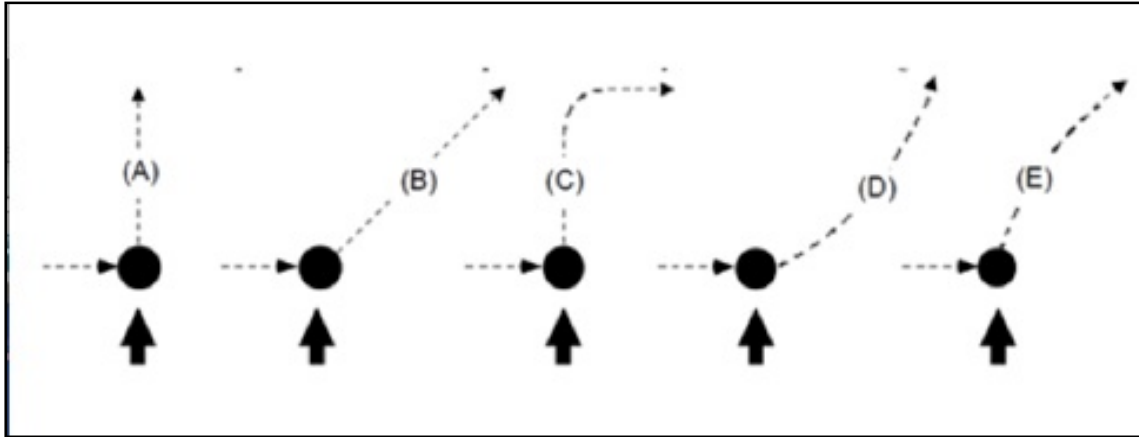
Figure 13. Options in pre- and posttest item on deflections

Discussion

Overall, the current study demonstrates the promise of designing conceptually-integrated games around the Knowledge in Pieces framework in terms of being able to foster, support and investigate conceptual change in the domain of Newtonian mechanics. Specifically, this paper makes two deeply intertwined contributions. The first contribution concerns the design of conceptually-integrated games for learning Newtonian physics and beyond. The second contribution concerns analytical and methodological issues for investigation of students' learning as they interact with conceptually-integrated games or games of other designs. We first explain how both of these dimensions are deeply intertwined because of the Knowledge in Pieces conceptual framework that we have adopted, and then discuss the two contributions separately.

Our pedagogical design emphasizes cultivating learners' *sense of mechanism* (diSessa, 1993) rather than emphasizing a process of simple replacement of one idea with another. As diSessa (1993) argued, cultivating learners' sense of mechanism is of vital importance for fostering conceptual change because the sense of mechanism can "provide a heuristic framework that helps students gradually refine their abilities quickly to develop adequate scientific models

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of situations" (p. 206). Thus, even in situations where learners' initial sense of mechanism may not be appropriate, learners can be scaffolded in refining their reasoning by leveraging other intuitive resources in their conceptual repertoire. While our analyses show Jamal's initial challenges, they also illustrate the gradual process through which the cueing priorities of various conceptual resources adjust, as Jamal engages in progressively more challenging, conceptually-integrated gameplay.

This process was evident in Jamal's iterative attempts in Levels 2, 3, and 4. For example, Jamal uses the same p-prim (*Force as Mover*) inappropriately in his initial attempts in Levels 3 and 4. His revised and successful attempts in these levels, however, still involved the application of the same p-prim, albeit in a different and more appropriate context (from a canonical perspective). Furthermore, as Jamal progressed through these levels, his intuitive conceptualization of deflections also became progressively refined. As explained earlier, this microgenetic case study demonstrates that this process of refinement can be understood in terms of *distributed encoding* (diSessa, 1993). That is, the sense of mechanism becomes progressively more distributed through the activation of additional productive intuitive resources (e.g., *Cancelling* and *Ohm's* p-prims) pertaining to the same phenomenon. It is through this process that Jamal develops a richer and more canonical sense of mechanism for conceptualizing deflections. As his sense of mechanism became progressively more distributed, Jamal was able to identify the roles of both the direction and magnitude of previous velocity in determining the new direction of motion upon application of a new impulse. We therefore argue that conceptually-integrated games can help support and foster conceptual change by supporting learners develop progressively refined intuitive understandings of the target concepts.

Our study has two specific implications for the design of conceptually-integrated games for learning physics. First, we have argued that key representational elements within the game (e.g., dot traces and impulses, in the domain of Newtonian physics) and learners' interactions with them (e.g., placement of impulses to design trajectories) *must be conceptually salient*. That is, these interactions must involve reasoning about the relevant canonical concepts. For example, reasoning about where to place an impulse on Surge's path involves first predicting the trajectory, which in turn involves reasoning intuitively about the speed (and change in speed and direction, as appropriate) of Surge. To this end, as we have argued earlier in the paper, the literature on microworlds in physics education (diSessa et al., 1991; White, 1993; Parnafes, 2007) has useful insights to offer.

Second, our study shows that designers of conceptually-integrated games can foster and support learners' conceptual change by helping them bootstrap their intuitive reasoning about the physical world by (a) designing situations (e.g., game levels) that highlight the contextual boundaries within which specific naïve (i.e., pre-instructional) conceptual resources are productive *and* unproductive; and (b) sequencing the levels so that solving them successfully increases the cueing priority of the relevant productive intuitive resources. Our study suggests that engaging learners in such opportunities supports the development of distributed encoding, and thus leads to the stabilization of productive and appropriate cueing and application of conceptual resources. We believe that future research on designing conceptually-integrated games could build on our work by focusing on designing *longer term* physics curricula integrated with the game that could ideally help learners develop intuitive understandings of more complex ideas in Newtonian mechanics, as well as develop more "formal" representational

practices through the reflective generation of *intermediate abstractions* (White, 1993) during game play.

In addition to implications for game design, our study also highlights the importance and effectiveness of the microgenetic method that involves conducting semi-structured clinical interviews after the successful completion of each game level, as a means of studying short-term conceptual change in game-based learning environments. The methods used in this study successfully identified knowledge structures used by students in various levels of game play in order to trace the evolution of student thinking. We have argued that while think aloud interviews would be appropriate for knowledge analysis, the need to maintain the *flow* of game play would present a potential obstacle toward adoption of that method based on the challenges highlighted by Ericsson & Simon (1998). Furthermore, collecting game-play video uninterrupted by think aloud interviews provides a clean video data source for triangulation with the clinical interview responses. Given the interpretive nature of knowledge analysis of semi-structured clinical interviews, we have argued that it is important to triangulate the analysis of learners' interview responses during the study with their actual game-play video and explanations of relevant phenomena in out-of-game contexts. Conducting the interviews after each successful level completion supports this triangulation because the interviews are still conducted while the game experience is still fresh and accessible to the students. We believe that future research should conduct comparisons, however, between our approach and other clinical and think-aloud protocols for interviewing learners in the context of game play.

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Appendix

Coding Scheme for Conceptual Resources in Game Play

Table A-1

Coding Scheme for Conceptual Resources in Game Play

| | | | Coding | | |
| | | | | Pattern Code | |
P-prim	**diSessa's Schematization**	**Sample Student Response**	**Descriptive Code**	**Salient Situational Elements (SSE)**	**Qualitative Relationship between SSE's**
Ohm's p-prim	"An agent or causal impetus acts through a resistance or interference to produce a result. It cues and justifies a set of proportionalities, such as "increased effort or intensity of impetus leads to more result"; "increased resistance leads to less result." These effects can compensate each other; for example, increased effort and increased resistance may leave the result unchanged."	"I put more force on Surge so that he could go faster and break through the brick."	Student increases the number of impulses acting on Surge to slow it down	1. *Impetus*: Impulse 2. *Effect*: Speed	Direct proportionality
Force as Mover	"A directed impetus acts in a burst on an object. Result is displacement and/or speed in the same direction."	"Surge will travel in the direction she's pushed."	Student places an impulse in the direction facing the "target"	1. *Direction of applied impetus:* Toward the target 2. *Predicted direction of motion*: Toward the target	Sameness

Force as Deflector	"A shove may act in concert with prior motion (momentum) to produce a compromise result, directionally between the two."	"When Surge is moving to the right and she hits a down arrow, she will move diagonally down to the right."	Student places an impulse directed vertically upward in the path of Surge moving horizontally in order to deflect Surge in a diagonal direction	1. *Direction of applied impetus:* Vertical 2. *Direction of previous motion*: Horizontal 3. *Predicted new direction of motion:* Diagonal	Compromise
Cancelling	"An influence may be undone by an opposite influence. Generally involves sequential acts that result in no net effect."	"Surge was moving up, so I used a down impulse to stop him."	Student places an impulse acting in the opposite direction to Surge's motion in order to being Surge to a stop. The magnitude of the newly placed impulse is identical to the initial impulse.	1. *Direction of applied impetus:* Opposite to the direction of motion 2. *Magnitude of the applied impulse:* Equal to the magnitude of the initial impulse responsible for previous motion	Equal and Opposite

CHAPTER IV

MODELING GAMES IN THE K-12 CLASSROOM

Introduction

Science is more than just a body of knowledge that explains the world. It is also a set of

disciplinary practices that are used to generate and refine scientific knowledge (Duschl,

Schweingruber, & Shouse, 2007; Lehrer & Schauble, 2006b; Pickering, 1995). In recent years,

there has been a push in science education to incorporate these practices, such as modeling and

the use of evidence-based explanations into the science classroom (National Research Council,

2011; Windschitl, Thompson, & Braaten, 2008). A growing body of research shows that digital

games can be used as a productive and engaging medium to foster scientific expertise in K-12

classrooms (Clark et al, 2009; Honey & Hilton, 2010; Wouters et al, 2013). Specifically,

disciplinarily-integrated games (Clark et al, 2015) have shown promise in supporting the co-

development of core scientific concepts and representational practices.

In this paper, we focus on the integration of disciplinarily-integrated games (DIGs) with

complementary model-based activities to support the development of scientific modeling in K-12

classrooms. Unlike most 3D immersive game-based environments that involve students in

virtual inquiry activities through compelling narratives and roleplaying, DIGs can engage

students in modeling through interpretation and translation across multiple representations of

phenomena in the game environment to progressively deepen their conceptual understanding

(Clark, Sengupta, Brady, Martinez-Garza, & Killingsworth, 2015; Sengupta & Clark, (in press)).

At their core, games are multirepresentational environments, and DIGs leverage multiple formal

representations as core elements of game play (e.g. crucial information to solve the level may be

communicated through a speed-time graph) and as tools to control the game environment (e.g. appropriate vector combinations must be chosen from the control panel to maneuver an object in the game) (Virk, Clark, & Sengupta, 2015). Research on use of microworlds and simulations in science education shows that the design of multiple and complementary representations of the same phenomenon, for example, dot traces that represent motion spatially, and speed-time graphs that represent motion temporally, can create opportunities for model evaluation through comparison of multiple and competing models of the phenomenon (Parnafes, 2007; Sengupta & Farris, 2012). To this end, we investigate two pedagogical approaches where students created models of motion both within and outside of the game environment. In one approach, model-based inquiries involved the material integration of virtual game play through a physical modeling activity in the classroom, and in another approach, use of a complementary modeling tool using an agent-based computational programming platform.

The digital game used in this study, SURGE NextG, was designed to support the development of conceptual understanding and representational practices in the domain of Newtonian mechanics. Research has shown that students face numerous difficulties differentiating between concepts such as speed, force, distance, acceleration, as well as understanding relationships between these concepts (Halloun & Hestenes, 1985; Larkin, 1981; McDermott, Rosenquist, & Van Zee, 1987). A central difficulty that novice learners face is understanding and representing motion as a process of continuous change (Halloun & Hestenes, 1985; Larkin, McDermott, Simon, & Simon, 1980). For example, students can usually observe differences in speed from beginning to end as an object rolls down a ramp, but are often unable to attribute these differences to a continuous process of uniform acceleration (Dykstra & Sweet, 2009). This difficulty can be addressed by first discretizing an event or process (e.g. an object

moving with uniform acceleration) and then reconstructing the smaller, discrete pieces to develop a model of motion as a process of continuous change (diSessa, Hammer, Sherin, & Kolpakowski, 1991; Sengupta & Farris, 2012; Sherin, diSessa, & Hammer, 1993). We examine two different approaches to integrate such representational experiences with SURGE NextG. Overall, this work shows that creating multiple but complementary representations of the same phenomenon and then translating across them as part of core game activities can meaningfully support the integration of DIGs within the curriculum in a science classroom. We investigate some of the challenges associated with such a pedagogical approach, and identify some ways in which such activities can indeed enrich students' conceptual development.

Background

Modeling and Digital Games

This work is grounded in the "Science as Practice" perspective, which views development of scientific concepts as deeply interwoven with the development of scientific practices (Duschl et al., 2007; Lehrer & Schauble, 2006b; Pickering, 1995). In this view, modeling is a core epistemic and representational practice in the development of scientific expertise (Giere, 1999; Lehrer & Schauble, 2006b; Nersessian, 1999). A model represents some aspect of the natural world and typically simplifies a system in order to highlight certain features of the system. The practice of modeling involves using a model to make predictions and generating explanations about a phenomenon, testing those ideas against data from the real world, evaluating how well the model fits the data and revising the model if necessary. In this way, models have communicative and explanatory power, and the practice of modeling is one of the key endeavors of scientific work (Lehrer & Schauble, 2006b).

Digital games may be a productive and engaging medium to support the development of modeling in the K-12 science classroom (Clark, Nelson, Sengupta, & D'Angelo, 2009; Gee, 2008; Hilton & Honey, 2011; National Research Council, 2009). At its heart, a digital game can be thought of as a model, and users make choices that alter the states of the model. When models and modeling are used as key interactive features within the game, students can build their own models by modifying or constructing central game elements to design game solutions. In this view, gameplay is an iterative process of model exploration and modeling, with users making predictions about their game play choices, observing the results and then revising their predictions based on continuing experimentation (Holland, Jenkins, & Squire, 2003). Digital games for learning science can support these modeling components by engaging learners in generating models during game play and then using the models to explain underlying causal relationships within the phenomenon. As levels within the game become progressively more complex, players must build progressively more nuanced models, iteratively refining their representations within the game. This iterative process of creating and refining representations in modeling can lead to an increasingly sophisticated understanding of the content being represented because the refinement of external representations co-evolves with the refinement of one's ideas (Lehrer & Pritchard, 2002; Lehrer, Strom, & Confrey, 2002).

Conceptually-integrated games are games in which domain-specific concepts are directly integrated into the primary movements and mechanics of the game environment while maintaining an engaging context and narrative for the player (Clark & Martinez-Garza, 2012). These games can provide students with opportunities to develop intuitive conceptual understandings of science. However, they often do not support students in making these understandings explicit. Learners may not feel as if they increased their understanding of

concepts during game play (Anderson & Barnett, 2011), and they often struggle to connect the tacit understanding developed during game play to formalized knowledge in a domain. Thus, conceptually-integrated games are limited in their ability to develop deep scientific understanding in a domain.

In order to address these challenges, conceptually-integrated games can be augmented in such a way to create conditions for students to reason about situations using increasingly complex, domain-appropriate, symbolic representations. Disciplinarily-integrated games (Clark et al., 2015) maintain a focus on conceptual relationships while also incorporating elements of modeling and other disciplinary practices into the core game environment. They can create opportunities for students to mathematize phenomena and symbolize salient aspects of motion and related concepts (Clark et al., 2015). This symbolization is integrated as an essential component of game play and offers a chance for students to supplement their intuitive understandings with more formal, domain-specific terminology and representations.

Creating opportunities for students to reason across multiple forms of representations can support students' modeling experiences in the game. As students progress through the game, they encounter more complex phenomena requiring progressively more complex symbolizations. By reasoning across multiple representations of the same phenomenon, such as dot traces of an object's motion and dynamically-linked, real-time motion graphs, students engage in *progressive symbolization* (Clark et al., 2015; Enyedy, 2005), and develop conceptual and mathematical understandings through abstraction and generalization (Ainsworth, 1999; Kaput, 1989). When students use these complementary representational systems as an essential component of game play, they can develop a deeper understanding of the underlying concepts depicted in the game.

This emphasis on the development of scientific practices during game play stands in contrast to other games that engage students in inquiry more broadly through the use of 3D virtual worlds. For example, games such as *River City, Quest Atlantis*, and *Crystal Island* are games for learning science that are based on immersion in virtual worlds and incorporate basic inquiry activities into game play. A key distinction between disciplinarily-integrated games and these forms of virtual environments lies in the nature of the inquiry activities. While these 3D virtual inquiry worlds offer notable affordances, such as rich visual environments, intricate contexts, and compelling narratives, they often focus on engaging students in inquiry activities by creating identities and roleplaying (Clark et al., 2015; Gee, 2008; Squire, 2011). Often, students are cast as scientists or investigators to solve a mystery by engaging in broad forms of inquiry that center on relatively simple puzzles or tasks (e.g. report a measurement from a radiation sensor in the game). However, these types of games, while offering many affordances for roleplaying and narrative in a scientific context (Gee, 2003), do not usually provide opportunities for students to engage in model-based reasoning. Disciplinarily-integrated games do not attempt to replicate these rich narrative and roleplaying environments of virtual worlds. Instead, they engage students in modeling through a set of disciplinary inscriptions in the game environment in which students interpret and translate across multiple representations of phenomena to progressively deepen their conceptual understanding (Clark et al., 2015; Sengupta & Clark, (in press)).

