Andrews University

J. N. Andrews Honors Program

HONS 497
Honors Thesis

Evaluating the efficacy of educational games in promoting interest and understanding of gravitational wave physics

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Abstract

The LIGO Scientific Collaboration Education and Public Outreach group seeks to ameliorate the lack of public understanding of gravitational wave physics. One such effort is Black Hole Pong, a remake of the 1972 arcade classic developed by researchers at University of Birmingham, UK. Black Hole Pong differs from other educational games in that it stretches the laws of physics to make the user experience more exciting. Another effort has been my own work in developing a game called Chickens in Space where players can create mass, which coalesces and eventually forms black holes, which serve as obstacles to the players. I present the results of a set of pre-tests and post-tests from Andrews University and Sheboygan North High School which measure Black Hole Pong's and Chickens in Space's effectiveness in teaching the concepts and benefits of gravitational wave astronomy.

Dedication

To my parents.

To my dad, because of the way this ex-physics teacher raised me to be curious about how things worked, and for introducing me to programming QBASIC in grade school. To my mom for the academic and emotional support, and for being the best coach and cheerleader anyone could hope for.

Without you, I would never been inspired to study physics nor had developed the discipline and earned the scholarships that made it possible to get to this point.

Acknowledgements

First, I want to thank God for creating the ordered, predictable, and knowable universe, and for endowing mankind with the mental faculties to model and test His creation. To Him be the glory.

I want to thank my advisor, Dr. Tiffany Summerscales, who always welcomed students into her office to discuss anything from research to the culture of physics. Especially I want to thank her for showing me opportunities to contribute to innovative ways to combine fun with exploratory learning through physics games. I want to thank her husband as well, Dr. Rodney Summerscales, for being a sounding board on game design and ways to engage my audience.

I wish to thank Dr. Lori Imasiku for pointing me to literature and resources in the education community to reference in creating educational games. I want to also thank her for vetting and suggesting improvements for my pre- and post-tests.

I also want to acknowledge Dr. Margarita Mattingly and the rest of the physics department for their investment in their students, and their sincere and earnest desire to see them succeed. Because of the interest of the department in my development, I was able to present my research at two conventions outside of Andrews. These valuable experiences shaped how I viewed my own research, and guided my inquiry.

And my wife, Mateja, who patiently endured a husband who spent a lot of hours debugging code and asking her to test the latest build.

Contents

Chapter 1

Introduction

1.1 LIGO Gravitational Wave Detection

For nearly a decade, the LIGO Scientific Collaboration has been working toward upgrading the equipment in their first generation gravitational wave (GW) detectors. With the equipment fully upgraded, and the second-generation GW detectors online, Advanced LIGO achieved the first direct detection of GWs on September 14, 2015[1].

The ability to directly detect gravitational waves will deeply affect cosmology, astrophysics, and astronomy. However, while there is a widespread interest in the scientific community of these projects, LIGO is relatively unknown to the public. Despite LIGO being the largest and most ambitious project to ever be funded by the National Science Foundation, many people in the non-scientific community never heard of it before LIGO disclosed its findings on February 11, 2016. Additionally, public knowledge of the methods and principles that allow for GW detection is still very limited and there is little known about GW interferometry compared with other massive modern physics endeavors, such as the Large Hadron Collider.

1.2 LIGO Outreach

The LIGO Scientific Collaboration (LSC) seeks to ameliorate the lack of public understanding through the 'Education and Public Outreach' (EPO) group. The EPO group seeks to design documents, videos, events, and other media to broadcast the vision and benefits of gravitational wave astronomy worldwide.

The University of Birmingham, UK, has contributed to the EPO group's efforts by developing a program in which students and faculty develop small educational computer activities. These activities seek to illustrate and communicate GW behavior and GW detector technology. In contrast with other organizations that develop computer activities with heavy a heavy focus on the accuracy of the physics involved (such as University of Colorado's PHET program), the group at University of Birmingham is seeking to create activities that occasionally "stretch" the laws of physics to make the user experience more exciting.

To date, the games developed by University of Birmingham have been freely available on their site, and optional questionnaires have allowed players to rate their experience of the game. Most of the players were enthusiastic about the game and gave the game a high rating. However, these results apply to how they enjoyed the game, and do not cover in detail the educational and attitude-changing elements that the games are intended to promote. The purpose of my research is to evaluate more rigorously the games for educational and inspirational merit amongst high school students, and to aid in the development of these and other games.

The results of this research will inform future developers of educational games on how to develop elements that promote student engagement with the field as well as how to communicate underlying principles about physical laws. What makes this research unique is that it is focusing on games where there laws of physics are being 'stretched' to see if a lack of scientific rigor can still have positive educational and research interest effects.

Chapter 2

Methods

2.1 Gravitational Wave Games

2.1.1 Black Hole Pong

In 2010, a summer research student at Birmingham University named Robert Unwin produced a remake of the 1972 arcade game Pong. In Black Hole Pong, rather than moving paddles around the screen, two players instead control the positions of their respective black holes. They position the black holes in such a way that stars slingshot around the black holes onto the opponents side. A point is awarded to a player when a star leaves the opponents' side of the screen. [5]

Similarly to the original game, all objects in the game are bound within the edges of the map on the top and the bottom. The black holes may move anywhere on their respective sides of the mid-line and can be controlled using either mouse, keyboard, or game controllers.

Black Hole Pong was met with enthusiasm at the 2010 "Looking for Black Holes with Lasers" British Science Festival.

2.1.2 Black Hole Master

Beginning in spring of 2015, a group lead by Daniel Brown and Andreas Friese set out to make an updated version of Black Hole Pong and renamed it Black Hole Master. Whereas the old game was programmed using the Processing framework, the team is developing Black Hole Master on the Unity framework. Black Hole Master will support more features and different levels

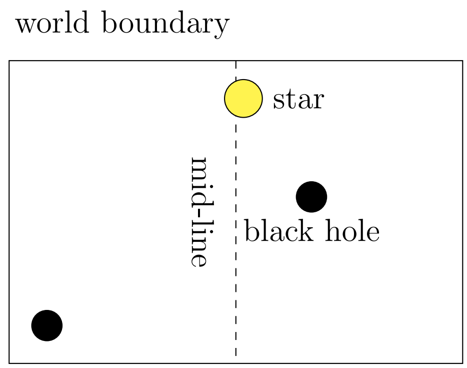

Figure 2.1: An in-game view of Black Hole Pong.

for an improved game experience. At the time of this writing, the game is still in development.[4]

I was an active contributor to this team in the Spring of 2015, especially in April and helped to contribute code for a Breakout-style level. In my level, a single player would move a black hole around the screen in an attempt to slingshot a star onto the far-side of the playing area. There were a number of bricks (or asteroids, depending on the settings) that needed to be destroyed in order to advance to the following level.

