Space Vector: A Videogame to Teach Introductory Physics

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Abstract

Space Vector is a two-dimensional, 80's-style, science fiction themed casual game designed to introduce preliminary concepts of Newtonian mechanics and eliminate some common misconceptions about motion. The game focuses on horizontal and vertical vectors, uniform motion, and acceleration. Players fly over extraterrestrial planets and drop objects on targets. Missions may contain incorrect physics that the player must identify at the end of the mission. Also, players have to make predictions about how objects will fall from their ships given a horizontal speed and gravitational constant. Players then see whether their predictions are correct. An initial pilot study showed improvement in understanding that weight does not affect acceleration and in understanding the trajectory of falling objects. Improvement needs to be made to help students understand the independence of horizontal and vertical motion as well as acceleration. This paper describes the first iteration of *Space Vector* and our vision for future work.

Introduction

Physics instruction is particularly challenging because nearly everyone develops misconceptions about motion through lived experience (Hestenes, 2006), so physics instructors have the dual challenge of not only teaching physics concepts but also dislodging firmly held misconceptions that have developed over a lifetime of daily observations. Students commonly believe that heavier objects fall faster than lighter objects and that objects that are thrown into the air are pushed upward by some "impetus" force (Halloun & Hestenes, 1985; Hestenes, 2006). These beliefs as well as many other misconceptions are contrary to Newton's laws of motion. Overcoming these misconceptions is necessary for developing an understanding of Newtonian mechanics.

Videogames show promise as instructional tools for teaching introductory physics concepts, as they present instructors with an opportunity to systematically address both concepts and misconceptions. Videogames can simulate incorrect physics, so they are able to make manifest students' ideas about motion, force, and mechanics and challenge those ideas when they are incorrect.

Space Vector is a videogame under development to teach introductory physics concepts to beginning physics students. Through careful choices of game mechanics, content, and structure, the game addresses both concepts and commonly held misconceptions about Newtonian mechanics and focuses on the ideas needed to understand freefall, such as vectors, velocity, uniform motion, and acceleration. In this paper, we describe the first prototype of *Space Vector* (*Space Vector 1.0*) and discuss the ongoing development of *Space Vector 2.0*. We also discuss our vision for integrating educational assessment with game design and using the evaluation of student performance to inform future versions of *Space Vector*. Given that videogames can simulate both correct and incorrect physics, can be played anytime, and can collect fine-grained data of student performance, we believe that videogames can have a powerful role in the future of introductory physics education.

Space Vector 1.0

Space Vector is a two-dimensional, 1980's-style arcade game that belongs to the side-scroller genre (the game elements scroll horizontally across the screen over time) of arcade games. It has a science fiction theme, in which the player acts as a pilot who chooses either to drop supplies to help explorers or to drop bombs on enemy robots. The science fiction theme both justifies the game mechanic (the primary action of the game, which is dropping objects from a spaceship) and provides a context for changing different parameters such as gravitational constants. Players score points when dropped objects hit their targets. After the player completes all the instructional units and achieves a certain point level, the player wins the game.

In *Space Vector 1.0*, the player works through a series of tutorial levels in which s/he learns to control the spaceship and practices dropping objects (see Figure 1). Eventually, more game elements are included such as ground missiles to add difficulty.

***Figure 1*. Tutorial mission where the player is dropping a supply.**

After the tutorial missions are completed to ensure that the player has mastered the game mechanic, instructional units are introduced. Each unit addresses a separate concept in Newtonian mechanics, and these units are presented in the following order: vectors and horizontal velocity, uniform motion, acceleration, and displacement. After each unit of instruction, the player is asked to make accurate predictions about the behavior of supplies or bombs that are being dropped. As shown in Figure 2, the player is presented with a grid with a ship and supplies or bombs, a horizontal velocity, and a gravitational constant. The player has to predict where the ship and object will be after 1, 2, and 3 seconds.