Multiple Forms of Modeling

Research in science education shows that students make significant advances in their understanding of science by generating and revising explanatory models (Gravemeijer, Cobb, Bowers, & Whitenack, 2000; Hall & Stevens, 1994). The nature of the model is key, and

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constructing models often involves designing representations to highlight certain features or processes, both observable and unobservable, of the phenomena and depicting relationships between these features or processes. Since all representations highlight certain elements of the phenomenon and obscure others, it is helpful for students to engage in model evaluation through comparison of multiple models of the same phenomenon (Lehrer & Schauble, 2010; Lesh & Doerr, 2003). Since different activities and materials have different affordances, designing multiple modeling experiences for the same phenomenon present new opportunities for learning in terms of building connections between the phenomenon and formal representations. Pedagogically, this can involve designing curricula that engages students in generating physical or virtual models outside of the game of certain phenomena so that they can then use the models to reason about the same phenomena within the game.

In this study, I investigate two cases where students in two different classes played a digital game for learning physics and then temporarily left the game environment in order to conduct related model-based inquiries in other environments. These modeling activities were interwoven into the core narrative of the game so that students could connect actions and concepts within the game to actions and concepts in other physical and virtual spaces through use of multiple, complementary representations. For one pedagogical approach, students engaged in material integration of their virtual game play by participating in a physical modeling activity involving materials such as a marble, ramp, ruler and stopwatch. In another, students engaged in virtual modeling activities within a computational programming platform designed to have representational systems complementary to the game. In both cases, students returned to the game environment after completing the modeling activities and engaged in game levels where

they had to use the models they developed in the activities to reason about events within the game.

In both the game and the related modeling activities, the learning objectives for the students centered on Newtonian concepts of distance, speed, acceleration and force, as well as the relationships between these concepts (e.g. the speed of an object represents a change in the distance traveled by the object per time unit; the change in speed of an object per time unit— acceleration—is directly proportional to the amount of force applied to the object). It is well understood that novice learners face conceptual difficulties in discriminating between kinematical quantities, understanding and explaining the mathematical relationships between these quantities, and interpreting concepts and relationships that are represented by a graph (i.e. a speed vs. time graph or a distance vs. time graph of the object's motion) (Halloun & Hestenes, 1985; Larkin, 1981; McDermott et al., 1987). In particular, understanding continuous change in motion can be especially challenging for students. For example, when investigating objects that are moving with uniform acceleration (e.g. a ball rolling down an inclined plane where the speed of the ball uniformly increases due to the constant acceleration caused by gravity), students are often unsure if the ball is accelerating continuously and find it difficult to differentiate between average velocity, instantaneous velocity, and acceleration (Halloun & Hestenes, 1985; Minstrell, 2001). Additionally, students often do not refer to speeding up or slowing down as a continuous process, and instead tend to describe any changes in speed in terms of differences in speed from beginning to end or the relative size of the speed change (i.e. it fell fast) (Dykstra & Sweet, 2009). Dykstra & Sweet (2009) referred to these descriptions of speed as "snapshot" views of motion which gives students a discrete view of motion at any instance in time. These snapshot views reflect an intermediate step for learners between a basic direction-only view of motion

(e.g. it fell down) and a more sophisticated view of motion as a process of continuous change (e.g. it sped up as it fell).

These well-known challenges in learning kinematics can be addressed by designing learning environments that integrate conceptual understanding with the development of representational practices using multiple forms of modeling across multiple representational systems. In this study, we designed two pedagogical approaches so that students could engage in modeling experiences that included various forms of media, materials and representations and could generate multiple models of the same phenomena for purposes of model evaluation and comparison. For the first pedagogical approach, we designed a physical modeling activity to leverage Pickering's notion of the "mangle of practice" where scientists often struggle to get materials and nature to "perform" in the way that they need for their investigations during the process of modeling (Pickering, 1995). This resistance from the natural world leads to a tension between human agency and material agency that can lead to interactive stabilization of scientific knowledge. To engage students in this productive tension, it is crucial to involve students in the *construction* of models, rather than working with models already provided to them (Lehrer & Schauble, 2006a; Schwarz, 2009; Windschitl, Thompson, & Braaten, 2008).

Therefore, the physical modeling activity was designed to provide students with the opportunity to construct a model of a phenomenon, through data collection and generation of a speed-time graph of the marble's motion, while grappling with the material difficulties of modeling and the challenges associated with devising and obtaining measurements. In this design, we hoped that students could develop a deeper understanding of motion as a process of continuous change by engaging in this form of modeling and designing formal (e.g. graphical) representations of speed, and thus be able to use their models to reason about similar phenomena

in the game environment. Specifically, the physical modeling activity was designed so that students would first segment the ramp into distance intervals in order to study the average speed in discrete units and then construct a speed-time graph from their data to show that the average interval speed increased constantly for the entire event.

In the second pedagogical approach, we designed an activity based on agent-based computation where users construct programs to control the behavior of a computational object or agent by providing simple rules (e.g. move forward, turn right). The enactment of the rules through execution of the program causes the agent to move in a computational space. In order to program the agent, learners must think like the agent by engaging in embodied and intuitive reasoning (Danish, 2014; Papert, 1980). The use of agent-based modeling has been shown to help students leverage their own intuitive ideas and representational competencies in order to develop scientific expertise in kinematics (Papert, 1980; Sengupta, Kinnebrew, Basu, Biswas, & Clark, 2013; Sherin et al., 1993). Since simple, agent-level actions can be repeated over time to generate continuous movement from discrete actions, students learn to piece together multiple "snapshots" of motion (Dykstra & Sweet, 2009), where each snapshot corresponds to the movement of the agent during one time interval. In this way, agent-based modeling can support students in developing a view of the changes in speed and position of the agent as a continuous process (Sengupta, Farris, & Wright, 2012), as well as mathematical representations of the agent's motion (e.g. speed-time graphs) that make explicit the pattern of change over time (Farris & Sengupta, 2014). In particular, this activity uses *visual programming* as the mode of computational modeling to facilitate the transfer of students' intuitive knowledge of scientific concepts into workable models that can be evaluated and revised.

To be clear, I am not positioning these two modeling activities against each other in order to determine which one is "better" than the other. These two different modeling activities were deliberately chosen to offer a contrast between forms of modeling activities so that we could investigate advantages and challenges of each one. The goal here is to explore the integration of disciplinarily-integrated games with modeling activities outside of the game, and the designed learning environments represent two reasonable pedagogical approaches to this goal. In this paper, I investigate how both the physical modeling activity and the virtual modeling activity, as enacted by the teacher and experienced by the students, can support the development of concepts that are targeted within the game. To this end, I present a comparison of two forms of modeling with disciplinarily-integrated games and investigate the following questions:

(1) How did modeling activities conducted within the game (SURGE NextG), as well as outside the game, support the development of model-based reasoning in students?

(2) How did the teacher use these modeling activities to support model-based reasoning through classroom instruction?

(3) What were some of the key advantages and challenges of each form of modeling activity?

In the next section, I describe the learning environments and modeling activities in detail in the context of a seventh grade science classroom.

Design of Instruction

The Digital Game Environment

The game used for this study is SURGE NextG, a disciplinarily-integrated digital game for learning physics that is designed to support students in understanding key concepts in Newtonian mechanics through use of prediction and explanation in game play. A primary learning goal of the game is to refine students' intuitive understandings of force and motion by

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having students manipulate the trajectory of a character named Surge through simulated space

and friction environments to complete various missions. The game-play area utilizes multiple

representations, such as the animation of the ship moving across the screen, force diagrams, and

dot traces, in order to help players connect their intuitive understandings with formal physics

concepts and representations. Players position impulses, or boosts, in the game area in such a

way to make Surge move at certain speeds and to direct the ship around different obstacles to a

target (Figure 1). The game engages the player in a predictive solution form, meaning that

players must design the system of impulses ahead of time.
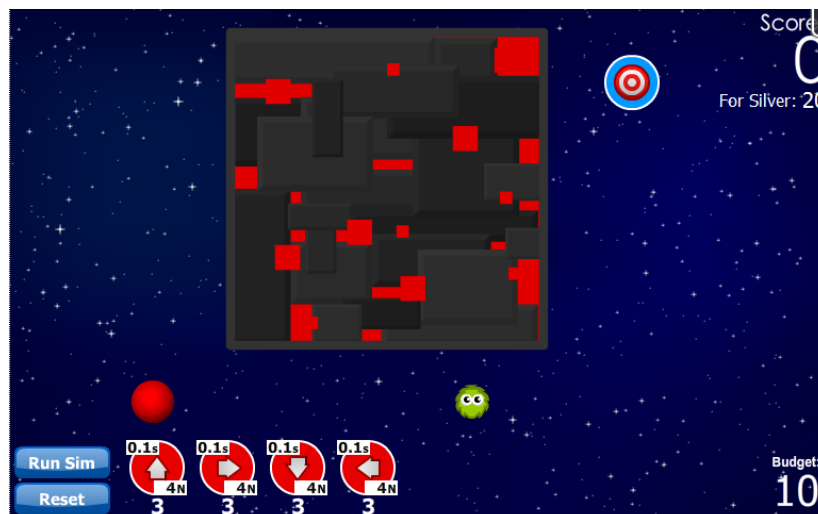
Figure 1. The SURGE NextG space environment

SURGE NextG also includes a graphing interface (Figure 2) that enables mathematical

representations of Surge's motion to be constructed in real time. In this interface, multiple

motion graphs are generated in each level, and students can view all of these graphs (i.e.

position-time, speed-time, horizontal velocity-time) via a drop-down menu. A slider bar on the x-

axis allows students to rewind the level to any point in time and determine Surge's position and
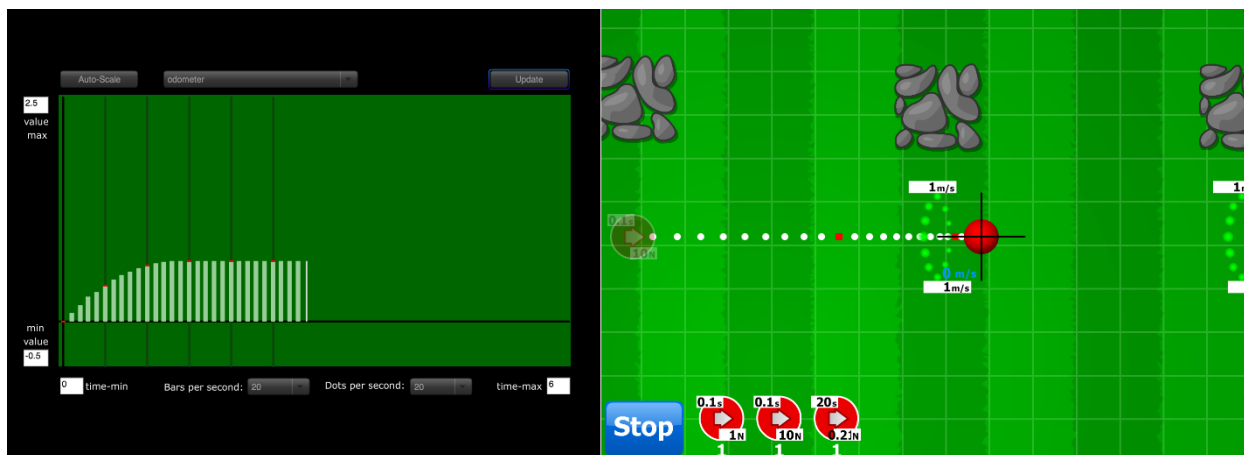
speed at that point.

Figure 2. Surge's friction world (on the right) and the graphing environment in SURGE NextG (on the left)

In SURGE NextG, students take part in modeling through game play by repeatedly engaging in a develop-deploy-revise cycle where they develop a model of motion through prediction of game outcomes, deploy the model by choosing strategic game elements to match the prediction and revise the model when the predicted outcome does not match the actual outcome. Through use of multiple representations of the ship's motion, students further engage in modeling by interpreting and translating across both spatial representations of position over time (e.g. dot traces) and temporal representations of changes in position over time (e.g. speed-time graphs). Levels in the game were sequenced in a way so that students encountered progressively more complex phenomena as they advanced in their game play. For example, early levels consisted of the ship moving only in one dimension, first in a non-friction (i.e. space) environment and then in a friction (i.e. surface of a planet) environment. Intermediate levels consisted of two-dimensional motion in both friction and non-friction environments and also required students to manipulate the speed of the ship in various ways. Advanced levels involved combinations of previous levels, as well as the addition of a mass variable where Surge could change the mass of its ship by picking up space creatures called "fuzzies." Levels featuring the

graphing interface were interspersed throughout the game play sequence, and those graphing

levels were structured in such a way that students had to interact with the graphing environment

in order to obtain vital data to solve the level.

Timeline of the Study

This study involved two seventh-grade classes taught by the same teacher. Each class

spent 1.5 hours per day for five consecutive days engaged in the study, for a total time of

approximately 7.5 hours of instructional time per class. The study spanned a two-week time

frame where activities for Class 1 occurred during the first week of the study and activities for

Class 2 occurred during the second week of the study (see Table 1). For the first three days of

each study, students played through increasingly difficult levels of SURGE NextG, and each

student had access to a computer so that he or she could play the game at an individual pace.

These three days of game play were virtually identical in each class, with the teacher using

similar instructional methods in both classes. At the beginning of each class, the teacher

reviewed main physics ideas that the students had encountered in the game during the previous

day, then she circulated around the room during game play to assist students with difficulties,

and frequently engaged in informal, one-on-one discussions with students by asking them

questions about their gameplay and the underlying physics concepts demonstrated in the game.

The instructional design for each class diverged on Day 4, with Class 1 engaging in a

physical modeling activity and using materials such as a ramp, marble, stopwatch and ruler to

investigate changes in speed of an object. In contrast, Class 2 engaged in a virtual modeling

activity involving a visual agent-based programming language designed to support modeling in

kinematics. On Day 5, each class returned to game play in SURGE NextG, and both classes

engaged in a similar modeling activity within the game in which they used the game as a

modeling tool to design levels to represent the physical and virtual models they had constructed the previous day. The task for Day 5 was similar in each class, with the primary difference between each group being the different modeling activities on Day 4.

Table 1. Activity Timeline of Study

	Day 1	Day 2	Day 3	Day 4	Day 5
Week 1: Physical Modeling Class	Game play with SURGE NextG			Physical modeling activity	Modeling activity within game based on physical modeling activity
Week 2: Virtual Modeling Class	Game play with SURGE NextG			Virtual modeling activity	Modeling activity within game based on virtual modeling activity

Design of Physical Modeling Activity

In Class 1, students engaged in a physical modeling activity on Day 4 where they were given a marble, track, stopwatch and ruler and tasked with investigating the changes in speed of the marble as it rolled down the ramp. Specifically, there were given the following questions/prompts: (1) "Describe the motion of the ball as it rolls down the ramp. What is happening to its speed? (2) What evidence can you use to support this claim about speed? Show all data and measurements that you use. (3) If you were to make a speed-time graph of the ball rolling down the ramp, what would it look like? Draw a sketch of this graph and explain why you drew it the way you did." Students were grouped by the teacher, and each group contained three to four students that worked together at one table with one set of materials. During the activity, the teacher circulated among the groups, asked questions to the groups, and conducted whole-class instruction when she observed common struggles among the groups.

After completing the marble-ramp activity on Day 4, students returned to the SURGE NextG game environment on Day 5 and engaged in a game narrative in which they were asked to help Surge navigate through a nebula that was interfering with communication. In order to successfully guide Surge's ship and follow certain parameters, they received a "clue" from the captain of the ship to help them with their navigational task—a video of a ball rolling down a ramp and then up another ramp until it stopped at its maximum height (Figure 3). This video was chosen because of its similarities to the physical modeling activity from the previous day (the marble rolling down the ramp) and also because this video extended the phenomenon with the ball rolling down one ramp and then up a different ramp. Students were explicitly asked to think about their experience from the previous day when watching the video. Then, they were asked to design a game level (Figure 4) so that the changes in the ship's speed matched the changes in the ball's speed as it rolled down and up the ramps. By successfully designing this level in the game, students could complete their mission to navigate Surge's ship safely through the nebula.