2.1.3 Chickens in Space

Starting in Fall of 2015, I began sketching out a game called Chickens in Space. In Chickens in Space, a single player controls a spaceship which has a fictional drive capable of creating mass out of nothing. This drive then ejects the mass in order to propel itself. This idea came from an exploitation of a rule in an April Fools edition of a Dungeons and Dragons magazine. In a table of flaws for commoners, one such flaw, called "Chicken Infested" read as follows:

> You've got chickens. Effect: Whenever you draw a weapon or pull an item out of a container, you have a 50% chance of drawing a live chicken instead. No, we don't know where your chickens come from; it's your character.[14]

In the Dungeons and Dragons universe, drawing an item out of a spell component pouch is considered a free action, and a character can make as many free actions per turn as they like. A player could therefore exploit this rule by carrying a spell component pouch full of iron filings, sit inside a space ship, and draw the iron filings out of the pouch. If drawn fast enough, the half of the filings that turned into chickens would build up tremendous amounts of pressure and would be expelled out the nozzle of the rocket.

I used this scenario as the story for Chickens in Space. Players have a playing area, and can fire chickens out of their rocket in order to propel themselves around the screen. The player and the chickens bounce off the side of the screen. When chickens collide with each other, they clump together into a larger chicken, and simultaneously emit gravitational waves in addition to feathers and eggs. Players increase their score by collecting feathers, but explode if they hit a chicken or an egg.

As chickens collide, their combined mass increases. After enough chickens collide, they reach a critical Chandrasekhar[1] mass. Chickens represented planetary bodies of various sizes. When coalesced chickens reach a mass of $m = 10$ chickens, they collapse into a black hole of 5% scale of what the chicken's size would otherwise be. When two objects collide, feathers and eggs are also emitted. Feathers represent photons and travel much faster than eggs, which represent small rocks or heavy metals in the case of core collapse. Collisions also create objects that are shown translucently and labeled "graviton." These propagate very quickly and cause a wobble effect on the objects they pass through.

The goal of the player is to earn as many points as possible in a given time limit. It is the hope that the player will be exposed to concepts such as supernovae and gravitational waves.

The original version of Chickens in Space was developed in Python and playable on iOS devices through an app called Pythonista. In January I explored programming the same game in Unreal, but found that the rendering overhead for an otherwise simple game to be too expensive. In February, I reprogrammed it to be played in a web browser using an HTML5 framework called Phaser.js. All of the game code was writing in Javascript.

[1] or "Chickensekhar" if you like.

2.2 Departures from Reality

In both games being tested, the games make changes to the actual physics of the universe in order to make the game more enjoyable to play. The developers of Black Hole Pong explained in an interview that using "true" physics made the game almost impossible to play, and that it is more important for a game to be fun than it is to be accurate. One of the concerns of this research is to evaluate how games that change the laws of physics affect players' attitudes, and how useful they are in education.

2.2.1 Unrealistic Elements in Black Hole Pong

While Black Hole Pong does a great job exhibiting optical behaviors of black holes, such as the dark center and gravitational lensing of background images, it does ignore several key features of black holes. However, in order to play a Pong-like game, some concessions have to be made in order to make the game playable.

If the player is to be able to move the black hole around the screen, they must be able to violate conservation of momentum rules, as the black hole follows the cursor or moves according to keyboard input without any visible forces within the game. The black holes have no pull on one another, and if players both position their black holes on the mid-line such that they overlap, they can still separate their black holes.

In Black Hole Pong, the black holes have a limited gravitational pull radius beyond which the black hole does not exert any gravitational pull on a star. The original designers found that when the gravitational potential traveled all the way across the screen, the game play was so unintuitive that players became frustrated when they could not get the star to go where they wanted it to go. By default, the radius is quite small, but can be adjusted by holding down a button. This small radius is necessary in order for a released star traveling towards the opponent side not to slow down or even return to a player's side. Because the range of the black hole's field can be boosted, a common strategy is to position the black hole just far enough from the trajectory of a ball so that it lies in the "boost" region, but not in the normal region, as shown in figure 2.2. The player can then "turn on" the gravity on the ball for a half rotation around the black hole in order to return it to the opponents' side. This boostable gravity is not seen in nature, but does make Black Hole Pong playable.

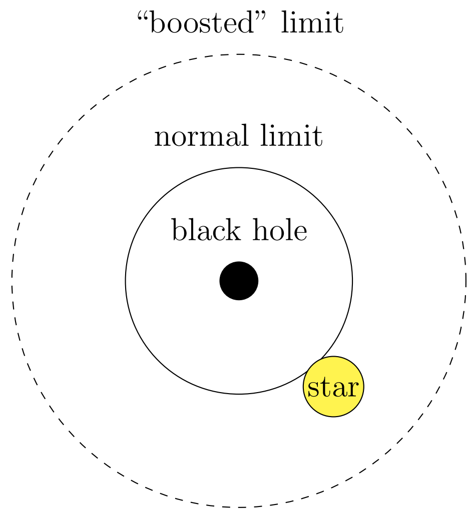

Figure 2.2: The player has some control over how far the black hole’s pull reaches.

It is not uncommon for a star to move directly towards and eventually into a black hole. In nature, when this happens, the black hole consumes the star and grows a small amount. The star can never escape the black hole. In Black Hole Pong, when a star enters into a black hole, it merely passes through it. All star objects have maximum velocity and linear drag properties to prevent division by small numbers near the center of the black hole from kicking them out of the black hole (this is a common problem seen in $1/r^2$ simulations). The end result is that a star, when captured by a black hole, will eventually decay its orbit into a small, non-zero jitter within the black hole’s event horizon.

The game makes use of the theoretical concept of wormholes at higher levels in order to create exciting game experiences. As the game progresses, the difficulty is increased by introducing more stars to be managed simultaneously. By pressing a button, a player can use a wormhole power-up to “suck” all stars on the playing field directly into itself. The black hole transports the stars into the other player’s black hole which spews them out in random directions. This is a power-up that players may employ if they find themselves overwhelmed with multiple stars on their side of the playing field.

2.2.2 Unrealistic Elements in Chickens in Space

Chickens in Space seeks to demonstrate a different set of physical behaviors from Black Hole Pong. In Chickens in Space, the player is able to observe true $1/r^2$ gravity across the entire playing area, exaggerated gravitational drag effects and gravitational wave distortions, and supernovae and core collapse events. However, Chickens in Space also departs from real physics in several areas.

As mentioned earlier, Chickens in Space is built about an assumption that you possess a drive that can create mass out of nothing, and can create sufficiently large amounts of mass that you can eventually spawn black holes. As such, considerations that result as a consequence of conservation of mass and momentum have to be reevaluated.

The universe in Chickens in Space has hard, rectangular walls that objects bounce off of. I initially wished to code the universe so that players could wrap around top-bottom and left-right world edges, resulting in a toroidal universe.[2] For simplicity's sake, the game was ultimately coded to have rectangular walls. The walls have a coefficient of restitution $e = 0.8$. This was implemented to cool the "temperature" of the universe, and slowed "unexpected" that bounce off of walls and potentially kill players. I found that being hit by fast objects that I could not see coming to be frustrating.

According to Einstein's special relativity, massless objects travel at the speed of light, relative to the observer. In Chickens in Space, graviton boxes and feathers are both supposed to represent massless particles, namely gravitons and photons respectively. The game currently programmed these to move at 400 pixels per second and 200 pixels per second respectively, with respect to the world coordinate system. In ideal circumstances, and if more time were devoted to development, each of these would propagate at the same speed c with respect to the camera which is fixed to the player. If the player tried to chase a feather, therefore, it would continue to escape him with the same speed.

