PONTIFICIA UNIVERSIDAD CATOLICA DE CHILE

ESCUELA DE INGENIERIA

A STRUCTURED METHODOLOGY FOR THE DESIGN OF GAMES FOR THE CONCEPTUAL UNDERSTANDING OF PHYSICS

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Thesis submitted to the Office of Research and Graduate Studies in partial fulfillment of the requirements for the Degree of Master of Science in Engineering

Advisor:
MIGUEL NUSSBAUM

Santiago de Chile, January 2012

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To my family and friends, and to all those who supported me during my research.

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RESUMEN

Los programas de simulación y los videojuegos se han utilizado satisfactoriamente para enseñar física conceptual. Sin embargo, no existe una metodología clara para guiar el diseño de este tipo de juegos. Para remediar esto, se propone una metodología estructurada para el diseño de videojuegos de física conceptual que consolide explícitamente los principios de integración intrínseca (Habgood & Ainsworth, 2011) con el análisis atómico de la estructura de juegos (Koster, 2005; Cousins, 2005; Cook, 2007). Para poner a prueba este proceder, se rediseñó un juego ya existente (cuyo objetivo era enseñar conceptos de electroestática) y se comparó la efectividad educativa de la versión original y nueva. La adaptación original era cualitativamente intrínseca, pero al aplicar la metodología propuesta se logró refinar y profundizar la naturaleza intrínseca de todos los objetivos educativos del juego. Los estudios también compararon una versión con fantasía endógena con una versión sin fantasía.

Los resultados reflejaron que los estudiantes que jugaban el videojuego rediseñado a través de la Integración Intrínseca Atómica, mejoraron significativamente sus resultados y mostraron menos dudas conceptuales que aquellos que jugaron la versión original. Sin embargo, las versiones con y sin fantasía no revelaron diferencias significativas en el desempeño de los alumnos. Por medio del análisis y rediseño del videojuego, se propone una posible metodología para asistir en el diseño de juegos para el aprendizaje de física conceptual. Se busca que esta metodología sirva como una guía simple para el diseño de estos videojuegos educativos.

Palabras Claves: simulaciones; videojuegos, mejorar la enseñanza en salas de clases.

ABSTRACT

Computer simulations combined with games have been successfully used to teach conceptual physics. However, there is no clear methodology for guiding the design of these types of games. To remedy this, we propose a structured methodology for the design of conceptual physics games that explicitly integrates the principles of the intrinsic integration approach for designing instructional games (Habgood & Ainsworth, 2011) with an atomic analysis of the structure of games (Koster, 2005; Cousins, 2005; Cook, 2007). To test this approach, we redesigned an existing game to teach electrostatics and compared the educational effectiveness of the original and redesigned versions. The original version was qualitatively intrinsic, but applying our proposed methodology refined and deepened the intrinsic nature of all core learning goals within the game. Our studies also compared an endogenous fantasy version of the game with a non-fantasy version.

Our results showed that students who played the game which had been redesigned using the Atomic Intrinsic Integration Approach achieved a statistically significant improvement in results and showed fewer conceptual problems than the students who played the original version. The fantasy and non-fantasy versions, however, did not display any significant differences in outcomes. Based on the analysis and redesign of the game, we defined one possible methodology to assist in the design of games for the conceptual understanding of physics. We believe that this methodology could be a simple and useful guide for designing other conceptual physics games.

Keywords: simulations, videogames, improving classroom teaching.

1. INTRODUCTION

1.1 Motivation

1.1.1 Videogames in education

Since the early beginnings of the videogame industry (1980s) educators have studied the different aspects of this medium in order to define the elements of game design that can be used to make learning environments more engaging (Bowman 1982; Bracey 1992; Driskell & Dwyer, 1984; Malone 1981). Academics state that videogames allow players to progress at their own rate, permit the transfer of concepts from theory to practice, give immediate feedback to actions, provide graceful failure and give freedom of exploration and discovery (Gee, 2003; Squire, 2003). In addition, multiple researches have shown that videogames can be incorporated into a learning environment with positive results (Clarke & Dede, 2007; Dede, 2009; Klopfer & Squire, 2009; Mitchell, Dede & Dunleavy, 2009).