Students used game mechanics to design a trajectory for the ship and to build a model of the rolling ball in the SURGE NextG environment. They then used the game environment to deploy the model, to evaluate its effectiveness at making predictions and to revise the model. Throughout the activity, students were prompted to create and use graphs of the ship's motion when designing their level, as well as make explicit connections between the game level, the video of the ball's motion, and the hands-on activity with the ball by using sketches of motion, graphs of motions, and written explanations of motion. After they had completed their initial level design, students were given another "clue" from the captain in the form of a speed-time graph (Figure 5) that the ship needed to generate in order to safely navigate through the nebula. If necessary, students then redesigned their levels in order to create a trajectory that would

produce a motion graph that matched the given speed-time graph from the captain. Throughout

the task, students were asked to sketch their level designs, including location and magnitude of

boosts used to guide the ship. They were also asked to draw and label the speed-time graph

generated in the game that corresponded to their level design. These written artifacts were

collected as data and used to analyze the performance of students in this modeling activity.
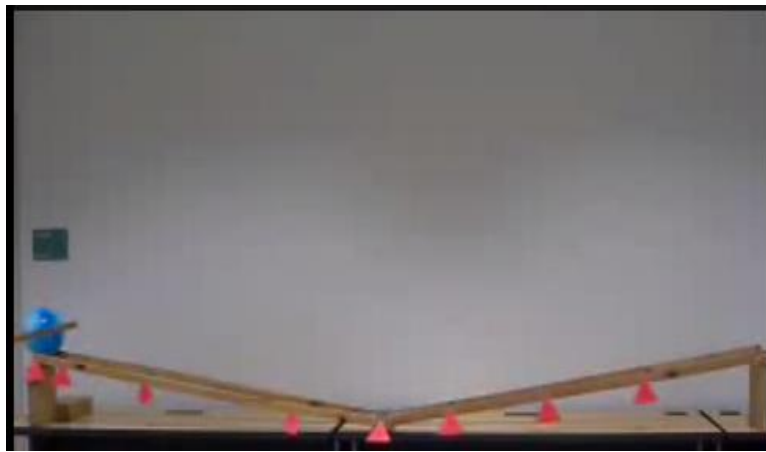

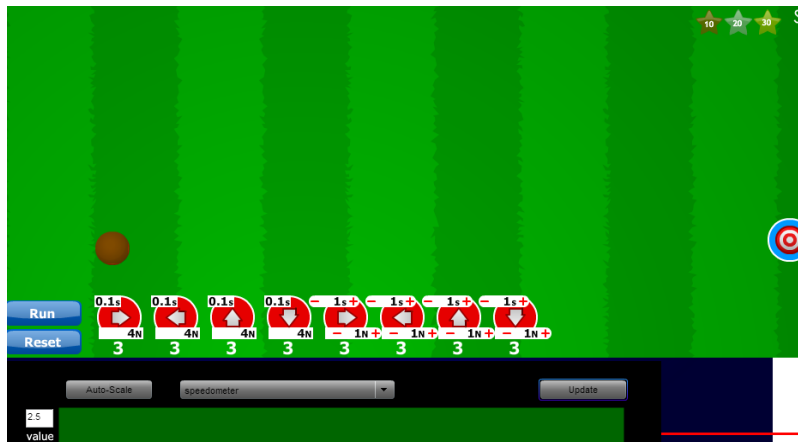*Figure 3*. Video of ball rolling down and up ramp

Figure 4. Level in SURGE NextG for modeling activity
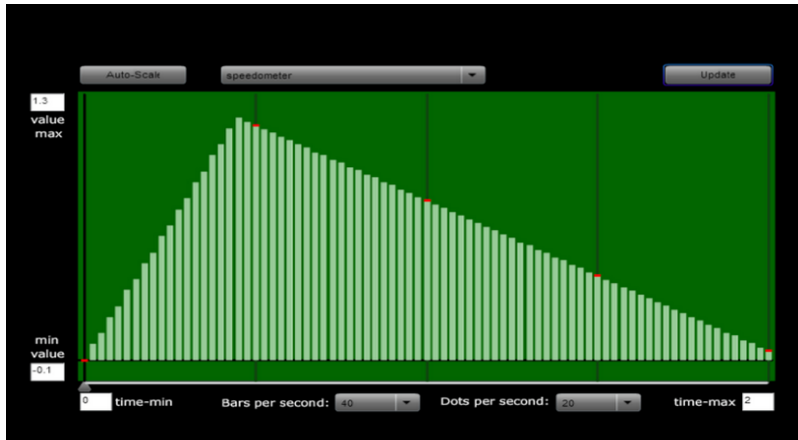
Figure 5. Speed-time graph of ball on ramp

Ideally, in this physical modeling activity with the marble-ramp system, students would make an observation (the marble speeding up as it rolls down the ramp), and then decide what to measure (distance and time), how to measure using the ruler and stopwatch, what to relate (speed = change in distance over time) and how to organize these ideas to make a claim (i.e. realize the need for more sophisticated measurements such as splitting the ramp into distance intervals and making measurements of distance over time in each interval in order to show a *change*, or increase, in speed). We anticipated that there would be difficulties with this activity, especially as students encountered the "mangle of practice" (Pickering, 1995) and grappled with how to create measures of speed for the marble rolling down the ramp (i.e. measuring the time it takes for the marble to roll through each equal distance interval) and with how to relate these ideas to one another in such a way to generate a model of the changes in speed of the marble. However, since modeling is often a practice based on materiality, we felt it was important to select a pedagogical approach that integrated material activities with games in the classroom and provided students with an opportunity to engage in tensions involving material aspects of inquiry and conditions for "seeing" in their investigations.

While there can be much richness in involving students in measurement activities, there are drawbacks as well. Due to the complex nature of the material world, these types of activities often require a significant amount of time to fully develop the model in the classroom. With time at a premium in classrooms, this is often a primary concern for many teachers when deciding what types of activities to include in their instruction. Additionally, since the goal of the physical modeling activity was to use the model created outside of the game in order to reason about concepts within the game, we anticipated challenges in moving from the physical modeling activity, which is situated in a non-representational space, to the game environment, which is located in a representational space with inscriptions (i.e. speed-time graphs). However, it was hoped that providing students with the opportunity to reason across multiple complementary representations (i.e. the game itself, the marble activity with the accompanying speed-time graph, and the ball/ramp video) would help mitigate this challenge. Throughout all modeling activities on Days 4 and 5, there was an emphasis in the design on connecting the physical modeling activity to the game environment.

Design of Virtual Modeling Activity

In Class 2, students engaged in a virtual modeling activity involving *ViMAP*, a visual agent-based programming language based on NetLogo (Wilensky, 1999) that is designed to support scientific modeling (Sengupta, 2011). In this programming environment, students used a drag-and-drop interface to place domain-specific and domain-general programming commands into a "construction zone" where an algorithm was generated to control the movements of a virtual agent. Additionally, these commands generated graphs of the agent's motion that depicted the changes in speed, as well as the changes in distance, of the agent as a function of time. Figure

6 shows the programming interface and the graphing interface. For this study, we designed a version of ViMAP to represent Surge as the computational agent.
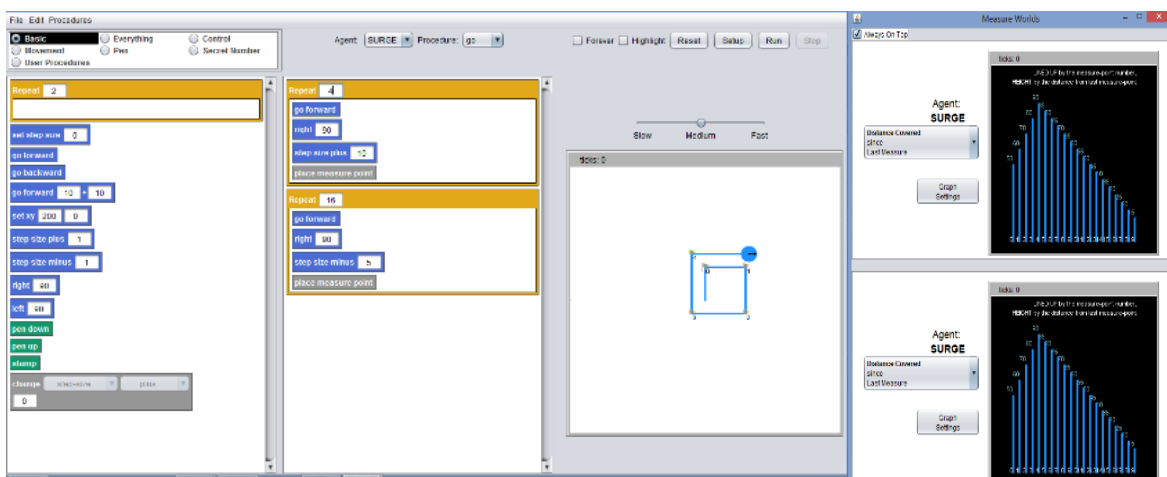
Figure 6. Screenshot of the ViMAP programming environment (left) and graphing environment (right)

In the modeling activity for Day 4, students first created simple programs with ViMAP to familiarize themselves with the programming language (i.e. students programmed the agent—in this case, Surge—to move forward in one dimension). Then, the students programmed the agent to move in specific ways, such as moving at constant speed, speeding up, and slowing down. While analyzing the graph after each activity, students had opportunities to manipulate variables within the program in order to change the shape of the graph. The graphing interface in ViMAP was explicitly designed to be similar to the graphing interface in SURGE NextG so that students would be able to leverage the complementary nature of the representations.

As the last ViMAP activity for Day 4, students were given a printed copy of a speed-time graph. This printed graph was identical in form to the graphs that they were familiar with in the SURGE NextG environment (see Figure 5). They were asked to create a program with the goal of making the Surge agent in ViMAP move in such a way to generate a graph similar to the

printed graph. The next day, students returned to game play in SURGE NextG and were given a similar premise as students from Class 1 (i.e. help Surge navigate through a nebula that was interfering with communication). Students were then asked to design a level within the game so that the ship moved in such a way to produce the same motion graph they had generated in ViMAP (see Figure 5). As in Class 1, students were asked to sketch their level designs, including location and magnitude of boosts used to guide the ship, and also to draw and label the speed-time graph generated in the game that corresponded to their level design. These written artifacts were collected as data and used to analyze the performance of students in this modeling activity.

The virtual modeling activity was designed as a complementary representational system to the game. Representations in the programming environment, such as speed-time graphs, were similar in form and function to representations within the game environment. These complementary representations in the virtual modeling environment made symbols explicit from one system to another. Therefore, we anticipated that it would likely be less challenging for students to switch between two similar representational spaces than in the physical modeling activity where they had to switch from a non-representational space to a representational one. However, unlike the physical modeling activity, measurements were not necessarily addressed in an explicit way, therefore potentially hiding some complexities in measurements. The lack of materiality in the virtual modeling activity meant that the activity required less classroom time, which more easily fits within the time constraints of teachers. However, without a material component to the modeling activity, students were unable to grapple with some of the challenges of measurement in the physical world that are arguably different (and greater) than measurement within a virtual world. Throughout all modeling activities on Days 4 and 5, there was an emphasis in the design on connecting the virtual modeling activity to the game environment.

Methods

Setting

The School. The setting for this study was a public middle school in a metropolitan area in the southeastern United States. This school spanned grades 5 - 8 with approximately 130 students per grade. The school was a high-poverty school with 91% of students classified as economically disadvantaged. It is also an ethnically-diverse school with the student body consisting of 36% Hispanic or Latino, 41% Black or African American, 1% Asian, and 22% White. This school was chosen as a research site because of a prior relationship between the teacher and the research team. Two seventh grade science classes taught by the same teacher, Mrs. W, participated in the study.

The Teacher. Mrs. W was in her second year of teaching at the time of the study. She held a Bachelor's of Science degree in Secondary Education and Math, and was near completion of a Master's of Education degree specializing in Urban Education. She taught both science and math classes at the school. For the students who participated in the study, Mrs. W was their science teacher, as well as their math teacher. Mrs. W was a highly engaged teacher who frequently elicited ideas from her students. She had also recently taken a graduate-level course on scientific modeling as part of her Master's program and was eager to incorporate the practice into her teaching.

The Students. Forty-five seventh-grade students participated in this study. Class 1 consisted of twenty-three students (12 girls, 11 boys), and Class 2 consisted of twenty-two students (11 girls, 11 boys). In each class, four students were nominated by the teacher for focused observations during class time. These observations were in the form of daily semi-structured clinical interviews, as well as recordings of all computer activity via screen capture

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software. These students were selected based on academic achievement levels and their ability to verbally articulate their thoughts during the learning process. Selected students ranged in academic ability from low-achieving to high-achieving.

Researcher-Teacher Partnership. Mrs. W was an active participant in all stages of this study. Before the study commenced, the authors of this paper and Mrs. W met on numerous occasions to map out the study, design levels in the game to accomplish her curricular goals in the classroom, and design the modeling activities so that they could easily fit within the limitations of the physical space of her classroom. We were also sensitive to the amount of time a research study can take, so we strove to find a balance in our planning of the study timeline to give the researchers enough time to collect the necessary data while considering other curricular demands on her time as a teacher. During the study, Mrs. W was actively engaged in all class sessions. She was the sole instructor during game play and the physical modeling activity for Class 1. She was also the sole instructor during game play in Class 2.

Once the study began, the first author attended every class session. Her role in the classroom was primarily as an observer and interviewer, and she did not participate significantly in leading classroom activities. Occasionally, she answered students' questions about the mechanics of the game (e.g. how to advance the screen to the next level) or solved technical issues that arose with the software or equipment. She also conducted semi-structured clinical interviews with the students who were selected for targeted focus. When the students did the physical modeling activity, she assisted the teacher with logistics, such as passing out materials, and interacted with the students when they had questions or difficulties using the modeling tools.

The second author of this paper attended the last two sessions of the study in Class 2. During the virtual modeling activity on days 4 and 5 in this class, Mrs. W and the second author

co-taught the classes, with the researcher serving as the ViMAP "expert" and guiding the students through the tutorial. Mrs. W focused on helping the students interpret their actions in ViMAP and the graphs generated by the program, as well as helped students make connections between ViMAP and SURGE Next G. In both classes, Mrs. W circulated around the room every day while students were engaged in game play or modeling activities and interacted with individuals and groups to probe their understanding of science concepts in the game.

Additionally, since Mrs. W was both the math teacher and the science teacher for these two classes, she was particularly interested in mathematical applications within the game and in the modeling activities. In her whole-class instructional time, she chose to highlight certain features of the graphing environment that helped her accomplish her curricular goals for her math class. Additionally, in many of her interactions with students, she asked students to interpret mathematical relationships between science concepts. This dual interest in math and science was taken into consideration when co-designing levels within the game and co-planning modeling activities to complement the game.

Data Sources

Data sources included video recordings of both whole class instruction and individual student-teacher interactions, as well as audio recordings of each group (3-4 students per table). For the eight students who were the focus of additional observations (four in each class section), Camtasia software was used to record the computer screens of the students, as well as generate video and audio recordings of each student. Additional data include field notes by both researcher and teacher, written teacher reflections, semi-structured interviews, pre-post tests, game play data recorded by the computer, and student artifacts such as drawings, written explanations, and graphs.

During each day of the study, a stationary video camera was positioned in the back corner of the room to capture whole class discussions, along with movements and gestures of the teacher and students. Additionally, another video camera was used during most whole-class instruction and was used to zoom in on student speakers and other interesting facets of instruction, such as drawings made on the white board at the front of the room. During game play days, the teacher carried a handheld action camera and recorded her interactions with individual students. The researcher also circulated around the room with a handheld camera and conducted semi-structured interviews with students. Camtasia software was used to record the computer screens of 4 students per class. This software also captured facial images and vocal utterances of the student using the computer.

During the modeling activities on Days 4 and 5, students generated written work such as sketches and graphs, as well as other artifacts generated within the game, such as typed responses to question prompts. All written work was scanned, and electronic student responses to questions within the game were extracted and compiled in a spreadsheet. Additionally, students in Class 2 also produced several ViMAP programs that were saved locally on the computers. At the end of each day, the teacher recorded field notes that included reflections on successes and challenges of the day, as well as plans for the following day.

Data Analysis

Although multiple forms of data were collected during game play for Days 1-3 in each class, analysis for this paper will focus exclusively on data collected during the modeling activities on Days 4 and 5 in order to investigate our research questions.

Thematic Analysis of Video Data. Analysis to investigate the research questions was done primarily through qualitative analysis of video data, students' written work, and field notes.

Data analysis began by becoming familiar with the data through watching all data videos for each day of the study, examining written student responses and reading field notes by both the teacher and the researchers. For this paper, we were especially interested in the modeling activities on Days 4 and 5 in each class, so we then re-watched the videos for each modeling activity in order to identify interesting episodes that involved teacher or student use of model-based reasoning or seemed to highlight student difficulties with the modeling activity. Then we transcribed all of the video data from the entire study for both classes (i.e. whole-class videos, teacher-student interactions, researcher-student interviews, and Camtasia recordings). Once the videos were transcribed, we then began inductive, thematic analysis (Braun & Clarke, 2006; Miles & Huberman, 1994) of transcripts of the video data to analyze instructional moves of the teacher, student responses during teaching and game play, and student interviews (Strauss & Corbin, 1990). A theme captures aspects of the data that are important in relation to the research question, and represents a patterned response (or meaning) within the data set.

In order to identify these themes, we developed an initial open coding scheme for the data using the constant comparative method and iteratively applied these codes to data, revising codes and grouping codes together as needed. Examples of initial codes are found in Table 2, along with examples of instantiations of the codes in the transcribed data. Additionally, since mathematical relationships among concepts and use of graphs were of particular interest to Mrs. W, specific codes were generated to identify teacher questions relating to mathematics and differentiate those questions from other types of questions.

Once the codes were applied to the data through an iterative process, we searched for themes among codes. Themes that emerged from this analysis centered on student difficulties in the modeling activities, teacher response to those difficulties, connections between the model and

the game environment and use of graphing in each class. These themes are examined in greater detail in the following section, along with a selection of verbal excerpts to represent the data and capture the full meaning of each theme.

Additionally, we examined all whole-class videos to determine if Mrs. W's teaching style was similar across both sections. To do this, we coded all questions that the teacher asked in both classes, as well as student responses to these questions. We found that the teacher used similar types of questions in both classes, and used them with similar frequency. We also found that her questions were sometimes directed toward an individual and sometimes to the whole class. We found no difference in distribution of individual/whole-class directed questions in each class. In general, her interactions with students were very teacher-centric, meaning that verbal utterances in class tended to follow a teacher-student-teacher pattern, with few student-to-student interactions during whole class instruction. This pattern was observed in both classes in the study. We also coded classroom videos for student responses to questions. We observed the students often chorused answers when the teacher addressed a question to the whole class, and found no difference in this type of response between classes. These observations led us to conclude that Mrs. W's teaching style was very similar across both sections and that she did not vary her teaching style significantly when conducting the two different modeling activities.