As it is currently coded, all particles leave a core collapse simultaneously. In nature, a collapsing star first releases gravitational waves, then a burst of neutrinos, and then light. When playing the game, players will see a burst of gravitational waves when objects collide off of the visible screen, followed

[2] I had also considered making a wrap-around that would yield a spherical universe, but this would require a significant amount of math and would be either unintuitive to the user or difficult to program in Phaser.

shortly thereafter by feathers and then eggs. This is not because they leave at different times, but because they are all traveling at different speeds.

Another way in which the game deviates from nature is in the type of events which cause gravitational waves. In Chickens in Space, the only sources of gravitational waves are direct collisions. In modern science, some of the events in which we are most interested are inspiraling black holes. Linear drag coefficients were introduced in Chickens in Space in order to cause objects to inspiral, but there exists no game mechanic which detects and produces gravitational waves as a function of these inspirals. Spinning compact stars can also produce gravitational waves. Chickens in Chickens in Space do not have any angular momentum associated with them, although this could be introduced with further development, and since chickens are not spherically symmetric, Chickens with very high angular momentum could emit gravitational waves.[3]

Finally, in earlier iterations of Chickens in Space, I discovered that players when experiencing games about space almost never consider that they themselves have gravity. The effects of gravity are notoriously small on a human scale, and this can be shown using Kepler's law for half an object assuming two objects, say myself (65kg) and a chicken (1kg) in free space separated by a distance of 10m.

$$t = \frac{\pi}{2\sqrt{2}} \frac{r_0^{3/2}}{\sqrt{G(M+m)}} \tag{2.1}$$

Thus for my chicken and me at an initial separation of $r_0 = 10$m, it would take 147 hours (or about 6 days) for us to collide.[4] While this is a long time, if I ignored my own gravitational pull and only focused on the pull of the chicken, this time would be increased to 1194 hours (50 days). These effects are extremely tiny, but in a game where the gravitational constant is exaggerated, a 7-fold difference in the collision time between two objects is very significant.

When developing the game in Pythonista, I discovered that my friends and I all found the fact that slow-moving objects clumping around the player

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[3]Chickens are symmetric if you make a spherical chicken assumption. Theoretical physicists are notorious for making such assumptions. See *Consider a Spherical Cow: A Course in Environmental Problem Solving* by John Harte.

[4]It could be said that a force on the order of a 7-day timescale has a "week" effect.

was very unintuitive, so in the version of Chickens in Space that I tested, I removed the gravitational pull of the player's ship.

2.3 Survey Instrument

My research involved a survey which participants would take part in. The survey consisted of a pre-test and post-test which are available in the appendix. These surveys were designed to evaluate changes in students' understanding in gravity and attitude towards gravitational wave research as a result of playing the games. These surveys can be seen in Appendix A.

There are two questions that gauged their knowledge of physics: the first asked the participant to check all the boxes that are true about gravity, and the second asked a student to check all the boxes that are true about black holes. Both questions were designed to assess student knowledge of commonly misunderstood facets of gravitational wave physics.

There were also two questions that gauged their attitude towards gravitational wave physics, specifically LIGO. The first asked if they are interested in learning more about the LIGO project, and the second asked if they believe that LIGO is a project that is useful to the human race.

In addition to these two repeated sets of questions, we also asked students to self-rate how their attitude towards gravitational wave research and physics understanding changed in the post-test.

Lastly, when preliminary research on the development of Black Hole Pong was presented at the Ohio State APS Conference, one element of a survey that was suggested was to measure whether students can detect when rules of physics are being stretched and how they feel about it.

2.3.1 Testing in High School

In early February of 2016, physics students at Sheboygan North High School had an opportunity to play Black Hole Pong. After having their parents sign a consent form, and then they themselves signing an assent form, they received an anonymous identifier code that they could use to participate in my study at home and receive extra credit for participating in the pre-test, playing the game, and then participating in a post-test. At the end of the study period, I matched students' anonymous identifier codes to their names in a lookup table and gave their physics instructors a list of students who had taken part in my research.

2.3.2 Testing in University

In late March of 2016, undergraduate students at Andrews University had an opportunity to similarly be involved in my research. Upon signing an assent form, undergraduate students received an anonymous identifier code that they could use to participate in my research. Participation did not come with the extra credit incentive that was available to high school students.

Chapter 3

Results

3.1 High School Testing

Although 17 students participated in the pre-test, only nine students finished the post-test. The seven students were sophomores and juniors (three males and four females). Each of the participants played Black Hole Pong.

Time spent playing	Number of responses
<5 minutes	4
5 – 15 minutes	2
15 – 30 minutes	2
30 – 60 minutes	1

Table 3.1: Most of the students who played Black Hole Pong played only a few minutes.

As shown in table 3.1, four of the students who took the high school exam played for less than five minutes. In their post-test and explaining what they would do to improve the game, many of the students responded by saying that they would try to make controls more intuitive, or to have some directions within the game so the player would know what to do.

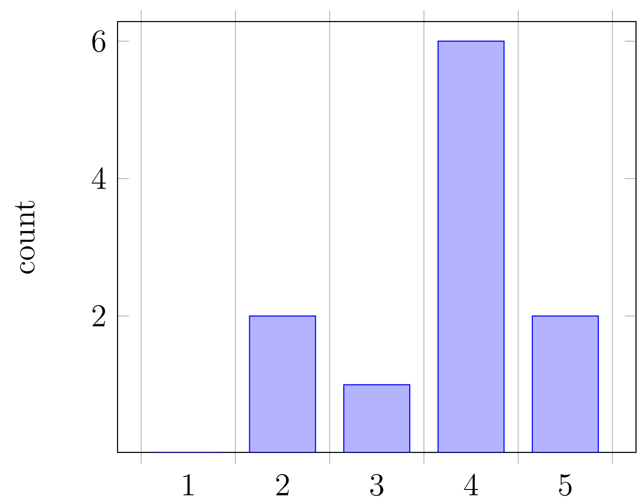


Figure 3.1: Student responses to the question: How would you rate the game that you played?

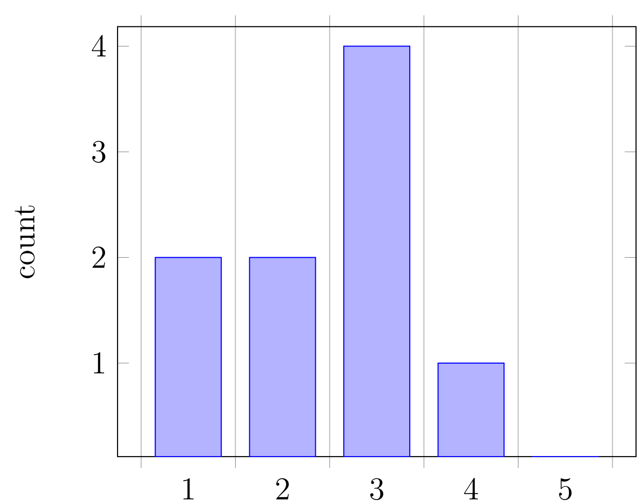


Figure 3.2: Student responses to the prompt: Based on this game, I feel like I understand topics of gravity and black holes more deeply. (1=strongly disagree, 5=strongly agree)