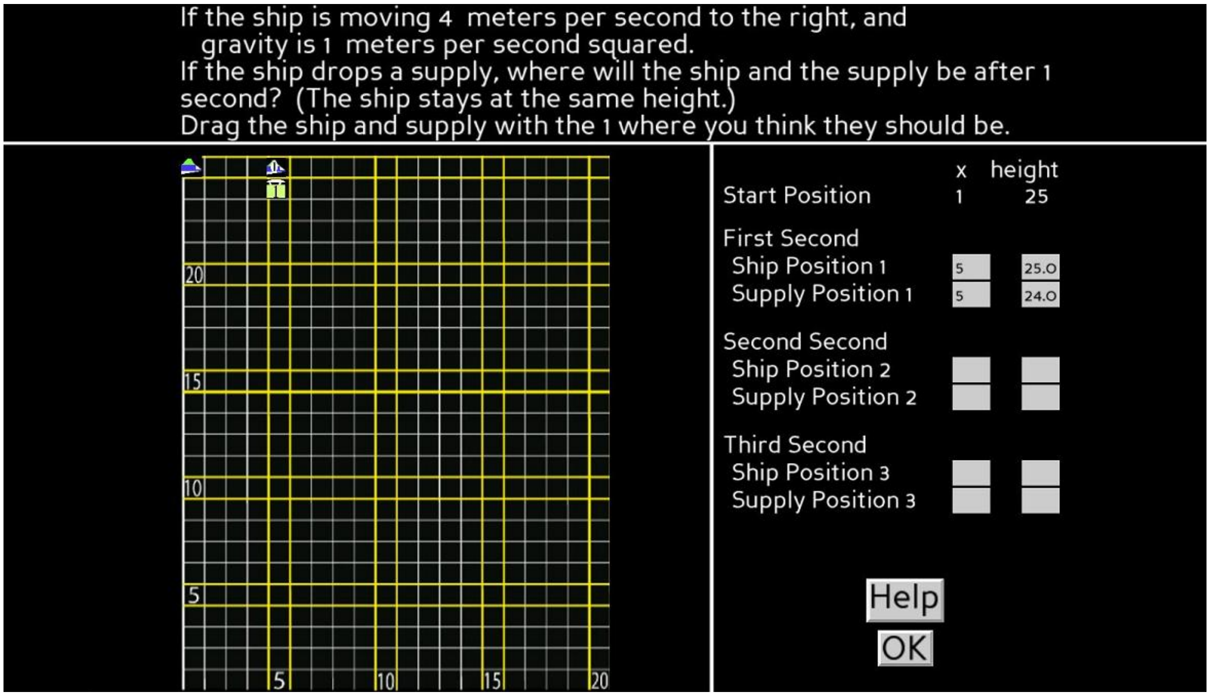

***Figure* 2. An example of the prediction grid.**

Once the predictions are made, the player becomes a copilot who no longer steers the ship and, instead, watches as the game engine's artificial intelligence steers the ship and drops the bombs or supplies according to the player's predictions on which the success of the mission depends. The player watches as targets are hit or missed. If the predictions are not correct, the player is asked to revise the predictions using what was learned as the copilot and also using hints that may be given if the player has difficulty making an accurate prediction.

Following a prediction mission, when the player embarks on a new mission as the pilot, the physics during the mission may be incorrect. For example, the supplies or the bombs can have two different masses (10 kg or 100 kg), and the heavier objects fall noticeably faster than the lighter objects. After the mission, the player is asked to identify what, if anything, was amiss (see Figure 3). If something was incorrect and the player identifies it correctly, the player receives bonus points.