Analysis of Graphing Activity. In addition to thematic analysis of video data, we also closely examined the written student work completed on the final day of the study. This work included student sketches of level designs for the final in-game modeling activity on Day 5 in each class, as well as the speed-time graphs that were generated in the game to correspond to their level design. First, sketches of the level design were coded for the type of final trajectory of the ship in the game (e.g. straight-line horizontal, straight-line vertical, diagonal, multiple slopes,

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curved, other). Then the final graph was coded for the overall shape of the graph (how closely it matched the target graph), regions of changing speed (speeding up and then slowing down, only speeding up, only slowing down, other combinations of changing speed), and whether or not the graph drawn was a possible outcome of the level design in the sketch.

Reliability. We used the double coding method (also known as the check coding method) described by Miles and Huberman (1994) to analyze and code the video data and graphing data. In this method, two or more researchers independently code data and then clarify their differences until consensus is reached. For this particular study, during the first three months after the completion of data collection, both the authors independently analyzed the videotaped interviews and transcripts and identified a list of salient themes. Over the next four months, the researchers then met periodically several times to compare and negotiate the themes each of them identified and iteratively refined the themes till consensus was reached. The emergent findings were then presented in front of a small audience of researchers in science education at Vanderbilt University, and feedback from this presentation led to further refinement of the codes. During this process of refinement, the authors conducted another round of analysis of the data, in which they independently used the refined codes to re-analyze the entire dataset.

Table 2. Initial Coding Scheme for Video Data

Code	Instantiations of code in data
Teacher makes explicit connection between model and game	- Whenever you're on the grass [in the game], it's always got that 'Step Size Minus' behind it no matter what you do.
Teacher uses or mentions graphs	- What do you notice about the graph? - How did the ship's speed change when the graph went up?
Teacher asks question or makes statement connecting to mathematics concepts	- Let's draw a number line. - It's an inverse relationship.
Teacher revoices student utterances with more formal and/or accurate scientific language	- Student: "The speed is zero point six m s." Teacher: "Zero point six meters per second—that's the speed."
Teacher seeks conceptual clarification or refinement	- What's the difference between force and speed? - What does this N mean?
Teacher seeks warrants and refinements of explanations	- How do you know that? - Can you explain it in a different way?
Teacher seeks quantitative information	- How fast is it going? - Do you need more push or less push?
Teacher connects concepts to tools in game	- How fast do you need to be going to get through this speed gate?
Teacher asking about game elements (clarifying function of game element, NOT connecting tools to concepts)	- What do those green circles mean?
Student uses or mentions graphs	- When the speed went up, the graph went up.
Student makes statement connecting to mathematics concepts	- I went up at an obtuse angle.
Student makes explicit connection between model and game (written or verbal)	- The grass is like 'Step Size Minus.' It's friction, it makes the ship go slower.
Student expresses difficulty with materials or measurements in the modeling activity	- We can't get the ball to stop exactly at one second.

<p style="text-align:center">Analysis</p>

In this section, I present two forms of analysis: (1) a thematic analysis for each class using transcripts of video data, and (2) an analysis of student performance on the graphing task at the end of the study design. Field notes by both the teacher and the researchers were used to support thematic interpretations of the video data. In the thematic analysis, I identify two major themes in each class that help describe the classroom experience for each modeling activity and address my research questions. For the analysis of the graphing task, I identify major differences between the two classes in the types of solutions and graphs generated in the game modeling task.

Thematic Analysis in the Physical Modeling Class

In the physical modeling activity for Class 1, we analyzed the transcription data for patterns among codes and found that many codes for Day 4 centered on student difficulties with conceptual understanding and materiality. Additionally, we found that there were fewer codes in Class 1 relating to connections between the game and the modeling activity than in Class 2. By iteratively grouping and refining codes, two central themes emerged to describe the students' experience in the physical modeling activity. These themes centered on (1) students' struggles in collecting and using data to develop a model of the real-life phenomenon, and (2) difficulties in using the model to reason about concepts within the game. Each of these themes is explained in further detail in this section, along with supporting evidence from the transcripts to illustrate the full meaning of each theme.

Theme 1: Challenges of measurement in physical modeling activity. On Day 4, students in Class 1 engaged in a physical modeling activity with a marble rolling down a ramp as

described earlier in this paper. For this activity, students were arranged by the teacher into seven groups, with each group having three or four students and each group having one set of materials. Each group was located at a separate table and worked together on the modeling activity. Students were first asked to make an observation of what happened to the marble's speed as it rolled down the ramp and then to devise a measuring method to obtain evidence supporting their initial observation. While most students claimed that the marble increased its speed as it went down the ramp, they struggled significantly with collecting data and organizing the data to provide evidence for their claim. They also faced conceptual difficulties when determining whether or not the marble continued to speed up, or accelerate, the entire time it rolled down the ramp. Through thematic coding, three primary difficulties that the students encountered during this activity were evident. These difficulties included (1) decisions about what quantities to measure, (2) splitting the ramp into equal distance intervals, and (3) interpreting the data correctly. Each of these difficulties is described in detail below, along with a description of how the teacher identified and addressed each of the difficulties.

Deciding what to measure. The first difficulty encountered by students involved decisions around what and how to measure. In this activity, students had to decide what quantities to measure (distance and time), how to measure these quantities (with a ruler and a stopwatch) and how to relate these quantities together (speed is the change in distance over time). During this activity, Mrs. W was actively engaged in instruction by walking around the classroom and talking to each group to assess their progress. It was in these informal assessments that Mrs. W. discovered that some students were only measuring time with a stopwatch and using that time as a proxy for speed. An example of this difficulty is described below in Excerpt 1. In this episode, Mrs. W is walking by group 5 when she hears Byron say,

"The speed increases by point ninety seven." This prompts Mrs. W to stop at their table and

engage in a discussion around the meaning of "point ninety seven."

Excerpt 1

1	Mrs. W:	Point ninety-seven what?
2	Melinda:	Speed of the ball.
3	Mrs. W:	How did you calculate the speed?

Byron then describes in detail the method that they used to obtain the speed of the marble

by adjusting adding books underneath one end of the ramp to adjust its height. The group first

measured the time for the marble to roll down the whole length of the ramp with one book

underneath the end. Then they put a second book underneath the end of the ramp—thus

increasing the steepness of the ramp and the speed of the marble on the ramp—and measured the

time for the marble to roll down the ramp again. Byron subtracted the two times to determine the

increase in speed ("point ninety seven"). Mrs. W continued her questioning:

4	Mrs. W.:	What do you mean by the speed? What did you measure that you say this is the speed?
5	Byron:	How fast the ball was going.
6	Mrs. W:	How did you measure that?
7	Byron:	Uh, I don't know. With a stopwatch?
8	Mrs. W:	Can you show me what you did?
9	*Byron repeats experiment where he rolls marble down ramp and measures the time that it takes to reach the end.*	
10	Byron:	OK, 3.03.
11	Mrs. W:	3.03 what?
12	Byron:	I don't know.
13	Mrs. W:	What does the stopwatch measure?
14	Byron:	Milliseconds? Seconds?
15	Mrs. W:	Seconds. So what is the speed?
16	Byron:	3.03 seconds.
17	Mrs. W:	Is seconds a way that we measure speed?
18	Byron:	I don't know.
19	Mrs. W:	Seconds is a measurement of what?

20	Byron:	Time.
21	Mrs. W:	Time. Do you guys remember how we measure speed?
22	Byron:	No. [*others shaking head*]
23	Mrs. W:	(*writing on paper*) Velocity equals d over t. We talked about this. Distance over time.

In this episode, Mrs. W realized that the group measured "speed" with the stopwatch (line 7) and conflated speed and time. Through questioning, she led the group to realize that the stopwatch measures time with a unit of seconds (lines 13-21). She used this opportunity to review the definition of speed (lines 22-23) that they had discussed in prior classes. Upon leaving this group, Mrs. W went to Group 4 and quickly realized that they were having a similar problem by only measuring time and claiming that they had measured speed. She briefly checked in with Group 1 who was having similar struggles. At this point, she identified a common conceptual difficulty among several groups in that the students knew *what* to measure (speed), but didn't know *how* to measure it. She then decided that a whole-class discussion was warranted to address this difficulty. This decision was evident in her reflections in her field notes where she noted that

> "During the first phase of exploration, most groups would time how long it took the marble to reach the end of the ramp (example: 3.03 seconds) and then tell me that the speed was 3.03. After seeing this a few times, I decided to pull the class back together and review the difference between time, distance and speed."

Mrs. W instructional moves as a response to this speed-time confusion are seen below in Excerpt 2. In this episode, Mrs. W was leading a whole-class discussion after pausing the modeling activity.

Excerpt 2

1	Mrs. W:	If I time something, and it comes out and says 3 on my stopwatch, that's what?
2	Several students (*calling out*): Seconds!		

3	Mrs. W:	And seconds is a measure of what?
4	Students:	Time
5	Mrs. W:	OK, now I see a lot of people trying to say, "It took the ball 3.3 seconds, so the speed is 3.3." But *speed* and *time* aren't the same. [Pause] Monica, how do we figure out what the speed of an object is?
6	Monica:	Velocity?
7	Mrs. W:	Velocity is a comparison of what two things?
8	Monica:	Distance and time.
9	Mrs. W:	*(writes equation for speed on board—speed = distance/time)* To find the speed, Terrell, what two things do we need?
10	Terrell:	We need height.
11	Mrs. W:	Well, what two things are literally on the board?
12	Terrell:	Distance and time.
13	Mrs. W:	Distance and time, so just finding the time isn't enough to figure out the speed of something at a certain point. Look at your measuring object there *(gestures to ruler)*. What is it measuring in?
14	Student:	Inches.
15	Mrs. W:	Inches. So *inches* is going to be the distance—the unit of distance that we're using. So any speed that we calculate is going be what per what?
16	Jasmine:	Inches per second.
17	Mrs. W:	*(writes "inches/second on the board)* Inches per second. Literally how many inches does it travel in one second? I saw a lot of people thinking that same thing. If you measure the time it takes to roll down the ramp, you've got a piece of information that's important, but you don't have the whole story. A lot of us are saying, "It's speeding up. The speed [of the marble] is increasing." But I need to know HOW you know that. How can you prove to me that the speed at the top of the ramp is slower than the speed at the bottom of the ramp? That's the task.

In this whole-class discussion, Mrs. W reviewed the definition of speed and emphasized

that *both* distance and time were necessary measurements in order to calculate speed. In this

way, Mrs. W helped students see what quantities they needed to measure and how these

quantities were related to each other. At the end of this discussion, she refocused the students on

the task at hand (line 17) which was to prove that speed at the top of the ramp was slower than

the speed at the bottom of the ramp. This episode highlights student difficulties with deciding what to measure (distance and time), how to measure these quantities using a ruler and a stopwatch, and how to relate these two measurements in order to make a claim about the observable speed of the object. It also highlights an instance where students were using a "snapshot" view of motion (Dykstra & Sweet, 2009) in that students were describing speed only in terms of the differences in speed from beginning to end (e.g. "the speed of the marble is increasing," line 17, Excerpt 2) and were not necessarily viewing speed as a process of continuous change.

Splitting the ramp into equal distance intervals. Once students returned to group work, Mrs. W began circulating among the groups again and questioned them about the method they were devising to prove that the marble was speeding up. Even though Mrs. W explicitly stated in the whole-class discussion that the speed of the marble was different at the top and bottom of the ramp (Excerpt 2, Line 17), students soon encountered a second difficulty. Although all groups were now measuring some type of distance and time, many students were having trouble using these measurements to show that the marble traveled at different speeds at different points on the ramp. A common method at this stage in the activity was to measure the length of the entire ramp and the time that it took for the marble to roll down the ramp. Students then used these two pieces of data to calculate one average speed, where speed is length of the ramp divided by time. Students were then unsure of how to use their speed calculation to prove that the marble was changing speed as it rolled down the ramp.

Transcripts from Mrs. W's interaction with Group 3 illustrate the difficulty that students were having with organizing their ideas to make a claim about the marble's changing speed. This group consisted of 3 students who had taken Mrs. W's discussion of "inches per second"

literally. In Excerpt 3, Mrs. W joined the students as they announced that they had calculated the speed of the marble.

Excerpt 3

1	Tasha:	It goes 13 and a half inches in one second.
2	Mrs. W:	The whole time?
3	*Tasha nods head yes.*	
4	Mrs. W:	So it was going the same speed the whole time?
5	*Derrick shakes head and says, "No." Tasha then begins shaking head no.*	
6	Mrs. W:	You're telling me it was going this speed the whole time. Every inch it takes--
7	Derrick:	That's the distance over time.
8	Mrs. W:	Every second it travels that much? So in half a second, it should go half of that? So you're saying it goes that speed the entire time? [Pause] That's the question I'm asking you. Did it stay the same speed? What does your intuition tell you?
9	Akailah:	I don't know. We just stopped it after one second.
10	Mrs. W:	OH, you STOPPED it after one second?
11	*Group nods yes.*	
12	Mrs. W:	I wonder what would happen in the next second.
13	Akailah:	In two seconds?
14	Mrs. W:	In the next—so after it stopped at one second and got to here (*points to 13.5 in mark on ruler),* do you think it would go 13 and a half again in that next second?
15	Akailah:	It SHOULD.
16	Mrs. W:	So it's going the same speed the entire time?
17	*Group tries to test this idea by positioning the marble at the 13.5-inch mark on the ramp, which is the marble's position at the end of the first 1-second interval, and restarting the marble from rest. They then try to stop it again after one second has elapsed.*	
18	Mrs. W:	Isnt' that kind of tricky? You have to stop it at one second. Is there another way you can take that same concept—you're trying to look at intervals and saying "Second 1, what happens?" and "Second 2, what happens?" Is there another way you could look at it?

In this episode, Group 3 clearly understood that speed was the change in distance per unit time, and they were trying to calculate the number of inches that the marble traveled in one second in order to determine the marbles speed (13.5 inches per second). Mrs. W pushed them to

think about the remainder of the ramp and asked them if the marble traveled this same speed the entire time. Tasha initially answered yes, while Derrick said no. Tasha then changed her answer and began to agree with Derrick that the speed of the marble was not 13.5 inches per second the entire time (lines 3 and 5). Then Mrs. W realized that the group stopped the marble at the end of one second instead of letting it roll down the entire ramp, so she asked the group if the marble would cover the same distance in the next second interval as it did in the first second. Akailah believed that it should be the same speed (line 15), which seemed to contradict earlier statements made by other group members that the marble did not travel at the same speed (line 5). The group decided to make a measurement to answer the question, but instead of starting the marble at the top of the ramp, they repositioned the marble where it was at the end of the first time interval (the 13.5 inch mark) and then released the marble from rest, attempting to stop it again after one second had elapsed and measure the distance traveled.

Although this group had the beginnings of an "interval method" of sorts (i.e. they were comparing speed traveled in one part of the ramp to speed in a different part of the ramp), they did not recognize the need to let the marble travel continuously through the intervals so that it would continuously speed up. This is further evidence that suggests that students did not view motion as a process of continuous change in that they did not seem to think that stopping the marble in the middle of the ramp would affect their measurements of speed in the two intervals. Despite the suggestion of the teacher (line 18), they also held tightly to the idea that they had to stop the marble after each second and measure the distance traveled, which was extremely difficult to do with the tools provided. This group encountered a material resistance when the materials would not "perform" in such a way as to let them make measurements in the way they wanted. There was uncertainty among the group as to whether the marble traveled at the same

speed the whole time, as well as uncertainty about how to structure intervals, how to measure

speed within the intervals and how to interpret that data to make a claim about any changes in the

marble's speed.

Other groups that Mrs. W talked to during this segment of the activity did not fare any

better. In fact, Group 3 was the only group that attempted to construct distance intervals along

the ramp at this point in the modeling activity. Mrs. W interacted with three other groups during

this phase of the activity, and none of the groups demonstrated a valid measurement method that

would prove that the marble's speed increased. At this point, Mrs. W made an instructional move

to manage the conceptual and material difficulties that were apparent to her. She again paused

the activity and led a whole-class discussion with the intent to lead them to the idea of intervals

along the ramp. This decision was evident in her field notes where she noted,

> "After this [first whole-class instruction], students still greatly struggled with how to
> prove the ball was speeding up. So I brought the class together again to see if anyone had
> any methods. I tried to highlight that the students were claiming that the marble had a
> different speed at each point in the graph, so there was a 'slow' top section, a 'faster'
> middle section, and a 'fastest' bottom section of the ramp. And we needed to prove those
> speeds were different."

In this second whole-class discussion, Mrs. W developed the idea of fast-faster-fastest in

relation to the speed of the marble as a way to engage students in conceptualizing speed as a

process of continuous change. She began this segment by drawing a ramp on the whiteboard in

the front of the classroom. She then called on specific students to identify the part of the ramp

where the marble was going the fastest and the part of the ramp where the marble was going the

slowest. Students correctly identified the bottom as the fastest part and the top as the slowest

part. She then asked about the middle section of the ramp and several students called out answers

that indicated that the speed in the middle was faster than the top, but slower than the bottom.

Mrs. W built on this idea of fast-faster-fastest to develop the idea of segmenting the ramp into sections, as evidenced in Excerpt 4.