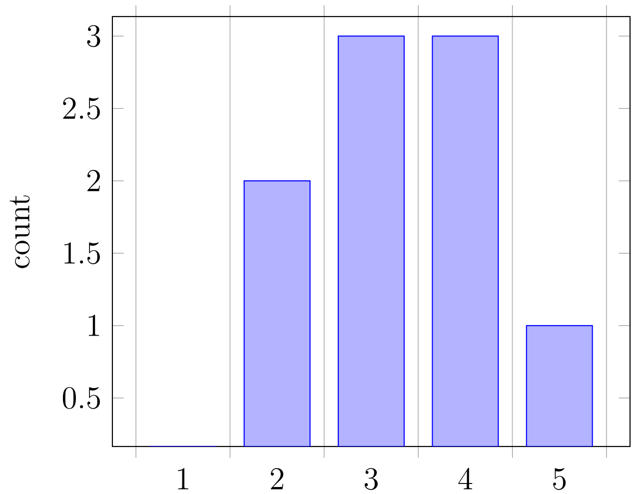


Figure 3.3: Student responses to the prompt: After playing this game, I am more excited to study astronomy and physics. (1=strongly disagree, 5=strongly agree)

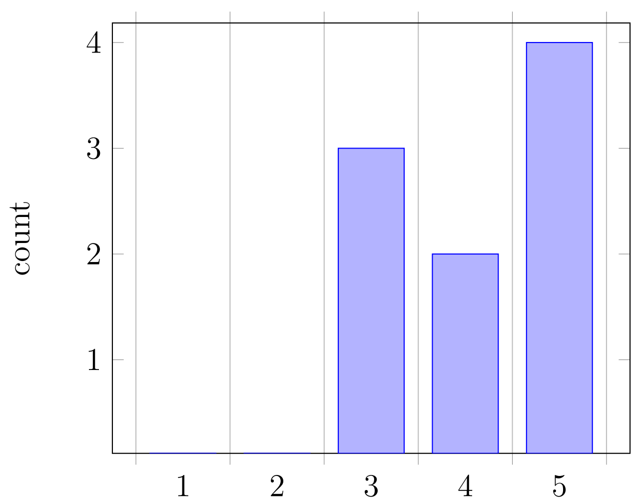


Figure 3.4: Student responses to the prompt: It is okay for a game to bend the rules of physics to make it more fun. (1=strongly disagree, 5=strongly agree)

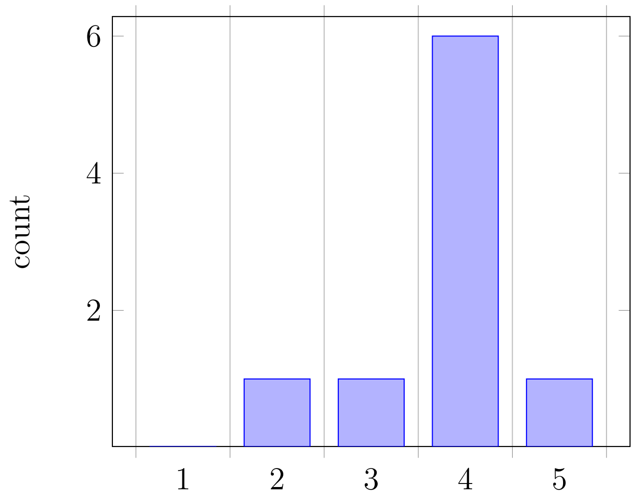


Figure 3.5: Student responses to the prompt: People may not realize when playing a game that the physics is not "real physics" and therefore develop a misconception of physical laws. (1=strongly disagree, 5=strongly agree)

Student responses	Interest in LIGO		Usefulness of LIGO	
	Before	After	Before	After
1	0	0	0	0
2	2	0	0	1
3	3	3	1	1
4	2	2	3	5
5	2	4	5	1

Table 3.2: Responses to the prompts: "I am interested in learning more about the LIGO project" and "I think that the LIGO project is something useful to the human race." (1=strongly disagree, 5=strongly agree)

Between the pre-test and post-test, overall student enthusiasm for LIGO did not change as a result of playing Black Hole Pong, and interest in studying astronomy and physics on average remained the same. Only one student agreed to the statement that they understood the topics of gravity and black holes more deeply as a result of playing the game. Students recognized that it was possible for players to develop misconceptions when playing a games that deviates from "real physics." However, many students agreed with the statement that it is okay to bend the rules of physics in order to make a game more fun.

Average score on 6-part true/false questions	Pre-test	Post-test
Gravity	5.9	5.7
Black Holes	3.8	3.9

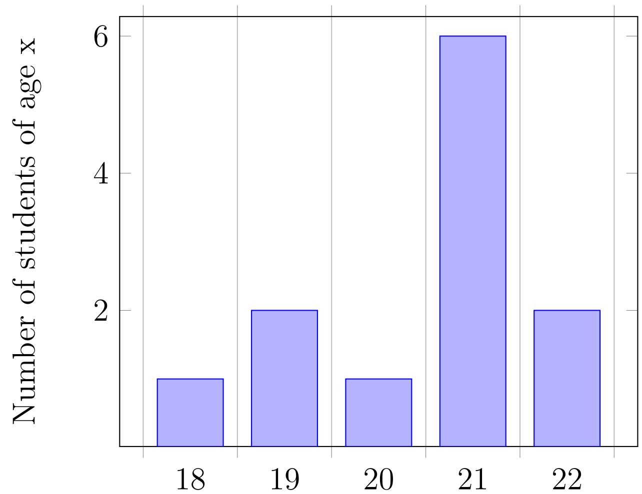
Table 3.3: Test scores on a 6-part true/false questionnaire did not seem to increase that much between the pre- and post-test

As shown in table 3.3, students did not display significant changes in their average score for questions about gravity or black holes. These scores represent averages, and while some students answered more questions correctly and others fewer, it is difficult to know how much of this is due to random guessing and how much was due to actual changes in understanding. Additionally, with $N = 9$, changes this small are not conclusive.

Students were more likely to respond that gravity is strongest between distant objects in the post-test than they were in the pre-test.

3.2 University Testing

Although 18 students participated in the pre-test, only 12 students completed the post-test (two female, ten male).