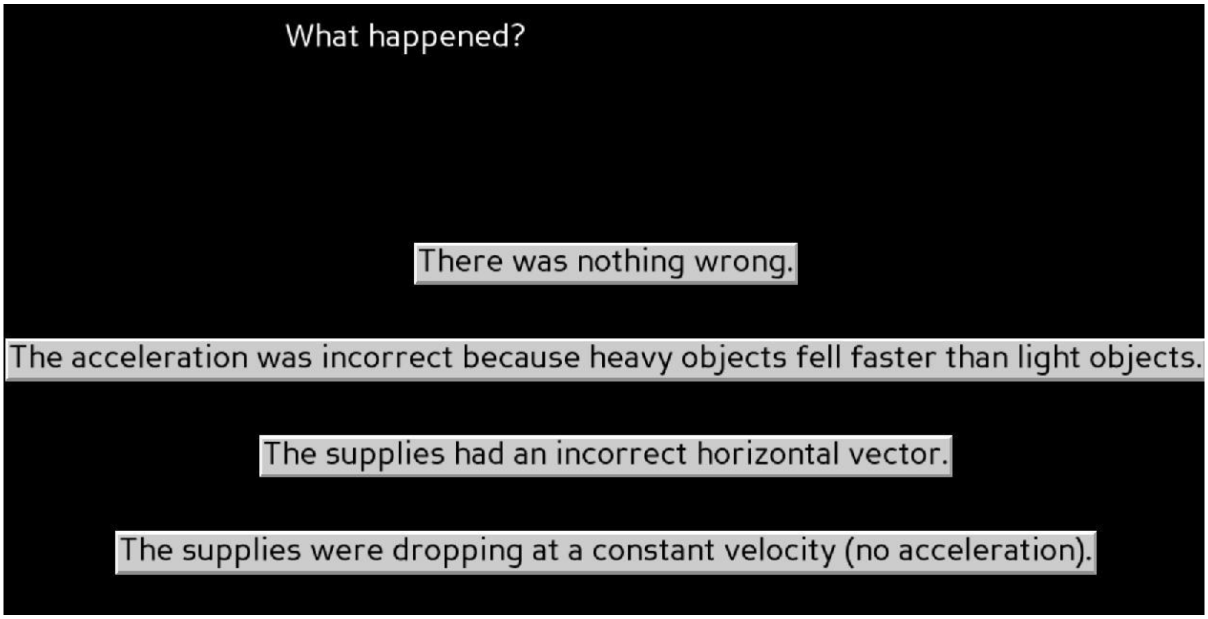

***Figure 3*. The player is asked to identify if the physics of a mission was incorrect.**

Space Vector 1.0 Pilot Study

After the first version of the game, *Space Vector 1.0*, was completed, a pilot study was conducted to examine students' understanding of Newtonian mechanics before and after game play. Students were recruited from an undergraduate educational technology class (a 300 level course) at Arizona State University, and students received course credit for participating in the study. The pilot study was conducted over two weeks, during which students came to a computer lab set up for the videogame and completed a background survey, a pre-test, a session of approximately ninety minutes of game play, a post-test, and an attitude survey in a single session lasting approximately two hours in total. Students arrived at the computer lab in groups of four to six though all work was completed independently.

The study sample was comprised of sixty-five students. Nearly twice as many women participated than men (41 women, 24 men), and the mean and median age among participants was 20 years old. Students were not asked their grade level to ensure confidentiality. Approximately two-fifths (42%) of the students who participated in the study had no prior physics instruction and another quarter of the sample (26%) had last taken a physics course in high school. Nearly half (46%) of those who participated in the pilot reported playing videogames "never or very rarely"; among those who reported ever playing videogames, "Sports and Racing" and "First Person Shooter" games were the two most popular genres with 77% and 39% respectively.

The pilot study utilized a single group pretest-posttest design. The students were asked to complete a pre-test to ascertain their level of understanding of physics concepts, they played the videogame, and then they completed the same test of physics concepts. The pre- and posttest was a subset of the Force Concept Inventory (FCI), a test developed to test students' understanding of force after a semester of physics instruction (Hestenes, Wells, & Swackhamer, 1992). It is a multiple-choice test with five choices per item. The FCI is especially useful since it can be used to identify specific misconceptions that students have about force. Fifteen questions (half the original test) were used. The questions selected covered the same concepts as those addressed in the game, specifically the relationship between weight and acceleration, trajectories of items in freefall, the application of forces, and distinguishing position, velocity, and acceleration.

With a single-group design, there is not sufficient evidence to support claims about the effectiveness of *Space Vector* as an instructional tool, but, as a formative assessment of the game's design, we feel the results of the pilot study were sufficient to identify both strengths and weaknesses of the first version of the game. A comparison of students' pre- and posttest scores suggests that students are learning something about physics from playing the game, but perhaps they are not making as many gains in all of the conceptual areas covered by the *Space Vector* instructional units. The mean pretest score was 4.14 ($M = 4.14$, $SD = 2.66$), and the mean posttest score was 5.15 ($M = 5.15$, $SD = 3.04$). Of particular interest was students' improved performance on specific items that deal with concepts addressed during game play.

Table 1: Test items with the number of correct pretest and posttest responses.