Excerpt 4

1	Mrs. W:	So you're telling me that [the speed] is changing over time, but we're trying to figure out how we can prove that this [middle] part of the ramp is faster than this part [top], and this part [bottom] is the fastest part. So try to think about different parts of your ramp. [Pause]
2	Mrs. W:	I'm going to picture a football. Imagine that Mrs. W is lined up with Adrian Peterson. And we're going to race. We're both going to run the whole football field. So we're both going to run 100 yards. We have the same distance. Is he going to go faster than me?
3	Students *(calling out):*	YES! Hopefully!
4	Mrs. W:	What does that mean about the time it's going to take him to run the length of the football field compared to my time?
5	Students:	He's going way faster!
6	Mrs. W:	So FASTER is going to take LESS time to run for the distance. So you're saying that he's going to run that 100 yards faster than I am?
7	Students	Yes!
8	Mrs. W:	I'm the slowpoke, so slower, I'm going to take more time?
9	Students:	Yes!
10	Mrs. W:	So think about this. You're saying that Adrian Peterson is faster than me, and he's going to run that distance in a shorter amount of time. How can we use that idea to prove which part the marble is running faster at? How do we compare this part to this part to this part? Terrell?
11	Terrell:	You get a stopwatch. Once it gets to about the middle, you can lap it. Then at the end, stop the stopwatch and see which part went faster.
12	Mrs. W:	Anybody want to add on to that? Confused by that idea? Want to say it's a good idea?
13	*Students are silent, no response.*	
14	Mrs. W:	So Terrell said "if you measure it about in the middle". Terrell, say more about that "about in the middle" part.
15	Terrell:	Like...[pause]
16	Mrs. W:	Does it have to be exactly in the middle or could we estimate?
17	Terrell:	No, it could be an estimate.
18	Mrs. W:	We could estimate the middle and then what would you do?

19	Terrell:	Lap it.
20	Mrs. W:	Lap it. And what would that tell you? You would get a time for the top of the ramp that it took.
21	Terrell:	And a time for the bottom.
22	Mrs. W:	Which time—someone else, I want to make sure we're understanding Terrell's idea—which time would be shorter? The time for the top half or the time for the bottom half? Which time would take less? Would be shorter?
23	Student 1:	Bottom
24	Mrs W:	Bottom? Is that going to be our hypothesis?
25	Students	Yes.
26	Mrs. W:	You said Adrian Peterson is faster than me and it takes him less time, so maybe that marble is going to take LESS TIME for the bottom of the ramp. Is that the idea that I heard?
27	Students:	Yes
28	Mrs. W:	Does anyone have a different idea of how we would prove that it's speeding up? Prove that it's different at each part?
29	*Students are silent, no response.*	
30	Mrs. W:	By the end of the day, I want you to find a way to PROVE it. You're welcome to use Terrell's method or you can use one of your own.

In this episode, Mrs. W developed the idea that the marble was traveling "fast" at the top, "faster" in the middle, and "fastest" at the end. Using the analogy of a race between herself and a professional football player, she illustrated that an object traveling at a "faster" speed is going to take less time to cover the same distance as an object traveling at a slower speed (line 6). She asked students to use the idea of "faster means less time" to devise a method of proving that the speed of the marble changed along the ramp. One student, Terrell, proposed a method to measure the time for the marble to travel from the top of the ramp to the middle of the ramp and then to use the lap function of the stopwatch to measure the time for the marble to travel from the middle of the ramp to the bottom of the ramp (lines 11-12). Mrs. W unsuccessfully attempted to engage other students in discussing this idea, and this idea was held up to the class as a possible solution

for proving the claim. Mrs. W chose to let the class discussion end at this point so that students could return to their group work.

Interpreting the data. Upon return to group work, groups worked on developing a reliable method to calculate the speeds at two different intervals. At this point, only 20 minutes remained in the class. Most groups were able to mark off intervals and obtain time values for each of these intervals during this time, but common struggles again emerged. Some groups did not use equal distances for their intervals and instead thought that the intervals only had to be "close enough." Others were unable to interpret the data from lap function of the stopwatch. For example, one group had pressed the lap function when the marble passed the midpoint of the ramp, resulting in two times reported on the stopwatch: the first time reading represented the time for the marble to travel from the top to the middle of the ramp and the second reading represented the time for the marble to travel from the top of the ramp to the bottom. Instead of subtracting these two time readings to calculate the time of travel through the second interval, the students in this group erroneously used the time for the entire distance as the time for only the second interval. Thus, it appeared that the time for the marble to travel through the top interval was actually *shorter* than the time for the marble to travel through the bottom interval, resulting in a claim that the marble would actually *slow down* as it rolled down the ramp—a direct contradiction to their observation. In this case, difficulties arising from the materiality of the activity (i.e. struggles with properly using the lap function of the stopwatch) led directly to conceptual difficulties in interpreting and organizing the data in a way to support a claim. Mrs. W recognized these difficulties as evidenced in her field notes,

> "Most students told me that the distances that they were comparing didn't have to be the same…The most common errors were not having intervals of equal length and comparing the top interval to the entire distance, rather than understanding and using the lap function [of the stopwatch.]"

Since the end of the class period was approaching, Mrs. W was not able to lead another whole-class discussion to address these problems. Instead, she made an instructional decision to address these problems in a hypothetical way the following day. In her field notes, she stated,

> "For tomorrow, I want to draw a diagram for students of a ramp with equally spaced intervals, and ask them two questions for their warm-up: label what each time interval will be if the marble is constantly speeding up and label what each time interval could be if the marble traveled at the same speed the whole time. We will think-pair-share this question before beginning the modeling activity on the computer."

In summary, the bulk of the physical modeling activity was focused on making measurements and the associated challenges with that task. Mrs. W had to first help students recognize that they needed to measure both distance and time in order to obtain speed. Once students were able to identify what quantities to measure and how to measure them, Mrs. W helped students realize that they needed to split the ramp into segments and make multiple measures of speed in order to show a change in speed over time. Although there was universal agreement that the marble was speeding up, there was less certainty that the marble was speeding up the whole time or that students needed to use segments of equal distances in order to make an accurate speed comparison. Students had significant difficulty obtaining accurate measurements and interpreting data in a correct way to allow them to prove that the marble was speeding up. In the end, although all groups were able to segment their ramp in some way, no group was able to obtain data that supported their claim, and no group was able to construct a graph of the speed of the marble over time or generate a model to represent the phenomenon. Mrs. W's interactions with students were almost exclusively focused on making measurements and developing a credible method for proving that the marble is speeding up, thus showing that the measurement demands of this physical modeling activity were very complex and challenging for students.

Theme 2: Teacher provides model for class and makes connection to game. On Day 5, following the modeling activity with the marble and ramp on Day 4, the teacher began class by addressing the problems that the students encountered during the previous day's activities. She drew a diagram of a ramp on the board with three equally spaced intervals in inches. She then asked students to pretend that they had divided the ramp from the prior modeling activity into three 16-inch sections and timed how long it took the marble to travel across each section if released from rest at the top of the ramp (i.e. time from Point A to B, from Point B to C, and from Point C to D, as seen in Figure 7). She then handed each student a sticky note and asked them to "give an example of how long each interval would take if the marble was consistently speeding up like we said yesterday… If everything had gone well yesterday and we had been able to get those time measurements, how long would it be here (*points to Interval AB*), here (*points to Interval BC*) and here (*points to Interval CD*)."
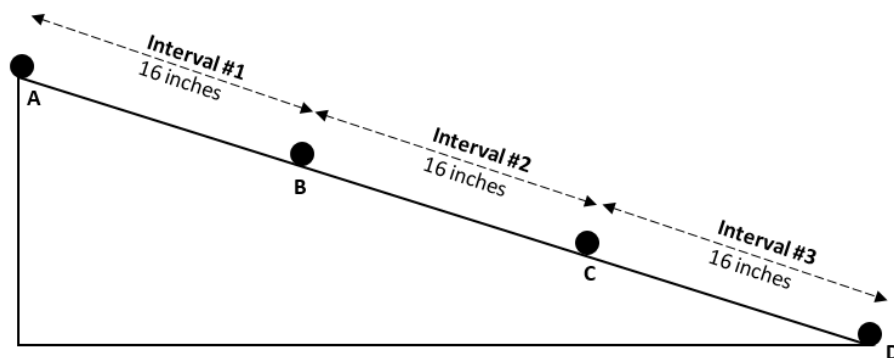

Figure 7. Diagram of marble-ramp system

After the students wrote their answers down, Mrs. W led a class discussion to establish which interval will have the longest time [Interval 1 in Figure 7] and which interval will have the shortest time [Interval 3 in Figure 7]. She then connected time to speed by pointing out that a longer time means a slower speed and shorter time means a faster time for equal distance

intervals. To further illustrate this connection between speed and time, she asks students to consider how to represent the speed of the marble using a graph. This was the first time that graphs were mentioned in the physical modeling activity. This discussion can be seen in Excerpt 5.

Excerpt 5

1	Mrs. W:	So [the marble] is speeding up the whole time. If I were to make a speed-time graph, and here's my time in seconds (*draws x-axis and y-axis on the board and labels x-axis as "time" and y-axis as "speed"),* and I start here (*points to origin of graph)*, what is my graph going to look like to represent that the speed is bigger every second?
2	Student 1:	It's gonna go up.
3	Mrs. W:	It's gonna go up? So if I were drawing a bar and my first bar was here (*draws bar of arbitrary height)*, would my second bar be the same, lower or higher? (*draws a taller bar next to the first bar)*
4	Chavon:	Higher.
5	Mrs. W:	And then what about the next second? (*draws a taller bar next to the second bar)*
6	Chorus of students: Higher.
7	Mrs. W:	And then?
8	Chorus:	Higher.
9	Mrs. W:	So this [graph] matches this (*points to diagram of marble rolling down ramp).*

In this excerpt, Mrs. W revisited the graph that they were supposed to generate the previous day at the end of the marble-ramp modeling activity. Since no student was able to design an appropriate method to prove that the marble was speeding up, no one was able to generate any type of speed-time graph. Therefore, Mrs. W led the students in creating a graph to represent the speed of the marble by asking students to think about the explicit connections between increasing speed and the height of the bars. In this way, Mrs. W provided a model for the previous day's activities that students were unable to generate on their own.

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After this class discussion about the marble-ramp activity, students then proceeded to play a game level of *Surge Next G*. This level was specifically designed to parallel the modeling activity in that students needed to design a trajectory for the ship that produced constant acceleration, similar to the constant acceleration experienced by the marble. In order to support students in thinking about the link between force, time and speed, the level contained three speed gates that the ship had to pass through to get to the target. The ship could only pass the speed gate if it was going at the speed labeled on the gate, and would explode instantly if the ship's speed was too fast or too slow. Students controlled the speed by adjusting the force magnitude and the time duration of the boost, and a speed-time graph was generated in real-time as the ship moved across the screen. The game level can be seen in Figure 8 and the corresponding speed-time graph for a successful completion of the level can be seen in Figure 9.
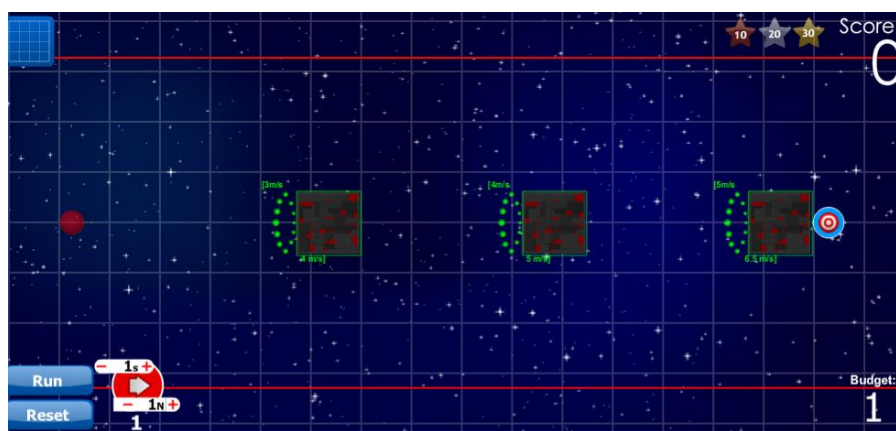

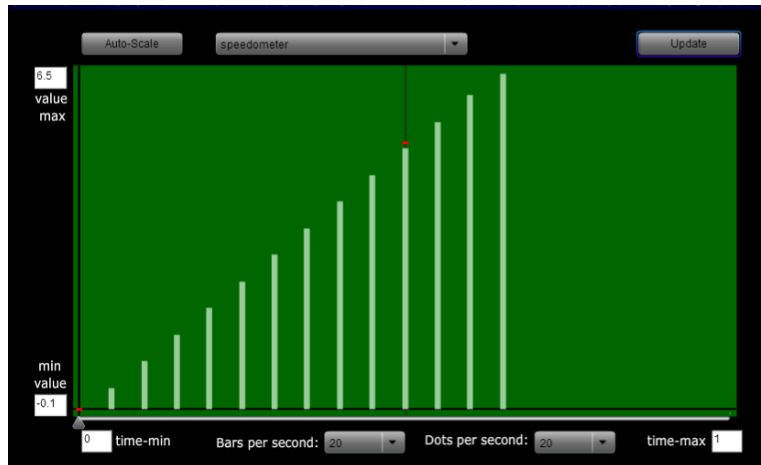*Figure 8*. Screenshot of Level 1 in SURGE NextG for Day 5, Class 1

Figure 9. Corresponding graph for Level 1 on Day 5, Class 1

While students were playing this level, Mrs. W circulated around the room, frequently stopping to talk to students about the level and probe their understanding of the underlying physics concepts. She primarily asked questions concerning general speed trends (i.e. Was the ship traveling too fast or too slow? Did you have too much force? What happened to your speed over time?) and the purpose of the speed gates. When the ship was not going at the correct speed, Mrs. W would often prompt students to look at the graph as a way to determine the speed of the ship and whether the speed needed to increase or decrease. The graph was positioned as a useful tool to help the students figure out how to solve the level. There was no discussion of how the graph was made or how changing variables such as force and time would alter the shape of the graph.

Once most students had successfully solved the level, Mrs. W led a whole class discussion to make connections between the marble-ramp modeling activity and the game level. This discussion is seen in Excerpt 6.

Excerpt 6

1	Mrs. W:	What is the similarity between the marble yesterday and the ship that you had to get through the three speed gates in space. What did the graph look like? Tamara?
2	Tamara:	(inaudible)
3	Mrs. W:	It had a lower time at the bottom? A lower speed? (*begins drawing graph axes on board next to graph of marble's speed from earlier in the class.*) Tamara, can you come here and sketch what your graph looks like? I want you all to compare your [graph] to Tamara's [graph] and see if you had something similar happen. And make sure you put those numbers.
4		*Tamara draws speed-time graph on board from game level and writes speed values for each bar that she draws.*
5	Mrs. W:	So what's similar about those graphs (*points to marble speed-time graph and Tamara's speed-time graph from the game*)? What is similar between Tamara's graph and the graph of our marble going down the ramp?
6	Derrick:	It sped up over time.
7	Mrs. W:	Tamara, what did you notice about your numbers and how your numbers went up over time?
8	Tamara:	They started off slowly and got faster.
9	Mrs. W:	I'm going to read off the numbers from her speed and see if we notice anything. She has 0.4, then 0.9, then 1.4, then 1.9, then 2.4, then 2.9. Is there a pattern of how the speed goes up every time? How much does the speed go up every time?
10	Student 1:	Five-tenths.
11	Mrs. W:	Five tenths. So it's going up the same amount. What would the next bar be?
12		Students shout out various answers such as 3.3, 3.2, 3.4
13	Mrs. W:	I think it would be 3.4 if we're following our pattern. What made it speed up? Why was this speed constantly going up? What did you have to do with your boost? Joseph, Byron, what did you have to with your boost to make it go through?
14	Joseph:	You had to speed the time up.
15	Mrs. W:	So you had to push it for longer?
16	Joseph:	You had to put the bottom on 3 and the top on 1.5.
17	Mrs. W:	So he used 3 *Newtons* on the bottom and 1.5 *seconds* on the top. So you had a force that was acting on it—it was pushing on it for 1.5 seconds. Does anyone have a different amount of seconds on their picture?

18	Tamara:	3 seconds.
19	Mrs. W:	So she had 3 Newtons for 3 seconds. The thing is--it was pushing. It didn't just give it a little push did it? What does that number of seconds mean? We're pushing on it for quite a bit of time…There's something that's pushing the ship. Think about the marble. Why did the marble get faster? No one was pushing the marble.
20	Joseph:	The way the ramp was set up.
21	Mrs. W:	OK, but what was pushing the marble?
22	Student 2:	The force?
23	Mrs. W:	The force of what?
24	*Students call out various answers:* The ramp, the weight, the air.
25	Mrs. W:	*(Mrs. W holds up marble in air)* What's going to happen when I let go?
26	Student 3:	Gravity will pull it down.
27	Mrs. W:	What pulled it down?
28	Chorus of students: Gravity!
29	Mrs. W:	What was the FORCE that pulled it down?
30	Students:	Gravity!
31	Mrs. W:	What was the force that made the marble roll down the ramp?
32	Students:	GRAVITY!
33	Mrs. W:	And does gravity stop?
34	Students:	No!
35	Mrs. W:	So is gravity pushing it at the beginning and the middle and the end?
36	Students:	Yes!
37	Mrs. W:	What made it speed up?
38	Students:	Gravity.
39	Mrs. W:	Gravity made it speed it. So what we're doing in the game is a *model* or a *representation* of things that happen in real life. In real life, we have gravity. In the game, we have our boosts. And our boosts represent forces. So what we're doing in the game is a model of something that actually happens. If you put a force on something for a couple of seconds, what's going to happen to its speed?
40	Students:	speed up.