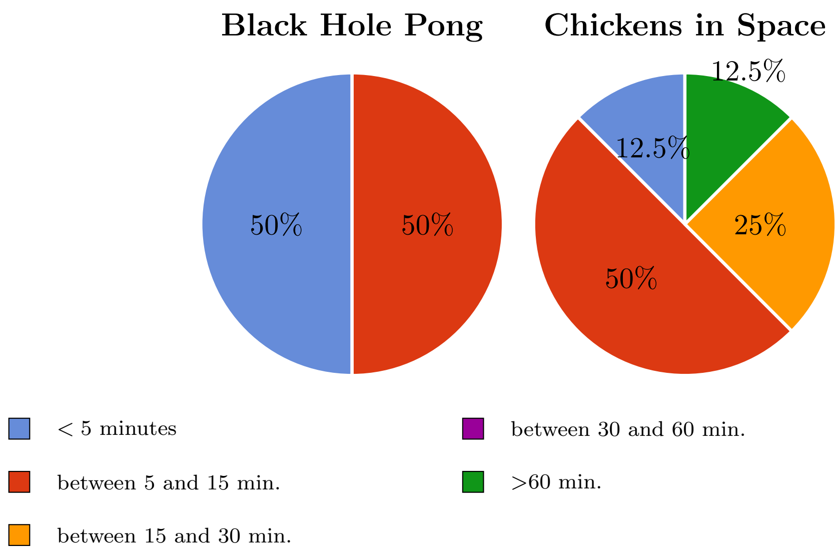


Figure 3.6: Amount of time spent by university testers in playing each game. ($N_{BHP} = 4, N_{CIS} = 8$)

Time spent playing	Black Hole Pong	Chickens in Space
<5 minutes	2	1
5 – 15 minutes	2	4
15 – 30 minutes	0	2
30 – 60 minutes	0	0
> 60 minutes	0	1

Table 3.4: Amount of time spent by university testers in playing each game. ($N_{BHP} = 4, N_{CIS} = 8$)

The results found in table 3.4 and 3.6 suggest that players were more engaged in playing Chickens in Space than they were in Black Hole Pong. This is coupled with the fact that out of 9 students recruited to play Black Hole Pong, only 4 (44%) finished the post-test. Out of 14 students recruited to play Chickens in Space, 8 (57%) finished the post-test.

Completion level	Black Hole Pong	Chickens in Space
Recruited	9	14
Pre-test	5	12
Post-test	4	8

Table 3.5: Number of students that completed each step of the research process. ($N_{BHP} = 4, N_{CIS} = 8$)

It is interesting to note that in 3.5, while a smaller percentage of students invited to play Black Hole Pong finished the post-test, once a student had taken the pre-test, most students played the game and finished. Whereas, a larger portion of students who took the pre-test did not follow-up by taking the post-test at the end of the survey.

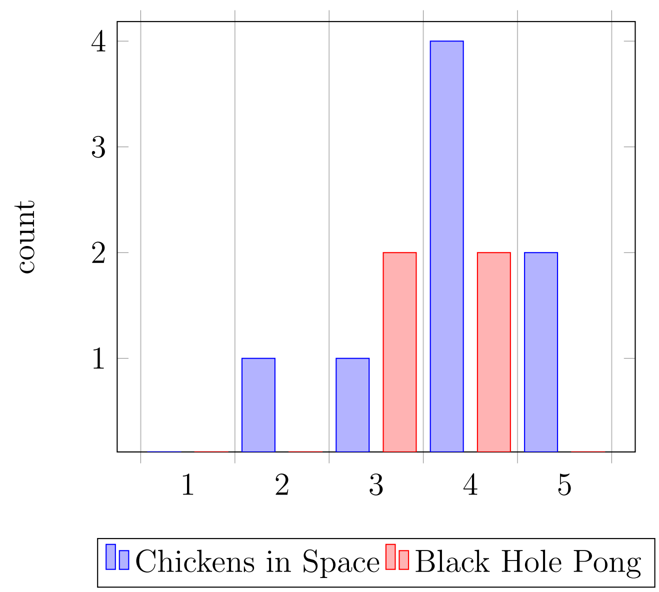


Figure 3.7: Student responses to the question: How would you rate the game that you played?

There was not sufficient evidence in figure 3.7 to say that students rated one game higher than the other. Students on average indicated that the games ranked at 3.75.

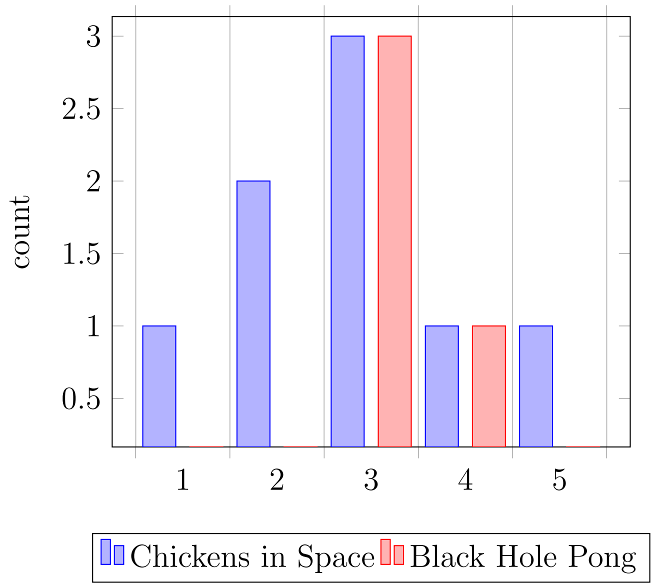


Figure 3.8: Student responses to the prompt: Based on this game, I feel like I understand topics of gravity and black holes more deeply. (1=strongly disagree, 5=strongly agree)

Based on figure 3.8, most students reported that the game had only a small, if any, affect on their understanding. One student expressed a strong negative reaction to the game, and another student expressed a strong positive reaction to the game.

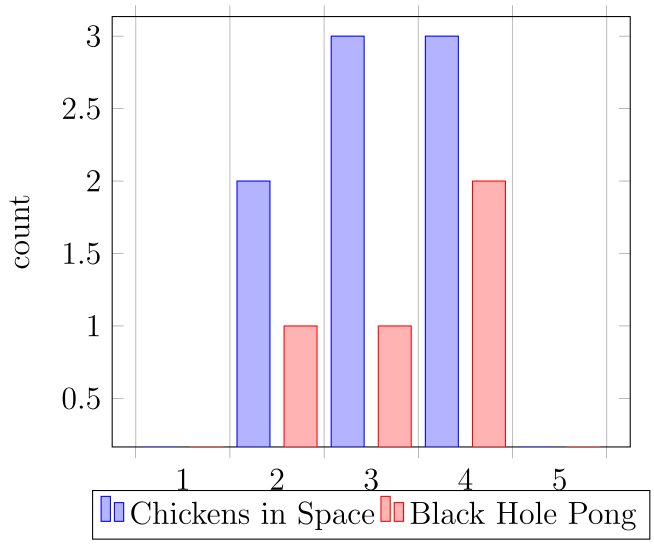


Figure 3.9: Student responses to the prompt: After playing this game, I am more excited to study astronomy and physics. (1=strongly disagree, 5=strongly agree)

After playing the game, most students did not express a significant change in motivation towards studying astronomy and physics.