Item	FCI Item Number	Pretest Correct (%)	Posttest Correct (%)	Change (%)
1	1	26 (40)	47 (72.3)	21 (32.3)
2	2	19 (29.2)	32 (49.2)	13 (20)
3	3	17 (26.2)	24 (36.9)	7 (10.8)
4	8	28 (43.1)	27 (41.5)	-1 (-1.5)
5	9	17 (26.2)	16 (24.6)	-1 (-1.5)
6	12	25 (38.5)	31 (47.7)	6 (9.2)
7	13	5 (7.7)	4 (6.2)	-1 (-1.5)
8	14	15 (23.1)	19 (29.2)	4 (6.2)
9	19	20 (30.8)	21 (32.3)	1 (1.5)
10	20	8 (12.3)	10 (15.4)	2 (3.1)
11	21	18 (27.7)	15 (23.1)	-3 (-4.6)
12	22	25 (38.5)	28 (43.1)	3 (4.6)
13	23	10 (15.4)	18 (27.7)	8 (12.3)
14	24	24 (36.9)	29 (44.6)	5 (7.7)
15	30	12 (18.5)	14 (21.5)	2 (3.1)

As shown in Table 1, students made the greatest improvement on items 1-3, gains that are consistent with the design of the game as the misconception that weight affects acceleration was a focus during game play. Students' performance on items 6 and 8 concerning the trajectories of objects during freefall did not improve as much as expected, suggesting that more support is needed for students to understand the types of trajectories that are made during freefall. The verbal instruction given in the units, the prediction grid, and observation during missions might not be sufficient for students to accurately perceive a parabolic trajectory. Likewise, for improvement on other items, game content needs to be modified.

Space Vector 2.0

A second iteration of *Space Vector* is now under development to address some of the instructional weaknesses of *Space Vector 1.0* that were suggested by the pilot study results. As noted above, students are not coming away from the game with a clear sense of an object's trajectory during freefall. There are several potential explanations for why students' understanding didn't increase as expected, including the sequencing and depth of content coverage as well as how content is being presented to players. Following the initial pilot, we identified several modifications that would make the game and the material more engaging to players, in turn increasing the game's effectiveness. In the first version, all the instruction was presented as written text, but, in *Space Vector 2.0*, interactive examples and interactive annotations will be added. Players can work through examples and generate examples, as well as practice the concepts before making predictions. Another modification to the game will be to use explicit visualizations to further illustrate key concepts. For example, if incorrect physics is simulated during a mission, players will be shown an example trajectory and allowed to change their frame of reference, i.e., they can watch an object fall from the spaceship from the perspective of someone on the ground or from the perspective of a ship flying alongside the spaceship. This will allow players of *Space Vector 2.0* to watch trajectories without having to infer them purely from observation and without being distracted by game elements as they may have been in the first version.

Integrating Educational Assessment and Game Design

The process of developing a second version of the game presents us with another opportunity to think not only about game design features but also to think critically about how those game design features facilitate learning. In general, when developing an educational game, decisions about the inclusion of content, the sequencing of levels, and the combination of types of tasks necessarily reflects our understanding of (or at least our expectations about) how players learn. In developing Space Vector 2.0, we are working to ensure that all of these game features are consistent with how students learn foundational physics concepts.

In the case of introductory physics, it has been argued (e.g. Hestenes, Wells, & Swackhamer, 1992; 1995) that our everyday understanding of force is actually dominated by commonly held misconceptions. Developing a Newtonian understanding of force requires overcoming six families of misconceptions and mastering six discrete families of distinct—though interrelated—families of concepts. As shown in Figures 4 and 5 below, each of these concepts might be mastered in a particular order. If we are thinking about learning physics as achieving conceptual mastery, this might lead us to implement a particular sequencing of missions versus an underlying model that describes overcoming misconceptions.