In this discussion, Mrs. W explicitly drew parallels between the marble-ramp activity and the game environment. She asked students to compare the marble's speed-time graph to the ship's speed-time graph, and physically displayed the two graphs side-by-side on the board (see Figure 10) so that students could see that the shapes of the graphs were the same (lines 3 - 5). She used student data from the game to identify patterns in the changes in speed of the ship and then asked students to make a prediction of what the next speed value in the pattern would be (lines 7 - 13). In Lines 19-39, Mrs. W made further connections between the game and the real world by linking the mechanism for speeding up in the game (boost applying force to ship) to the mechanism for speeding up in the marble-ramp activity (gravity as a force on the marble). In this way the teacher paid a pivotal role in providing the "correct" model for students in the form of a speed-time graph and drawing analogies between model, real world and game environment.

Figure 10. Speed-time graph for the ship in the game (left) positioned next to the speed-time graph for the marble (right)

Students then returned to the game to play Level 2. In this level, students engaged in a game narrative in which they were asked to help Surge navigate through a nebula that was

interfering with communication. In order to successfully guide Surge's ship and follow certain parameters, they received a "clue" from the captain to help them with their navigational task—a video of a ball rolling down a ramp and then up another ramp until it stopped at its maximum height (see Figure 3). This video was chosen because of its similarities to the physical modeling activity from the previous day (the marble rolling down the ramp) and also because this video extended the phenomenon by also having the ball roll down one ramp and then up a different ramp. Students were explicitly asked to think about their experience from the previous day when watching the video. Then, they were asked to design a game level (see Figure 4) so that the changes in the ship's speed matched the changes in the speed of the ball rolling down and up the ramps. By successfully designing this level in the game, students could complete their mission to navigate Surge's ship safely through the nebula. After they had completed their initial level design, students were given another "clue" from the captain in the form of a speed-time graph (see Figure 5) that the ship needed to generate in order to safely navigate through the nebula. If necessary, students then redesigned their levels in order to create a trajectory that would produce motion graphs that matched the given speed-time graph from the captain.

While students were completing the level, Mrs. W again circulated around the room, stopping to discuss physics concepts in one-on-one discussions with various students. As in Level 1, most of Mrs. W's conversations centered on helping students identify general speed trends of the ball in the video (i.e. the ball started out slow, sped up and then slowed down). An example of this type of discussion can be seen in Excerpt 7 with Mrs. W's conversation with Jasmine about Level 2.

Excerpt 7

| 1 | Mrs. W: | What happened to ball on ramp? |
| 2 | Jasmine: | It was going up, and then it was going down. |

3	Mrs. W:	The ramp?
4	Jasmine:	The speed.
5	Mrs. W:	So the speed increased and then got slower?
6	Jasmine:	Yeah.
7	Mrs. W:	That's all you want to do. You can go from here. Just make the ball increase in speed and decrease in speed.
8	Jasmine:	But how?
9	Mrs. W:	What would you do in terms of boosts to make it go faster?
10	Jasmine:	I thought you had to do it like—
11	Mrs. W:	—it doesn't have to go up and down like the ball did. The *speed* has to match. The motion doesn't have to match.

In Excerpt 7, Jasmine was trying to make the ship's trajectory match the path of the ball (Line 10-11). Mrs. W refocused her on the changes in the ball's speed. Jasmine qualitatively understood that the speed increased and then decreased, but was unsure of how to make the ship replicate that motion (Line 8). Mrs. W only focused Jasmine on the general changes of speed. There was no discussion of how much to speed up or slow down, how to change the slope of the in-game graph to match the slope of the target graph, or how to make the ship stop at the target as depicted in the given speed-time graph. In this instance, Mrs. W directed Jasmine toward a simplified model of the speed-time graph that only focused on increasing speed and then decreasing speed and did not focus on proportionality between the force and the changes in speed.

There was not enough time at the end of Level 2 for Mrs. W to engage in a whole-class discussion about the level as she had done for Level 1. Instead, Mrs. W's sense of how her students fared with the activity came exclusively from one-on-one conversations with the students. In her field notes at the end of class, Mrs. W writes,

"In terms of the friction level, I think the connection to the ramp was shaky at best. Students could easily articulate what had happened to the speed of the ball over time, and then could describe what they wanted the ball to do…I noticed that many students did not

pass that level because they did not speed up and slow down in the correct proportion. Their slow down was right before the target and really rapid, or their speed up was a lot steeper than the slow down, etc. So the symmetry of the speed wasn't really mimicked. At the end, we tried to point out that the force which made the ball in the game move is a model for the forces which act in the world."

Mrs. W recognized that most students did not make the connection between one of the mechanisms of slowing down in the game (i.e. friction) and the mechanism of slowing down in the video (i.e. gravity). She also noticed that although students could easily identify that the ball sped up and slowed down, they had no real understanding of how to alter the variables in the game, such as the force and time duration of the boost, in order to change the shape of the graph.

In summary, since the majority of the physical modeling activity on Day 4 was focused on making measurements and not developing a model of the phenomena, Mrs. W had to provide the model for the students on the next day. She drew the correct speed-time graph for the marble on the board and explained to the students how she got it, highlighting speed as a quantity that was constantly increasing. She drew explicit connections between mechanisms in the game for speeding up (boosts) and mechanisms in the real world for speeding up (gravity). When students returned to the game environment to play a level based on the marble-ramp activity, Mrs. W. again make specific efforts to point out parallels between the marble's speed-time graph and the ship's speed-time graph. She did not have time to draw the same parallels between the final friction level in the game and the video of the ball rolling down the ramp, and, as a result, she felt that very few students were able to connect the game to the video by themselves. Without the teacher explicitly providing the model to the students and providing connections between the game, the modeling activity, and the real world, students struggled to make these connections themselves. Students in this class also interacted with the graphs in a very limited way, focusing primarily on general changes in speed such as speeding up and slowing down. There was no

discussion during the physical modeling activity or the following game activity about how to change variables in the game or real world to alter the shape of the graph.

Thematic Analysis in the Virtual Modeling Class

In the virtual modeling activity for Class 2, we examined transcription data and looked for patterns between codes. We found that the codes for Class 2 indicated a greater frequency of connections between the model and the game, and these connections were made by both the teacher and the students. Additionally, we found that there were significantly more codes generated in Class 2 to identify instances of the use of or mention of graphs in Class 2 as opposed to Class 1. One theme that emerged from this analysis of codes centered on connections made by the teacher and students between commands in ViMAP, actions in the game, and physical concepts represented in each environment. Another theme found in the virtual modeling class was an emphasis on the generation and interpretation of graphs both in the ViMAP environment and the SURGE Next G environment. Each of these themes is explained in further detail in this section, along with supporting evidence from the transcripts to illustrate the full meaning of each theme.

Theme 1: Connections between ViMAP, Surge Next G, and physical concepts. On Day 4, students in Class 2 engaged in a virtual modeling activity as described earlier in this paper. For this activity, students each had access to a personal computer and worked individually to write programs in ViMAP. The second author of this paper and Mrs. W worked in tandem to lead students through a tutorial process so that students could create programs to make the object move at constant speed, make the object speed up, and make the object slow down. In ViMAP, the "object" was designed to look like the space ship in the game and was verbally referred to as "the ship" during the modeling activity. Throughout this tutorial process, both Mrs. W and the

researcher continually prompted students to make connections between commands they were using in ViMAP and actions in the game. In each new command that students learned, connections were made to physical concepts such as distance, speed, and change in speed. For example, in ViMAP, the command *Step Size* represented the distance traveled in one time unit, or the speed of the object. If a student used the command *Set Step Size 50,* the object would move forward 50 units of distance in one second of time, representing a speed of 50 units/seconds. Using an additional command of *Step Size Plus* then made the object speed up (e.g. continuing with the previous example, a command of *Step Size Plus 10* would make the object first travel at 50 units/second, then 60 units/second, then 70 units/second and so forth). In a similar way, the *Step Size Minus* command is used to slow down an object in ViMAP.

In Excerpt 8, the *Step Size Plus* command was introduced to the class, and the researcher led a discussion about the role of *Step Size Plus* both in ViMAP and the game. The students started with an initial step size of 50, and then used the *Step Size Plus 10* command to increase the speed of the object by ten units per second.

Excerpt 8

1	Researcher 1:	What does *Step Size Plus* do? [students are silent and offer no response]
2	Researcher 2:	What happens when you say plus?
3	Unidentified students: You're adding. It goes up.	
4	Researcher 2:	So what is it going up by every time, plus what?
5	Students:	Ten
6	Researcher 2:	So every time, you're adding how much?
7	Students:	Ten
8	Researcher 2:	Does that make sense? Every line and every repeat, it's setting step size plus, which you've all told me means add. Adding 10 more.
	…	
9	Researcher 1:	Let me ask you about the speed of the ship. Is the speed of the ship the same in each turn?
10	Student 1:	No

11	Researcher 1:	No. Why not?
12	Student 1:	Because it goes up by 10 each time.
13	Researcher 1:	The speed is changing by 10 each time, right? There are 2 really important lessons here. *Step Size* in the program is the speed of ship in SURGE. Does that make sense? *Step Size* in the program is like the speed of the ship in SURGE. And *Step Size Plus* is when you're giving it a boost. Does that make sense?...*Step Size Plus* is change in speed. That's how much you're changing speed. In SURGE, what happens? How do you change your speed?
14	Student 2:	Add one of those circle things.
15	Researcher 1:	And what are the circle things?
16	Student 3:	You have to add a Newton.
17	Researcher 1:	And what's a Newton?
18	Student 3:	Force.
19	Researcher 1:	Yes, you add a force, and what happens when you change the speed?
20	Student 4:	It goes faster, sometimes it goes slower.
21	Researcher 1:	It goes faster, sometimes it goes slower depending on how what the force is, right?

In Excerpt 8, the students were trying to make sense of a new command that had just been introduced, *Step Size Plus,* and how the motion of the object was different with this new command than with the old command of *Step Size.* To facilitate this understanding, the researchers explicitly connected the speed of the ship to the command *Step Size* in the program (line 13) and also connected the *Step Size* command in ViMAP to the speed of the ship in SURGE NextG (line 13). Furthermore, they also drew parallels between *Step Size Plus,* speeding up in ViMAP, and speeding up in the game (line 13). When one student responded that "one of those circle things" (line 14) was responsible for changing the speed of the ship in the game, the researcher pushed the student to explain further until the students identified the "circle things" as Newtons (line 16) and later force (line 18) that could either make the ship go faster or slower (line 20). In this way, connections between commands in ViMAP responsible for changing speed

were directly linked to mechanisms within the game environment that were also responsible for changing speed.

Later in the modeling activity, after *Step Size Minus* had been introduced as a way to slow the ship down in ViMAP, Mrs. W led a whole-class discussion (Excerpt 9) to analyze the graph that was generated by the *Step Size Minus* command, and she also connected the shape of this graph to mechanisms in the game for slowing the ship down.

Excerpt 9

1	Mrs. W:	The speed [of the agent in ViMAP] is decreasing as evidenced by the fact that these lines [on the graph] are getting shorter and shorter. We're covering less distance. So if you're going slower, you're not going to get quite as far. Is that true? [Pause] Think about it. If you run really fast, and you have 10 seconds to run really fast, which will get you farther—if you run as fast as you can or if you just kind of do an old lady jog. Which one will get you farther?
2	Several students *(calling out):*	As fast as you can!
3	Mrs. W:	As fast as you can. *(Gestures to the first line of the shape generated in the enactment area of ViMAP).* This is as fast you can, it's going to get your farther. And then every time, you are slowing down, till eventually you're that old lady on the track who's running like this. And you don't get very far every time you take your little step. So this is related—the length of those lines [in the ViMAP graph] is related to how the speed of the ship is changing. What do you think on the game might have happened to get the speed of your ship to decrease? Raise your hand. What would get the speed to decrease? Damian?
4	Damian:	Opposite forces.
5	Mrs. W:	So you have forces in opposite directions. What else might make your speed decrease over time?
6	Damian:	That fuzz!
7	Mrs. W:	Oh, if you picked up a fuzzy.
8	Damian:	Yeah.
9	Mrs. W:	There's one more case. I'm looking for one more thing that will get your speed to slow down over time.
10	Natasha:	Friction!

11	Mrs. W:	Say it again, Natasha.
12	Natasha:	Friction.
13	Mrs. W:	So what happens if you're on the grass? It slows down.

In Excerpt 9, Mrs. W linked the graph and the game to another complementary example of real-world motion in which she asked the students to imagine running fast and running slow (lines 1 and 3). She also explicitly linked the model developed in the computer program to the changes in speed of the ship in the game, and she asked the students to identify actions within the game that could possibly generate a similar graph by decreasing the speed of the ship (line 3). Damian identified a method of using a force in the opposite direction as a way to slow the ship down (line 4). He also recognized that the ship could also decrease in speed when it picked up a fuzzy (line 6) and increased its mass, therefore resulting in a lower speed due to conservation of momentum. Mrs. W pressed for one final way to slow the ship down, and Natasha identified friction as a mechanism in the game for decreasing the ship's speed (line 10). This method of decreasing speed likely was of particular importance to Mrs. W as she knew that the students would have to use friction as a way to slow the ship's speed in the modeling activity slated for the next day, so she may have purposefully pressed the students for this answer.

Not only did Mrs. W and the researchers identify explicit connections between ViMAP and SURGE NextG in the modeling activity on Day 4, but in later game play on Day 5, students also took up this language to connect symbols in the game, commands in ViMAP and physical quantities when explaining how they designed their model in the game. It is useful to look at the case of Christopher to illustrate this student take-up. Christopher designed a level in a friction environment so that the ship's motion produced a graph similar in shape to the target graph he was given as a clue (see Figure 11). This was the also similar to the graph that he created in ViMAP on Day 4. In an interview with a researcher after he had built his model in the game

environment, Christopher was asked to explain his design choices. He placed a boost directed to the right in order to move the ship forward (Figure 11). He adjusted the time duration of this right boost to one second and the force magnitude to 3 Newtons in order to make the ship speed up. In addition to using friction as a mechanism for slowing down in the game, he also placed a boost directed in the opposite direction with a time duration of 2.5 seconds and a force magnitude of 1 Newton in order to make the ship slow down gradually over a longer time interval.
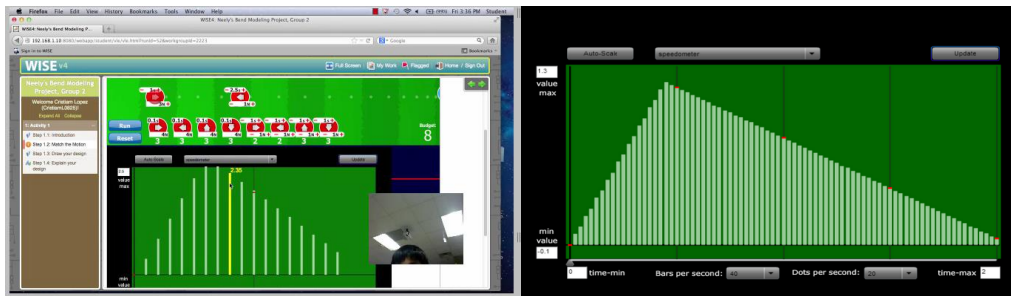

Figure 11. Christopher's designed level in SURGE Next G (left) and the target graph (right)

In Excerpt 10, Christopher explained why his model was a good fit for the speed-time graph that he was trying to replicate, and he made direct connections between the ViMAP and game environments.

Excerpt 10

1	Christopher:	Right here, what Mrs. W said, the grass is like *Step-Size Minus*. It's friction, it makes the ship go slower. This [left arrow] would actually combine with the friction to make the ship go slower.
2	Interviewer:	What was the command in the program for to slowing down?
3	Christopher:	Step Size Minus.
4	Interviewer:	What was the command for speeding up in the program?
5	Christopher:	Step size plus.
6	Interviewer:	So what is *Step Size Plus* here?
7	Christopher:	The force. This is like the direction—what was it, it showed something…direction, 90.

8	Interviewer:	Right 90. What does Right 90 do?
9	Christopher:	Right 90 moves the arrow where the ship is going to go…This is what's going to make it go faster [points to right boost]. Like right here [pointing to individual bars in graph], the ship is going, uh, like this is the speed up. The speed is going up, and then this and the friction is what makes the ship go slower.
10	Interviewer:	What does right 90 do in the program?
11	Christopher:	Right 90 makes the direction of the ship turn…If it were 180, the ship would go to the other side, the direction would be the other side.

Here, Christopher makes clear connections between ViMAP and SURGE NextG by drawing parallels between elements in VIMAP and elements in the game. For example, Christopher correctly identifies friction and the left-directed force as serving the same roles in the game as "step-size-minus" did in ViMAP (Line 1). Both elements served to slow the ship down. He also connects the force in the game to the "step-size-plus" command in ViMAP that caused the ship to speed up (line 6). He further connects the two environments by linking the directional arrow in ViMAP (Right 90) to the directions of the arrows on the boosts in the game (line 9). Christopher demonstrates an understanding of physics concepts in SURGE NextG that seem to be clearly connected to the concepts he explored in ViMAP.