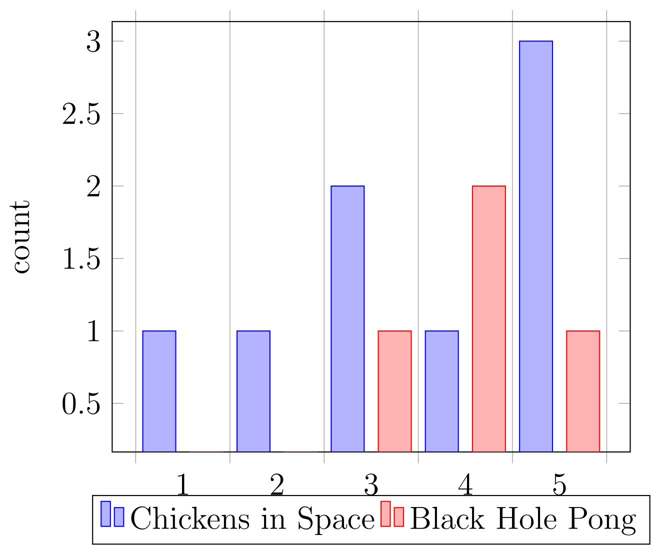


Figure 3.10: Student responses to the prompt: It is okay for a game to bend the rules of physics to make it more fun. (1=strongly disagree, 5=strongly agree)

Regardless of which game was played, students indicated in figure 3.10 that they believed that it is okay for a game to bend the rules of physics in order to make it more fun. The student who strongly disagreed with the student explained in a free response answer that if a game deviates from science, the game should make it explicitly clear.

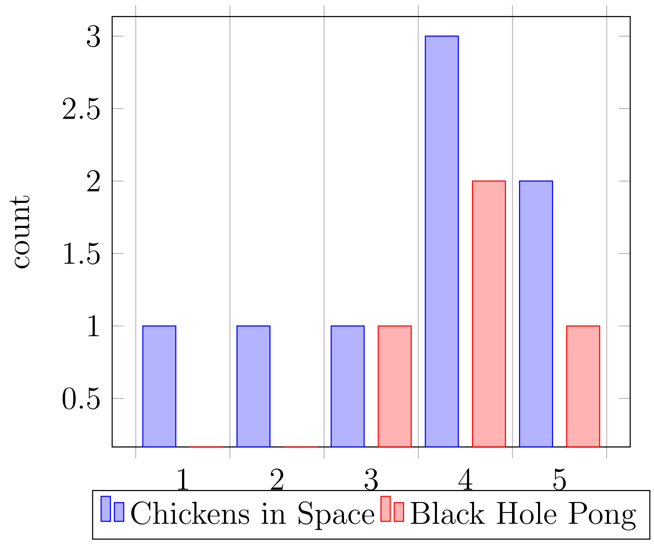


Figure 3.11: Student responses to the prompt: People may not realize when playing a game that the physics is not “real physics” and therefore develop a misconception of physical laws. (1=strongly disagree, 5=strongly agree)

Most students agreed that it is likely that people will develop misconceptions in playing a game that deviates from “real physics”, indicated by a strong right bias in figure 3.11. However, as they indicated on 3.10, this is a risk that is worth taking if it makes the game more fun.

Student responses	Interest in LIGO		Usefulness of LIGO	
	Before	After	Before	After
Chickens in Space				
1	0	0	1	1
2	1	2	0	1
3	3	0	0	0
4	3	4	4	3
5	1	2	3	3
Black Hole Pong				
1	2	0	1	0
2	0	1	0	0
3	0	1	2	3
4	2	2	0	0
5	0	0	1	1

Table 3.6: Responses to the prompts: "I am interested in learning more about the LIGO project" and "I think that the LIGO project is something useful to the human race." (1=strongly disagree, 5=strongly agree)

Players who played Chickens in Space demonstrated a slight increase in interest in LIGO as a result of playing Chickens in Space. However, there was no accompanying increase seen in the player's perceived usefulness of LIGO after playing Chickens in Space.

Players who played Black Hole Pong demonstrated a similar increase in interest in LIGO, as well as a marginal increase in the perceived usefulness of LIGO. However, these trends cannot be conclusively justified with a sample size of $N = 4$ and $N = 8$.

Score	Pre-test	Post-test
Chickens in Space		
Gravity	5.63	5.38
Black Holes	3.88	4.13
Black Hole Pong		
Gravity	5.25	5.00
Black Holes	4.00	4.75

Table 3.7: Test scores on a 6-part true/false questionnaire did not seem to increase that much between the pre- and post-test

Between the pre-test and the post-test, students decreased slightly in their understanding of gravity, though their understanding of black holes increased slightly (on average, a .4 points across all 12 students in both games).

Chapter 4

Discussion

The two games tested did not show any significant change in students understandings. The free responses of students did not show evidence that they had learned anything new, but they did show that they recognized elements that they were already aware of. For example, students who had taken more physics courses identified more complex behaviors, whereas students who had taken only basic or no physics classes only noted things such as 'gravity affects other objects' or 'IDK,' whereas students who majored in these topics identified specific elements like 'inverse square law.'

4.1 Interpretation of the survey data

The results seem to suggest that students tended to observe elements that they were already acquainted with, and were looking for. For example, after seeing gravitons emitted from a collision, a student who indicated in her pre-test 'I somewhat understand what a black hole is, but I don't think I could explain it' said that 'The gravitational waves and effects of them were pretty spot on from what I could tell.' However, a knowledge of how gravity works was not always a predictor on how well they would understand game elements. A student who indicated 'I have a pretty good idea of what a black hole is, and could explain it to someone else' in a free response question wrote 'The whole concept was very bizarre and nothing was explained. I have no idea what the circle of "gravity" squares mean.'[1]

[1] These squares actually say graviton, but move so quickly across the screen it is difficult to read.

Because most students only played a few rounds (most students played fewer than 15 minutes), it is not a surprise that changes in attitude and understanding were not detected. Chickens in Space only gave a short explanation of the objective of the game, and neither game offered even a qualitative explanation of the physics it was trying to demonstrate to the player. On average, students neither disagreed nor agreed that they understood physics better as a result of playing the game. Of the seventeen suggestions on how to improve the game, only one of the suggestions recommended focusing on the actual details of the physical processes occurring. The other 16 recommendations mostly suggested user interface improvements and new features such as the ability to play against the computer in Black Hole Pong.

4.2 Identifying "stretches" in the games

Most of the participants who played Chickens in Space, when asked how realistic the game was and which parts were not, expressed that they felt that the notion of birds in the vacuum of space was unnatural. Statements ranged from "[chickens] are supposed to explode on their own when in a vacuum" to "The chickens, feathers, and eggs are obviously not very scientifically accurate."[2]. Students also recognized that conservation of mass was being violated when they realized that "expelling 100's of chickens from a rocket slightly larger than the chicken does not affect mass ratio of chicken to rocket." No player reported any inaccuracy without mentioning chickens.

When playing Black Hole Pong, participants noticed errors that were more "realistic" as opposed to the comic-like inaccuracies of Chickens in Space. One high school student pointed out that the backgrounds constantly changed and show different parts of the universe, but the change of scenery was nice and thought it made the game better. Two highs school students and a college student identified that wormholes were scientifically inaccurate, which was also identified on the Black Hole Pong website. One student said that the black hole was black in the center, which made it unrealistic. Four of the high school students when asked which parts of the game were unrealistic responded "none/nothing," "I don't know" or "I think it was fine." Two students identified that balls or stars could escape from the black hole.

[2]NASA has done a decent amount of research on the topic of living organisms existing in space-like environments. Skin is sufficiently strong to keep organisms from exploding. [7]

Conversely, when asked which parts of the game were realistic, students who played Chickens in Space most frequently described the gravitational waves and the recoil effects as accurate. In Black Hole Pong, most students commented that the gravitational pull of the Black Hole seemed accurate, and only one student commented on the gravitational lensing.