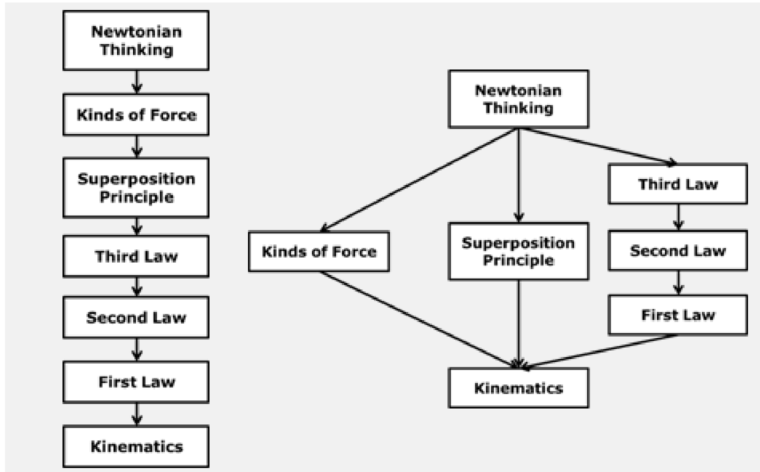

Figure 4. **Candidate student models of Newtonian thinking.**

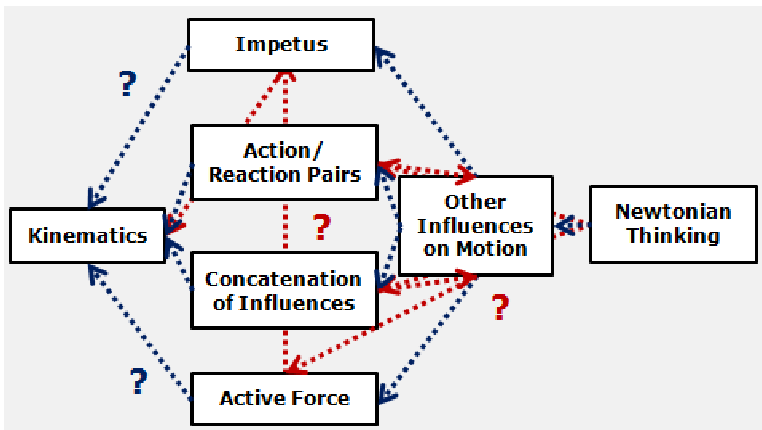

Figure 5. **Alternative student models of Newtonian thinking.**

For each of these concepts, or families of concepts that comprise a Newtonian understanding of force, we can imagine that students could be total novices, they could already be Newtonian thinkers, or they might have achieved only partial mastery. It is not uncommon to see learners achieving only partial mastery of physics concepts: there are many students who achieve a purely mathematical understanding but have difficulty linking those mathematical formulae to those concepts as seen or experienced "in the real world" (Hestenes, 2006). There are other learners who may learn by doing but still are not able to grasp the mathematical underpinnings, even if they "know it when they see it." It is these students who are working to achieve mastery but need additional instructional support that are of particular interest when modifying Space Vector 2.0 to be a more effective mode of physics instruction.

Mastering Newtonian mechanics requires mastering both the underlying concepts and the mathematics behind Newtonian mechanics and making appropriate linkages between them. Gaming environments may engender a conceptual understanding but provide little guidance to connect students' understanding gained through action to the underlying mathematical principles. Our observation of students' persistent difficulty understanding object trajectories in freefall even after playing the first version of Space Vector is consistent with this. In the development of the second version of the game, the additional visualizations and annotations provide additional support for making linkages between the mathematical, albeit at a very rudimentary level, and conceptual dimensions of Newtonian thinking.

In *Space Vector 2.0*, the content, structure, and features embedded within each mission are designed to build Newtonian physics concepts in a systematic way that can help eliminate specific misconceptions. Success requires that players demonstrate a conceptual and a preliminary mathematical understanding. Self-assessment and practice missions establish a baseline that can help to identify particular misconceptions. Players' performance in missions facilitates conceptual mastery, and predictive missions then require players to demonstrate the necessary mathematical as well as conceptual understanding. For those students who are successful in one but not both venues, interactive examples and game annotations are designed to make explicit the linkage between the mathematics and the concepts as they are captured through the action of the game.

Making explicit the theory of learning underlying the game's construction also aids in building game features that will facilitate (or hinder) the assessment of learning as well as supporting the learning itself, because some of what players do may reflect how they play games rather than how they learn, and it will become necessary to distinguish between the two. For example, as demonstrated in the pilot, although students may be computer literate they are not necessarily familiar with this genre of game, and it is important to ensure that students' performance in the game is a reflection of their knowledge and not their gaming ability or lack thereof. In Space Vector 2.0, one-dimensional and two-dimensional practice missions ensure that students are familiar with game mechanics independent of their mastery of the instructional material. In a similar vein, game literacy may impact how people formulate strategies of play, which could then impact learning. Even for those familiar with similar types of games, different styles of play emerge. For example, some players fly as slowly as possible to hit everything they possibly can; other players proceed as quickly as possible through each mission. The identification of data as evidence of learning must recognize these different strategies.

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Acknowledgments

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