Another example of a student taking up the language of ViMAP to explain actions in the game can be found with Javier. Javier was unique in that he was interviewed by both Mrs. W (Excerpt 11) and a researcher (Excerpt 12) after completion of the modeling level in the game on Day 5. Javier also successfully completed the in-game modeling activity by designing a level where the ship sped up and then slowed down, yielding a graph in the game that was similar in shape and proportions to the target graph.

Excerpt 11

| 1 | Mrs. W: | What boosts did you put on the ship? |

2	Javier:	I put boosts at the beginning.
3	Mrs. W:	What happened over time?
4	Javier:	Slowed down.
5	Mrs. W:	Why did it slow down?
6	Javier:	Friction.

Here, Javier described qualitatively that the ship's speed decreased over time (line 4). He also identified the mechanism in the game for the ship's decrease in speed as friction (line 6). In the subsequent interview with a researcher, Javier further connected friction to the *Step Size Minus* command in ViMAP, as seen in Excerpt 12.

Excerpt 12

1	Researcher:	What moved it forward?
2	Javier:	Force
3	Researcher:	And what is it similar to in the [ViMAP] program? What is the force similar to?
4	Javier:	Step size plus.
5	Researcher:	And what is the friction similar to?
6	Javier:	Step size minus
7	Researcher:	What are the Step Size Plus and Step Size Minus doing?
8	Javier:	Step Size Plus makes it go higher.
9	Researcher:	Makes what go higher?
10	Javier:	Speed. Step size minus makes the speed go slower.

Javier identified connected the boosts that sped up the ship in the game to the Step Size Plus command in ViMAP (line 4), as well as friction to Step Size Minus (line 6). Furthermore, Javier demonstrates a clear understanding of the function of Step Size Plus and Step Size Minus by identifying how they changed the speed of the ship (Lines 7 – 10). These interactions with Javier are interesting because of the different focus of the questions. Mrs. W's questioning of students tended to focus on connections between actions in the game and concepts depicted in the game, while the researcher's interview questions centered on connections between ViMAP

commands and actions in the game. Taken together, these conversations with Javier showed that not only could Javier equate ViMAP program commands to actions within the game, but he also demonstrated a conceptual understanding of how these actions in the game affect the speed of the ship and the shape of the graph.

At the end of Day 5, Mrs. W reflected on the ViMAP modeling activity and the subsequent game play and noted the connections being made by the students between the commands in ViMAP, the motion of the agent/shop and the graph. In her field notes, she stated:

> "I was impressed at the connections being made between the commands, the motion of the ball, and the graph. I noticed that, during the [game play] activity, far fewer students were trying to mimic the actual up and down motion (as we had seen with Group 1). Seeing the commands in ViMAP and making the connection that the 'Step Size Plus' command would increase speed and the 'Step Size Minus' command would decrease speed made the graph [in the game] make very clear sense as to what the ship needed to do. [This is] in contrast with Group 1, who had to infer the change in speed from the motion of a real world object. So the connection between the speed changing was clearer for this group."

Mrs. W recognized that understanding the connections between the ViMAP commands and the corresponding changes in speed of the agent/ship helped the students "make very clear sense" of the graph in game. She also noted that the absence of these connections may have hindered the students who participated in the physical modeling activity from correctly interpreting the graph in the game.

In summary, during the two day modeling activities both in ViMAP and in SURGE Next G, teachers and students made explicit connections between the physical concepts depicted in both environments, the programming commands in ViMAP that affected the ship's speed, and the mechanisms in the game that affected the ship's speed. While these connections were initially made by Mrs. W and the researchers in the study, there is evidence of take-up of these

connections by students when they were explaining decisions made in the game to generate a certain shape of graph.

Theme 2: Focus on generation of and interpretation of graphs. During the ViMAP activity, Mrs. W spent time in whole-class discussion helping students conceptually interpret the graphs generated in ViMAP. She focused on connecting the motion of the ship in the ViMAP enactment area to the shape of the speed-time graph. In ViMAP, the distance traveled in one time interval in the enactment area equals the speed of the ship at a point on the graph. If the object in the enactment area is programmed to speed up, then the length of the line in the second time interval will be longer than the line in the first time interval. To help students see the difference in distances traveled in subsequent time intervals, it is often convenient to have the object make a 90-degree turn to the right after each time interval so that the student can clearly see the endpoints of the distance traveled in each time interval. For an object that is speeding up, this leads to a shape that spirals outward (see Figure 12). For an object that is slowing down, the distance traveled in each time interval decreases. If the object makes a 90-degree turn to the right at the end of each time interval, then the resulting shape will spiral inward (see Figure 12).
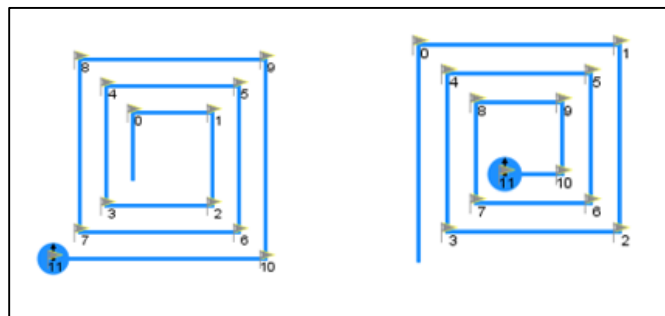
Figure 12. Shapes generated in enactment area of ViMAP by object speeding up (right) and slowing down left)

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To help students understand the connection between the motion of the object in the enactment area and the shape of the speed-time graph, Mrs. W equated the length of the lines drawn by the motion of the ship during one time interval to the height of the bars in the corresponding speed time graph. For an object that is speeding up, a longer distance traveled in the next time interval corresponded to a higher bar on the speed-time graph at the next point in time. Adjacent bars on the graph that are increasing in height as a function of time depict increasing speed as the ship is covering more distance in the same amount of time. Mrs. W illustrated this point to her students as evidenced in Excerpt 13. In this portion of class, Mrs. W led a whole-class discussion on the meaning of *Step Size Minus* and linked the spiral-inward shape to the decreasing height of the bars in the speed-time graph. In this specific program, students set an initial step size of 50, meaning that the initial speed of the ship was 50 units/second or that the ship traveled a distance of 50 units in one seconds. They then programmed the ship to reduce its speed by 10 units every second by using the command *Step Size Minus 10*. This effectively reduced the distance traveled each second by 10 units, resulting in decreasing speeds of 40 units/second, 30 units/second and so forth.

Excerpt 13

1	Mrs. W:	This is the distance covered since last step size. What's happening to the [speed-time] graph? Keisha?
2	Keisha:	(inaudible response)
3	Mrs. W:	Why is this going down? What is the [speed-time] graph measuring?
4	Keisha:	It's measuring how the lines are--the longest line matches 50.
5	Mrs. W:	What's that line name, first, second, third or fourth?
6	Keisha:	First.
7	Mrs. W:	That was the first line that we made. What happened to the length of every line after that *(gestures to the lines in the enactment area)*?
8	Jamal:	It got shorter.

9	Mrs. W:	It got shorter and shorter. And what happened to the graph? What do you see happening--this is the speed graph. What's happening to that speed over time?
10	Stacey:	It's going down by 10.
11	Mrs. W:	It's going down by 10 every time. So what's is this measuring that's going down?
12	Student 1:	Speed
13	Mrs. W:	The speed. The speed is decreasing as evidenced by the facts that these lines are getting shorter and shorter. We're covering less distance. So if you're going slower, you're not going to get quite as far. Is that true? [Pause] Think about it. If you run really fast, and you have 10 seconds to run really fast, which will get you farther--if you run as fast as you can or if you just kind of old lady jog. Which one will get you farther?
14	Student 2:	As fast as you can.
15	Mrs. W:	As fast as you can. [points to first line of shape in the enactment area corresponding to 50 units/second.] THIS is as fast you can, it's going to get your farther. And then every time you're slowing down, till eventually you're that old lady on the track who's running like this. And you don't get very far every time you take your little step. So this is related--the length of those lines is related to how the speed of the ship is changing.

In Excerpt 13, Mrs. W shows students that when they program the ship to initially travel 50 units/second in the enactment area, the ship will travel 50 units in that time. The length of the line drawn by the program in the enactment area to represent this distance corresponds exactly to the height of the first bar in the speed time graph, which is 50 units/second. When the ship only travels 40 units in the next second due to the *Step Size Minus 10* command, the length of the line drawn by the program to represent a distance of 40 units corresponds exactly to the height of the second bar in the speed-time graph, which is 40 units/second. In Line 4, Keisha picked up on this connection by stating that the speed-time graph is "measuring how the lines are—the longest line matches 50." Later in the discussion, Jamal observed that the bars on the graph are getting shorter (line 8) and Stacey added that the bars are decreasing by 10 every time (line 10). Mrs. W

concluded the discussion by illustrating the concept with a different analogy of running fast versus running slow (i.e. "old lady jog," line 13).

Once the students had successfully written tutorial programs for constant speed, speeding up and slowing down, they then wrote a program that combined the two commands of *Step Size Plus* and *Step Size Minus* to make the ship first speed up and then slow down. Mrs. W then led a discussion with the students to interpret the shape of the resulting speed-time graph, as seen in Excerpt 14.

Excerpt 14

1	Mrs. W:	Can you guys answer a question for me? You have two commands in there. You had *Step Size Plus* and *Step Size Minus*. I want someone to raise their hand and tell me for each part, what's happening to the speed as it goes through the *Step Size Plus* commands.
2	Student 1:	The speed goes up.
3	Mrs. W:	Speed increases. And then what's happening to speed in *Step Size Minus?*
4	Student 2:	Subtracting.
5	Mrs. W:	It's subtracting, so it's slowing down. Speed decreases. Think about what the graph would look like if the speed is first increasing (*gestures upward*) and then decreasing (*gestures down*). What should it look like?
6	*No students respond.*	
7	Mrs. W:	It speeds up and then it slows down. So if you're looking at a graph, what should happen?
8	Student 3:	Speed up then go down.
9	Mrs. W:	What do you mean--what will that look like? Is it going to say the word speed up and slow down? [inaudible response by student]
10	Mrs. W:	Can you describe the height of the bars? Describe it Javien.
11	Javien:	It goes up then it starts going down.
12	Mrs. W:	Right. It's going to go up and then come down. Where are the highest bars going to be? Where is the speed the highest?
13	Student 4:	In the middle.
14	Mrs. W:	In the middle, right? Is that what we see up here? *(shows image of graph on the screen)* Is this what you predicted?

Mrs. W led students through a qualitative interpretation of the speed-time graph associated with an increasing then decreasing speed. At first, she simply focused on general changes in speed (i.e. speeding up and slowing down) and did not try to quantify speed changes (i.e. by how much is the speed decreasing) as she did in Class 1. After this interpretation exercise, students were given a picture of a speed-time graph similar to the graph they had already seen in their prior game play (see Figure 5). The researcher and Mrs. W co-led the class in a discussion of similarities and differences between their existing graph from the ViMAP program and the target graph printed on the paper (Excerpt 15).

Excerpt 15

1	Researcher 1:	What do you think we need to do to our program to get a graph that looks more like the graph printed on the paper? What changes do you think we need to make?
2	Mrs. W:	What's the difference between the graph on your computer and the graph on your paper?
3	Researcher 1:	Let's talk about similarities and then differences. How are the two graphs similar?
4	Student 1:	Both go up and down.
5	Researcher 1:	What are these graphs showing?
6	Student 2:	Speed going up and down.
7	Researcher 1:	What are differences?
8	Student 3:	Longer
9	Student 4:	The phase is longer.
10	Student 5:	Phase 2 is longer. Phase 2 is going down more.
11	Researcher 1:	What changes do we need to make to the program? What can we do to stretch out Phase 2 on your computer?
	…	
12	Mrs. W:	It's slowing down for longer. What in the program do you need to do to make it speed down or get slower for that longer amount of time…what do you think we could do to these commands to make it keep slowing down?

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The class then spent the next several minutes trying different options within the program that could possibly change the slope of the slowing down phase in ViMAP so that it more closely matched the slope of the speed-time target graph. Students tried extending the number of times that the *Step Size Minus* command was executed so that there would be more decreasing bars on the graph. They also changed the size of the command from *Step Size Minus 10* to *Step Size Minus 5* to compare the effect of decreasing speed at a slower rate. By modifying commands in ViMAP that controlled physical variables, students were able to see instantaneous effects of those changes on the shape of the speed-time graph. Students learned how to change variables in ViMAP in order to alter the shape of the graph in specific ways.

After this final programming activity, students transitioned back into the game environment and played a game level nearly identical to the final level played by Class 1. Students were given the same target graph that they had worked with in ViMAP as a "clue" for Surge to help the stranded captain navigate his ship. They were tasked with designed a level in the game so that the speed-time graph generated by the ship matched the target graph. As Mrs. W circulated around the room during this activity and talked with individual students, she focused specifically on helping students figure out how to get the speed to change in certain proportions. This goal was evident in her field notes where she stated,

> "Students seemed to understand that they needed to manipulate the location and duration of the boosts to mimic the graph given. The most helpful and frequent question I found myself asking was 'what is different about the graph you made compared to what you want? What needs to change to get it closer?' and students could identify things like it did not speed up enough (the graph wasn't tall enough) or it didn't have enough time slowing down before it stopped."

In this way, the teacher supported the students as they engaged in model revision in the game by changing variables of the ship (i.e. time, force, location of boost) in order to change speed in certain ways to match graph.

In summary, Mrs. W focused a significant part of her instructional time during the virtual modeling activity on interpreting graphs and manipulating variables to produce certain changes in the shape of the graph. By highlighting the connection between the lengths of the lines drawn by the motion of the ship in the enactment area to the height of the bars in the corresponding speed-time graph, Mrs. W was able to illustrate speed as a process of continuous change in the virtual modeling activity (i.e. the bars in the graph were constantly increasing, reflecting a constantly increasing speed). The mechanism for generating the speed-time graph was made explicit in this activity and directly connected to the change in distance per time interval of the Surge agent in ViMAP. Furthermore, throughout the virtual modeling activity, connections were repeatedly made between the ViMAP model (e.g. *Step Size Plus*), the real world (e.g. object increased in speed) and the game (e.g. boosts in the game caused the ship to speed up).

Analysis of Graphing Activity

The modeling activity in each class concluded when students designed a level in the game so that the ship's changes in speed in the game matched either the ball's changes in speed on the ramp in the video (Class 1 only, physical modeling activity) or the target speed-time graph (Class 2, virtual modeling activity and Class 1, physical modeling activity). Each student in each class was given a piece of paper in which they were asked to draw a sketch of their level design, including position and magnitude of boosts that they used to design the level, as well as the corresponding speed-time graph that was generated by the ship's motion in the game. These written artifacts were collected and analyzed. First, sketches of the level design were coded for

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the type of final trajectory of the ship in the game (i.e. straight-line horizontal, straight-line vertical, diagonal, multiple slopes, curved, other). Then the final graph was coded for the overall shape of the graph (how closely it matched the target graph), regions of changing speed (speeding up and then slowing down, only speeding up, only slowing down, other combinations of changing speed), and whether or not the graph drawn was a possible outcome of the level design in the sketch.

In Class 1, twenty-three students participated in the study. Of these students, fifteen students completed the written task at the end of the modeling activity. Two students were absent on this particular day, and six students who were present for the activity did not complete the written activity. The data from these six students is missing either because they failed to turn in their written sheet to the research team at the end of class or they turned in a paper with no sketches on it. These six students may have designed a level in the game to match the target graph, but without their written work, it is impossible to determine what type of solution they designed. In Class 2, twenty-two students participated in the study. Of these students, seventeen students completed the written task at the end of the modeling activity. Three students were absent on this day, and two students were present but did not turn in a written sketch or graph.

Through analysis of the codes for the shape of the graph, three categories emerged to categorize student data: (1) graphs that depicted the ship speeding up and then slowing down to the target, which is considered a "match" to the target graph (Figure 13), (2) graphs that depicted the ship only speeding up with no decreasing speed evident (Figure 14), and (3) graphs where there were multiple regions of speeding up and slowing down along the path toward the target (Figure 15). For example, a graph in this last category could depict several short-duration boosts spread across the path to cause short bursts of acceleration, followed by rapid deceleration.
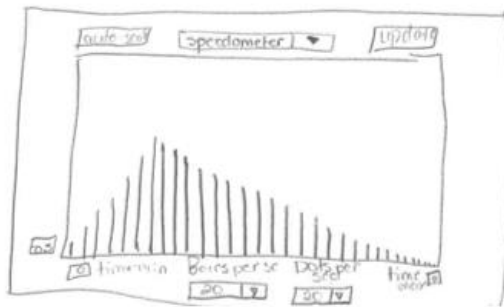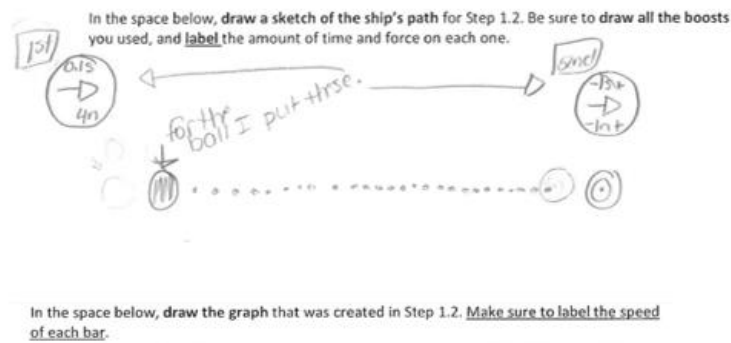
In the space below, **draw a sketch of the ship's path** for Step 1.2. Be sure to **draw all the boosts** you used, and **label** the amount of time and force on each one.