4.3 Ways to improve based on survey responses

Students who played Black Hole Pong suggested two ways to improve the game. The first suggestion was to make the game playable by only one player, most likely by introducing some AI for a computer player. Additionally, while instructions are available on the website, many students suggested that developers improve the game by including a set of instructions within the game itself.

Students who played Chickens in Space expressed a wider range of suggestions. Some recommended making it easier to obtain points, and explained that they were frustrated by getting low scores. Another student suggested changing the game mechanics such that when you click, the net result is an acceleration towards the mouse cursor rather than away from the mouse cursor. In previous iterations of this game's design when such a behavior was implemented, test players suggested the behavior that is currently implemented. Thus a preferences panel where the user could choose a behavior that felt most natural to them may improve the game experience. Additionally, as with Black Hole Pong, students asked for more instructions and explanations of the game to be included in the game itself.

The research process was setup in order to measure what changes a user would experience by playing on their own machine in their own free time. Users did not play the game in any centralized playing location such as a computer lab or school room. Thus these results reflect what we would typically happen if somebody found the game as a result of a Google search or shared on social media. It seems from these data that stumbling across these games does not significantly alter excitement or understanding of gravitational waves.

However, as mentioned on the Black Hole Pong website, students met Black Hole Pong with great enthusiasm at science fairs[5]. It is not unreasonable to suppose that the effectiveness of the game may depend on the environment in which it is played. If the player has been exposed to even a 30 minute explanation during the game, or has the opportunity to play a multi-player game such as Black Hole Pong against someone with a deeper understanding of gravitational wave astronomy, the player may experience a greater benefit from the game. Such an environment could be implemented in a school setting following a lecture on gravitational waves. Another scenario might involve a researcher giving a public lecture and suggesting several games to play after their talk. A follow-up study to confirm this hypothesis may compare retention of concepts as a function of whether or not students were exposed to games such as those tested in this paper. While these games in and of themselves may not be educational, they may be engaging (evidenced by some students played up to a half hour, and in rare cases, in excess of an hour).

One other effort that may be useful in arousing student interest is a board game such as *Observe!*[12]. In *Observe!* players compete to be the first person to discover gravitational waves. Such a game would allow for more conversation than a game played on a console or computer, and would allow for students to ask more questions. However, the game requires a greater time commitment, table space, printed materials, and reading through instructions. Further investigation could combine a board game-style play of *Observe!* with a computer game environment.

Chapter 5

Conclusion

The object of this research was to evaluate gravitational wave games for their merit in educating and exciting students with regard to gravitational wave physics. In the two subject groups tested, and across the two games tested, no significant changes in understanding of gravity or black holes were observed. There was no significant change in attitude towards LIGO, nor a significant change in the perceived usefulness of LIGO.

This is, however, not surprising. Most university students played the game for less than fifteen minutes, and most high school students played for about five minutes, only enough time to play through a few rounds. This time-scale of exposure is not large enough to effect a significant change in attitude. This survey did not test whether a student's awareness of gravitational wave physics changed as a result of playing the game, but it would be difficult to design an instrument that would not confound the measurement of a student's awareness.

In conclusion, the educational video games that were tested in this study are not effective as a stand-alone media in increasing knowledge or excitement of gravitational wave physics. However, students did say that the games were enjoyable, and in a few cases held students attention in excess of an hour. These media may be more useful in conjunctions with other methods, such as classroom lectures, discussions, science fairs, or even novel methods like board games, in raising awareness and understanding of gravitational wave physics.

Bibliography

[1] B. P. Abbott et al. Observation of gravitational waves from a binary black hole merger. *Phys. Rev. Lett.*, 116:061102, Feb 2016.

[2] Wendy Adams, Kathy Perkins, Noah Finkelstein, Sam Reid, Michael Dubson, Noah Podolefsky, Carl Wieman, and Ron LeMaster. Research-based design features of web-based simulations, 2005.

> Types of features that UC boulder includes on their games. For example, the presentation advocates for using minimum text because students rarely read, and that instructions should be placed in useful help blurbs around the simulation. Also, too much instruction, either onscreen or from instructor seriously limits student curiosity.

[3] L Carbone, C Bond, D Brown, F Brückner, K Grover, D Lodhia, CMF Mingarelli, P Fulda, RJE Smith, R Unwin, et al. Computer-games for gravitational wave science outreach: Black hole pong and space time quest. In *Journal of Physics: Conference Series*, volume 363, page 012057. IOP Publishing, 2012.

> Developers of the original Black Hole Pong describe the motivation and process used to create Black Hole Pong and similar games. Preliminary findings based on online questionnaire and qualitative observations at science fairs are also presented to demonstrate participant enthusiasm for the games.

[4] Friese, Andreas. Black Hole Master. https://www.laserlabs.org/blackholemaster.php. Accessed: 2016-03-22.

The successor to Black Hole Pong, Black Hole Master offers the user better graphics, and smoother playing experience, and more features. At the time of this publication the game is not yet available to the public.

[5] Friese, Andreas. Black Hole Pong. http://www.gwoptics.org/processing/blackhole_pong/. Accessed: 2016-03-22.

Black Hole Pong was a game that was created in 2010 by a summer research student. The game was met with excitement at the Lancaster Science Fair.

[6] David Hestenes, Malcolm Wells, Gregg Swackhamer, et al. Force concept inventory. *The physics teacher*, 30(3):141–158, 1992.

The researchers used a combination of a pre- and post-test to identify qualitative misconceptions regarding Newtonian laws. Analysis and discussion identify patterns and difficulties that students face, based on test results and interviews with students. The paper also suggests modifications that can be made to traditional teaching methods that can shift the focus away from a quantitave approach that implies that physics is only about numbers, towards a qualitative approach that equips students to think like scientists.

[7] Parker, James F. Jr. and Vita R. West. *Bioastronautics Data Book*. National Aeronautics and Space Administration, second edition, 1973.

This handbook discusses known data about humans in space-like conditions. Based on these results, one can generally extrapolate to know (at least on the order of magnitude) how a chicken would behave in the vacuum of space.

[8] Noah S Podolefsky, Katherine K Perkins, and Wendy K Adams. Factors promoting engaged exploration with computer simulations. *Physical Review Special Topics-Physics Education Research*, 6(2):020117, 2010.

The paper references elements that can be incorporated into physics simulations in order to make them more engaging to students. One of these methods is to provide simulations that make use of analogies. While physics experts frequently employ analogies to make it easier understand principles, students frequently don't know principles well enough to know what analogies are valid. Additionally, students are given 'affordances,' or control over parameters of the simulation that are useful in answering their own curiosities about the simulation by varying input.

[9] Noah S Podolefsky, Katherine K Perkins, Wendy K Adams, M Sabella, C Henderson, and C Singh. Computer simulations to classrooms: tools for change. In *Physics Education Research Conference*, pages 233–236, 2009.

Computer simulations can serve as an alternative to learning in the laboratory, giving students opportunities to investigate cause-and-effect relationships without the overhead of managing equipment. When asked to compare the benefits and drawbacks of simulations vs. laboratory experiments, 26% of the students explicitly stated that PhET simulations were beneficial in understanding concepts, 64% of the students cited advantages of sim learning over real equipment, 22% indicated that they preferred real equipment over sim learning, and 42% students indicated advantages of using both (students were frequently coded into more than one category).