In the space below, **draw the graph** that was created in Step 1.2. <u>Make sure to label the speed of each bar</u>.

Figure 13. Student sample illustrating speeding up and slowing down in the final game level

Analysis of the written work from this modeling activity showed a significant difference in performance between Class 1 (physical modeling activity) and Class 2 (virtual modeling activity), with more students in Class 2 being able to make the ship move in such a way to generate a graph that resembled the target graph (Figure 16). In Class 1, only three students generated a graph that depicted the ship speeding up and then slowing down. Nine students created a level design in which the ship did not slow down at all, resulting in a speed-time graph showing a positive slope with increasing speed. Three students designed a trajectory involving multiple regions of speeding up and slowing down. This is in contrast to twelve students in Class 2 who generated a graph that closely matched the target graph, one student who generated a graph depicting only speeding up, and three students who generated a graph depicting multiple regions of speeding up and slowing down.

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In the space below, **draw a sketch of the ship's path** for Step 2.4. Be sure to **draw all the boosts** you used, and **label** the amount of time and force on each one.
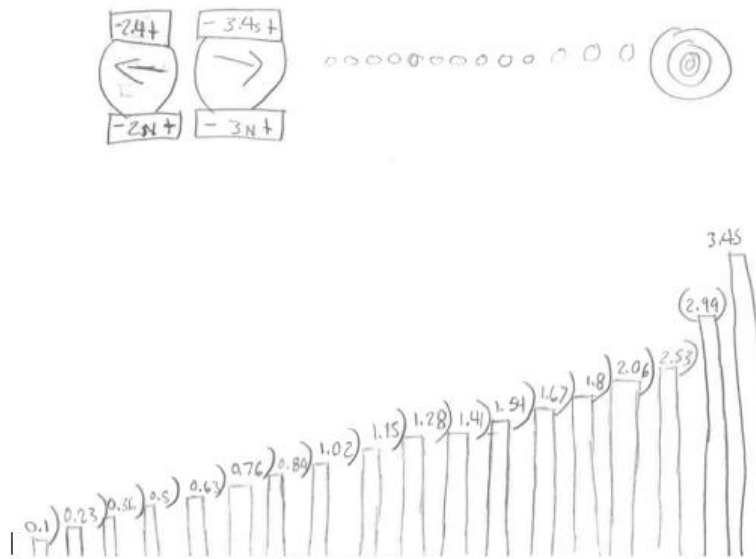

Figure 14. Student sample illustrating only speeding up in the final game level
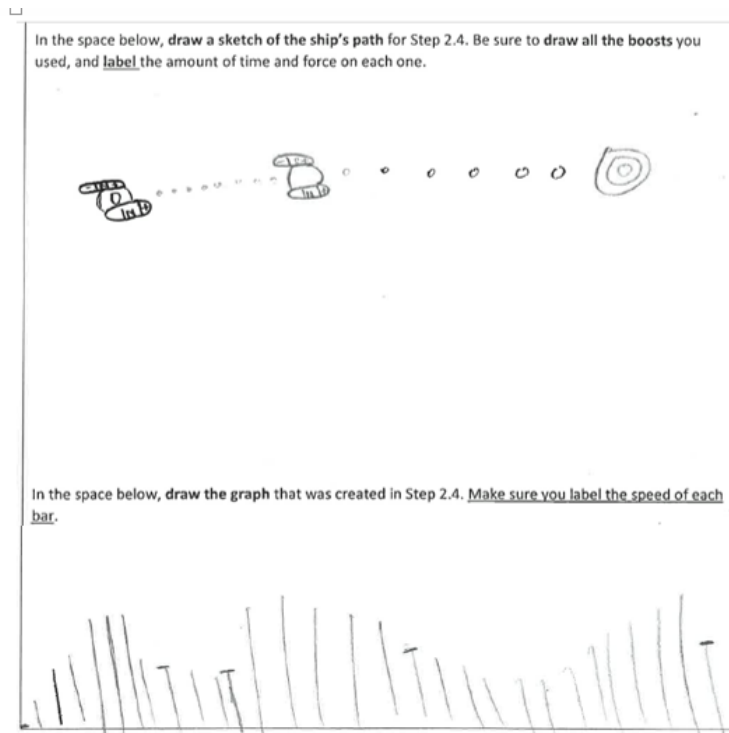

Figure 15. Student sample illustrating multiple regions of speeding up and slowing down in final game level
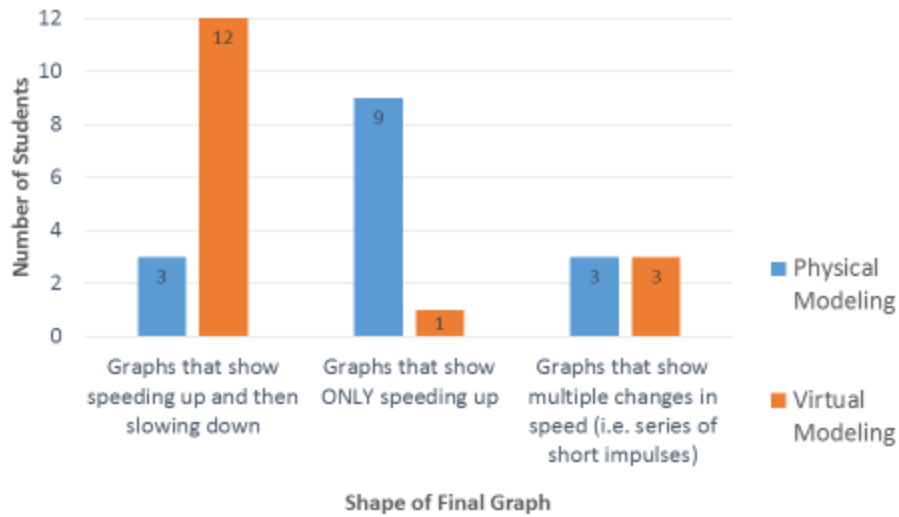
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Figure 16. Analysis of Graph from In-Game Modeling Activity

Analysis of student performance on the graphing activity in the final in-game modeling

activity shows differences in performance between Class 1 and Class 2, with more students in

Class 2 being able to make the ship move in such a way to generate a graph that resembled the

target graph. This suggests that while students in Class 1 may have been able to qualitatively

state that the ball on the video sped up as it rolled down the ramp and slowed down as it rolled

up the ramp (see Excerpt 7 for an example), most students in Class 1 were unable to recreate that

scenario in the context of the game. That is, they were unable to place boosts in a way such that

the ship in the game also sped up and slowed down to match a target graph. This inability to

control the ship's speed through strategic use and placement of boosts could stem from the

teacher's focus in Class 1 on general changes in speed throughout the modeling activity and

limited interactions with graphs. In the modeling activities in Class 1, students did not have the

opportunity to change variables in order to alter the shape of speed-time graphs in specific ways.

In contrast, a significant portion of the virtual modeling activity involved analyzing and

interpreting speed-time graphs in order to manipulate variables to change the shape of the graph in certain ways.

Discussion

Thematic analysis of video data and analysis of written student work reveal interesting differences regarding how students participated and performed in the final modeling activity in each class, as well as related instructional moves by the teacher. In the physical modeling activity, Mrs. W spent the majority of her time supporting students as they encountered numerous conceptual and material difficulties that prevented them from developing a model of the marble-ramp system in the form of a speed-time graph that represented the marble's change in speed as a function of time. Consequently, Mrs. W had to spend time the following day developing the "correct" model for the students and drawing explicit connections between the model, the real world and the game environment. Students in this class struggled during the in-game modeling activity to connect the model developed for the marble-ramp system to concepts in the game, and there was no evidence of student take-up of language or representations from the physical modeling activity when reasoning about events in the game. Furthermore, only three students in this class were able to generate a graph in the game that matched a target graph depicting increasing speed and then decreasing speed, while the majority of students generated a model within the game that only depicted speeding up.

This performance on the final graphing activity stands in contrast to the virtual modeling activity where twelve students were able to generate a graph in the game that matched the target graph, and only one student created a model where the ship only increased in speed. In the virtual modeling activity, students did not encounter material difficulties due to the virtual nature of the activity. Therefore, Mrs. W spent the majority of her time during the modeling activity

helping students draw connections between the programming environment, the real world and the game environment. She also spent significant time in class helping students interpret motion graphs and manipulate them in order to change certain variables. When engaging in the modeling activity within the game, there were numerous instances of student take-up of language and representations from ViMAP when explaining their reasoning about events in the game, in contrast to students from the physical modeling class.

One of the purposes of this study was to investigate how the modeling activities within the game and the complementary modeling activities outside of the game could support the development of model-based reasoning in students. Our analysis shows that each activity required different types of representational work, and the representational and measurement demands in the physical modeling activity were different (and greater) than in the computational modeling activity. The physical modeling activity required students to start from a real-world phenomenon and invent mathematical structures and representations in order to develop a model of the phenomenon. It was an activity that took place in a non-representational space that was likely more challenging for the students to reason with, and transforming this non-representational space of the physical world into a representational space of a speed-time graph proved to be difficult for students. To mitigate this difficulty, the teacher made deliberate instructional moves as ways of managing the challenges and complexities that became explicit to her, and she provided the representational system (i.e. the speed-time graph) that the students needed in order to model the changes in speed of the marble on the ramp and the ship in the game. However, in her reflection notes on the last day of the study, Mrs. W herself noted that that students in Class 1 still faced challenges when trying to correctly interpret and generate a speed-time graph in the game to match the target graph. She attributed these challenges to the

difficulties they encountered in generating representations in the physical modeling activity. She postulated that the students had to "infer the change in speed" of the marble by observing and measuring the motion of a marble rolling down a ramp, and therefore faced greater representational demands when trying to generate a speed-time graph of the marble based on these inferences.

In the virtual modeling activity, the teacher did not have to invent or provide a representational system to the students in order for them to engage in model-based reasoning. Instead, she was able to leverage the fact that ViMAP used a representational system that was complementary to the game. In other words, very little additional representational work was needed in the virtual modeling activity in order for students to transfer from the ViMAP environment to the game environment. This stands in contrast with the physical modeling activity in which the representational demands were significantly greater. The programming tasks in the virtual modeling activity were designed to complement actions and symbols in the game. ViMAP employs three different representations of the motion of the object: the code of programming commands, the shape generated by the object as it enacts the code, and the speed-time graphs that correspond to the motion of the object. In SURGE NextG, there are also multiple representations of the ship's motion using dot traces, the trajectory of the ship and the resulting speed-time graph which is similar in appearance and function to the ViMAP graph. As students engaged with generating and translating across these multiple complementary representations of motion, students were able to develop progressively refined understandings of the relationships between actions in ViMAP, physical concepts in the game, and mathematical relationships between concepts.

Another goal of this study was to examine how the teacher used these modeling activities to support model-based reasoning through classroom instruction. Here, we see the clearest distinction between the two activities in terms of how graphs were attended to in each class. In Class 1, there was no mention of graphs at all during the course of the physical modeling activity on Day 4. Due to the challenges of the measurements for this activity, Mrs. W spent all of her time supporting students in developing a measuring method and making connections between physical phenomenon and representations of the physical phenomenon. There was no mechanism within the modeling activity of generating a graph. In other words, the process of generating a graph was "black-boxed" or hidden from the students so that they saw a graph that was generated within the game but did not explore in depth *how* that particular graph came to be.

In ViMAP, however, the mechanism for generating a graph is a central focus of the modeling activity. Students engaged in tasks where they changed variables in ViMAP in order to alter the shape of the graph in different ways. Additionally, the teacher deliberately engaged in a prolonged class discussion to help students understand the relationship between the motion of the object in the enactment area and the graph generated as a result of that motion. In this way, the teacher "glass-boxed" graphs in ViMAP so that students understood exactly how the height of speed bars in the graph corresponded to the length of the lines in the enactment area and how changes in the speed of the object corresponded to changes in the shape of the graph. They were able to see how changes to variables in the program were made evident by changes in the graphs. As a result, a majority of the students in Class 2 were then able to re-enter the game environment and make similar changes in variables in the game in order to manipulate the shape of the resulting graph in specific ways. They were able to use the model developed in ViMAP in order to reason about concepts in the game in a productive way. Additionally, the teacher noted in her

field notes at the end of the study that she was able to ask different questions to the students in Class 2 than to the students in Class 1. Mrs. W focused the majority of her one-on-one questions in Class 2 on the manipulation of variables within the game in order to change the shape of the graph in ways that made it match the target graph more closely. This stands in direct contrast to her questions to students in Class 1 where she only focused on general trends in speed changes and did not attempt to have students change the slope of the graph in any way.

The lack of a mechanism for generating a graph in the physical modeling activity likely limited the teacher's ability to engage her students in Class 1 in meaningful understandings of graphs. Instead, the teacher focused her questioning during whole-class instruction and one-on-one interactions on helping the students simply recognize qualitative changes in speed on the graph. It is interesting to note that Mrs. W attempted to engage her students in Class 1 in a discussion to explain how the speed-time graph for the marble-ramp system was generated. She demonstrated via a drawing on the whiteboard that as the speed of the marble increased, the bars on the graph got higher (see Excerpt 6). To do this, she drew a bar on a graph and asked students to predict what would happen to the height of the second bar if the speed increased. Building on student responses, she developed a general trend of speed in that increasing height of bars meant increasing speed. However, she was unable to show students *what determined* the height of the bars in the first place and *why* the bars got higher when speed increased. For example, when Tamara came to the board to draw her graph from Level 1 in the game (see Excerpt 6), Mrs. W asked her to label the speed values on each bar. Mrs. W used the speed numbers generated in the game to show a pattern of increasing values (0.4, 0.9, 1.4, etc.), but there was no discussion of *how* the numbers were generated. The lack of inherent mechanism both in the physical modeling

activity and the game for generating graphs limited the representational tools available to the teacher to support conceptual understanding and model-based reasoning in students.

When examining some of the key advantages and challenges of each form of modeling activity, it is important to note that the nature of the resistances in each activity were different. The measurement demands for the physical modeling activity were complex and students encountered numerous difficulties both with the materials they were using to collect data and with the underlying conceptual relationships in the phenomenon. In this particular instance, the measurement and representational demands proved to be too challenging given the time constraints of the study and the physical limitations of the classroom materials.

In ViMAP, students did not encounter the same measurement-related resistance because ViMAP does not problematize measurement in the same way as the physical modeling activity. However, they encountered other resistances when they had to write programs to tell the object what to do and how to move. In the physical modeling activity, the marble moved in a predictable way based on immutable laws of nature (i.e. gravity always pulled the marble down the track despite any conceptual or material difficulties on the part of the student). In ViMAP, the object only moved in the way it was programmed to and there were no "physical laws" that prevented the object from in unnatural ways (i.e. the object could theoretically speed up forever since it was in a virtual world not governed by real-world constraints such as friction or physical boundaries). While students in the physical modeling activity spent most of their time attempting to achieve a productive stabilization between the agency of the learner and the agency of the tool (Pickering, 1995), students in the computational modeling activity may have been able to reach productive stabilization sooner because of the complementary nature of the

representational systems in ViMAP and SURGE NextG, as well as the lack of materiality with measurements.

It is important to note that we are not arguing in this paper that the structure of the physical modeling activity is harder or worse that the virtual modeling activity. Each activity has different challenges and affordances that can affect the types of resistances that students encounter and the types of learning opportunities available to students. In this study, we strove to illustrate the types of modeling activities that could be augmented with disciplinarily-integrated games in order to support teachers and students in developing modeling practices in the classroom, and to examine the ways in which the activities could help or hinder student use of model-based reasoning within the game. To be clear, we find value in physical modeling activities that bring students into contact with phenomena in the real world. This study demonstrated that it is difficult to transfer from the game to the real world without some kind of adequate bridging exercise that uses complementary representations to the game. In future studies, it would be useful to design instruction so that students first engage in game play, then in a virtual modeling environment similar to ViMAP with inscriptional systems that are complementary to the game, followed by a physical modeling activity where students could leverage understandings developed using the representational systems in the game and ViMAP.

Conclusion

While both modeling activities have affordances that can support productive student learning, the representational tools available for modeling are important. Representing motion as a process of continuous change is difficult without using tools that are designed to support breaking a process into smaller discrete events or chunks (e.g. *Step Size* in ViMAP) and then

piecing the chunks back together (e.g. ViMAP graphs). Without these tools, it becomes difficult to accomplish representational tasks when conducting physical inquiry activities, such as the modeling activity with the marble-ramp system.

This study highlights the significance of designing multiple complementary representations of the same phenomenon as a core element of game play and related modeling activities. Translating across these representations can deepen students' conceptual understanding, and engaging students in modeling experiences that involve various forms of media, materials and representations can provide students with opportunities for model evaluation and comparison. Despite their many pedagogical affordances, digital games for learning have not been widely implemented in science classrooms. By integrating the virtual world of games and programming with the material world of the classroom, teachers may have more opportunities to appropriate a digital game as part of their broader curricular goals. Unlike most immersive game-based environments, disciplinarily-integrated games can be leveraged to support the support the development of representational practices such as scientific modeling in the K-12 classrooms.

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