[10] Edward F Redish and Richard N Steinberg. Teaching physics: Figuring out what works. 1999.

Authors summarize different approaches that have been used to quantitatively and qualitatively asses student learning. Some settings included Force Concept Inventory style pre- and post-tests, other settings included video-taped interviews where students explained solutions to problems per their understanding.

[11] Carl L. Rodriguez, Meagan Morscher, Bharath Pattabiraman, Sourav Chatterjee, Carl-Johan Haster, and Frederic A. Rasio. Binary black hole mergers from globular clusters: Implications for advanced ligo. *Phys. Rev. Lett.*, 115:051101, Jul 2015.

Article gives discusses exciting updates to the LIGO project, suggesting that because the expected number of GW events depends greatly on the parameters from our limited understanding of cosmology, we may have grossly underestimated the frequency of these events

[12] Rollins, Jameson Graef and Wong, Michael H. Observe. 2016.

Observe is a board game where players compete to be first person to observe gravitational waves. It offers a multiplayer analog way of learning about gravitational wave science and experimental physics.

[13] Kurt Sqire. Changing the game: What happens when video games enter the classroom? *Innovate: Journal of online education*, 1(6):5, 20015.

Using Civilization III by Sid Meier, Sqire discusses the pros and cons of using digital games in the classroom. For example, students that have 'learned helplessness' by conventional curriculum have an engaging opportunity for trial and error and model forming. On the other hand, students that excel in our current curriculum complain that digital games in the classroom fail to prepare them for college or standardized exams.

[14] Ted Ragonstaff. Flaws of Commoners. *Dragon Magazine*, 29(11):87, Apr 2005. Accessed: 2016-03-22.

The April fools edition of the Dragon Magazine included a rule set that allowed the commoner class (if properly set up) to perform some extremely useful tasks, such as creating chickens from almost nothing. This served as the base idea for Chickens in Space.

[15] Carl Wieman and Katherine Perkins. Transforming physics education. *Physics today*, 58(11):36, 2005.

Traditional teaching methods frequently teach our students how to find numerical solutions to problems, without teaching them how to think like a physicist or to grasp the concepts behind a problem. The article references studies that state that students after traditional lectures, when asked the content of those lectures, are rarely able to recall anything beyond the general topic of the course.

[16] Carl E Wieman and Katherine K Perkins. A powerful tool for teaching science. *Nature physics*, 2(5):290, 2006.

C. E. Wieman and K. K. Perkins, Nature Physics, p. 290-292 , May 2006. Authors present an overview of PhET simulations, mentioning a few pedagogical elements not presented in other research papers, such as behavior in extreme situations (for example, simulated circuit batteries bursting into flames if current goes to high, etc.) Simulations are created with tiered complexity to allow instructors ability to tailor activities for the difficulty level of the class content. Notably conclusions based on research at UC Boulder, such as improved correlation to real-world scenarios and heightened engagement are discussed in results section.

[17] Carl E Wieman, Katherine K Perkins, and Wendy K Adams. Oersted medal lecture 2007: Interactive simulations for teaching physics: What works, what doesn't, and why. *American Journal of Physics*, 76(4):393–399, 2008.

Authors describe the formal process behind developing Simulations for University of Colorado's PhET program, including the step-by-step procedure of reviewing and revising features based on student feedback in live interview with the developers. These processes and the insights provided can help guide the development of educational features in my own game development.

Appendix A

Survey Questions

A.1 Pre-test

- **How would you describe your relationship to physics and astronomy?** Select one
  - I'm taking this course because I have to
  - I'm just taking a course or two, but don't plan to continue taking courses in these topics
  - These topics interest me, and I would like to study these topics in college, but not major in them
  - I would like to major in one of these these topics
- **What exposure have you had with the concept of gravity?** Select all that apply
  - Just the daily encounters with it in everyday life. e.g. falling down stairs, throwing footballs
  - I have studied it before in a physics class
  - I am studying it right now in a physics class
  - I have seen it talked about in documentaries
  - I have seen it used in SciFi movies
- **How much do you feel you know about black holes?** Select one

  - I do not know what a black hole is
  - I somewhat understand what a black hole is, but I don't think I could explain it
  - I have a pretty good idea of what a black hole is, and could explain it to someone else.

- **Please check all statements that are true, and leave all false statements unchecked. (There may be more than one true statement)**
  - Gravity is a force
  - Gravity is only a theory, and hasn't been fully proven
  - Gravity makes things fall
  - Gravity is what holds the earth moving about the sun
  - The moon has no gravity
  - Gravity is strongest between distant objects

- **Please check all statements that are true, and leave all false statements unchecked. There may be more than one true statement)**
  - You can see a black hole directly
  - Black holes affect the way our sun moves through space
  - Black holes are pulling on you right now
  - Black holes can change size
  - Black holes used to be stars
  - If our sun became a black hole, it would suck all the planets into it

- **I am interested in learning more about the LIGO project.** Scale of 1 (strongly agree) to 5 (strongly disagree).

- **I think that the LIGO project is something useful to the human race.** Scale of 1 (strongly agree) to 5 (strongly disagree).

A.2 Post-test

- **Which game did you play?** Choice between Black Hole Pong and Chickens in Space
- **How would rank the game that you played?** Scale of 1 to 5
- **How much time did you spend playing the game?**
  - Less than 5 minutes
  - Between 5 and 15 minutes
  - Between 15 and 30 minutes
  - Between 30 minutes and 1 hour
- **Which parts of this game do you feel are scientifically accurate?** Free response
- **Which parts of this game do you feel are not scientifically accurate?** Free response
- **Is it okay for a game to bend the rules of physics in order to make it more fun?** Scale of 1 (strongly disagree) to 5 (strongly agree)
- **People may not realize when playing a game that the physics is not "real physics," and therefore develop a misconception of physical laws.** Scale of 1 (strongly disagree) to 5 (strongly agree)
- **How would you improve the game if you were a developer?** Free response
- **After playing this game, I am more excited to study astronomy and physics** Scale of 1 (strongly disagree) to 5 (strongly agree)
- **Based on this game, I feel like I understand topics of gravity and black holes more deeply** Scale of 1 (strongly agree) to 5 (strongly agree)
- **Is there anything else you would like to share based on the previous questions?** Free response

- **I am interested in learning more about the LIGO project.** Scale of 1 (strongly agree) to 5 (strongly disagree).
- **I think that the LIGO project is something useful to the human race.** Scale of 1 (strongly agree) to 5 (strongly disagree).
- **Please check all statements that are true, and leave all false statements unchecked. (There may be more than one true statement)**
  - Gravity is a force
  - Gravity is only a theory, and hasn't been fully proven
  - Gravity makes things fall
  - Gravity is what holds the earth moving about the sun
  - The moon has no gravity
  - Gravity is strongest between distant objects
- **Please check all statements that are true, and leave all false statements unchecked. There may be more than one true statement)**
  - You can see a black hole directly
  - Black holes affect the way our sun moves through space
  - Black holes are pulling on you right now
  - Black holes can change size
  - Black holes used to be stars
  - If our sun became a black hole, it would suck all the planets into it