At the present time videogames are being integrated into diverse academic topics such as Mathematics (Lee & Chen, 2009), Electrostatics (Squire, Barnett, Grant, & Higginbotham, 2004, Garcia-Campo, 2010), Biology (Annetta, Minogue, Holmes, & Cheng, 2009), History (Watson, Mong & Harris, 2011) and Social Science (Cuenca López & Martín Cáceres, 2010). All these efforts seek to teach specific contents through the use of intrinsic game mechanics and fixed learning objectives.

1.1.2 Fantasy in educational videogames

In 1980, Malone used videogames to study the intrinsic motivation of players and, through a series of surveys, observations and interviews, defined three main elements that made games fun: Challenge, Fantasy (narrative) and Curiosity. Malone stated that the game narrative should appeal to the players' emotions by incorporating a metaphor

that would be suitable for the educational experience. In later researches, Malone would expand this concept by defining intrinsic and extrinsic (or endogenous and exogenous) fantasy (narrative). In an intrinsic approach "there is an integral and continuing relationship between the fantasy context and the instructional content being presented" (Malone & Lepper, 1987), while in an extrinsic, "fantasy depends on the skill being learned but not vice versa" (Malone & Lepper, 1987).

In 1996, Rieber illustrated the use of exogenous and endogenous fantasy in the game "hangman". He concluded that exogenous narrative had no impact on gameplay, while an endogenous fantasy was more suited for educational games because it merged successfully with gameplay and motivated learners through the use of story elements.

In 2003, Gee identified fantasy (narrative) as a key element of educational games, because it allowed students to become embodied in the gameplay experience (take a role in the story) and actively solve the multiple challenges presented by the game.

In 2006, Dickey proposed a theoretical framework for integrating narrative into a game-based learning environment. This design heuristic considered six principles:

- Present the initial challenge.
- Identify potential obstacles and develop puzzles, minor challenges, and resources.
- Identify and establish roles.
- Establish the physical, temporal, environmental and emotional, and ethical dimensions of the environment.
- Create a backstory.
- Develop cutscenes to support the development of the narrative story line.

1.1.3 Previous work

Garcia-Campo et al (2010) developed a Classroom Multiplayer Presential Game (or CMPG) (Susaeta, 2010) about electrostatics called "First Colony". In this game, students played as astronauts that had to collect electrically charged crystals in order to gather energy for their colony. The experience showed that CMPGs can be used to successfully transfer specific leaning objectives that have been proved to be difficult for students, such as charge interaction and Coulomb's Law (Maloney, 2001). Figure 1-1 shows a screenshot of the game.

Figure 1-1: First Colony

1.2 Hypothesis

The first hypothesis of this work is that the use of the "intrinsic integration" paradigm (Habgood, 2005) to redesign an existing educational videogame will improve the learning outcomes. The game will allow students to integrate concepts through practice, while permitting exploration and conceptual analysis.

The second hypothesis is that the integration of a fully developed fantasy will increase the educational effectiveness of the game. The use of backstory, characters and cutscenes will motivate students and allow them to become embodied in the gameplay experience.

1.3   Objectives

Consistently with the proposed hypothesis, the general objective of this thesis is to develop an educational videogame to teach electrostatics (more precisely, Coulomb's First Law) based on the work done by Garcia-Campo et al (2010). This new version will redesign the mechanics and challenges through the use of the 'intrinsic integration' paradigm, in order to improve the teaching of multiple learning topics.

A second objective is to implement two versions of the same game, which will use the same mechanics and challenges but differ in their degree of fantasy: the first one will incorporate a fully-fledged narrative, while the other will be stripped of all fantasy elements. To do this, the theoretical framework proposed by Dickey (2006) will be used.

To validate the two hypotheses, the game will be included in a class and students will play it to practice the concept provided by the teacher. Half of the students will play the fantasy version while the other half will use the non-fantasy iteration. A posttest will evaluate the students' learning and a Game Experience Questionnaire will be used to measure the players' engagement.

1.4   Chapter Overview

The current chapter describes the redesign process of the game as well as the integration of game narrative. Section 1.5 will give a brief description of the game and highlight its main features. Section 1.6 will present the game mechanics and objectives. Section 1.7 will describe the game narrative and the aesthetical differences between the two

versions. Section 1.8 will show the graphic user interface implemented for the game. Section 1.9 will analyze the level design process. Section 1.10 will describe the experiments. Section 1.11 will discuss the general conclusions and propose research paths for future work.

Chapter 2 describes the methodology used to design the game and integrate intrinsic mechanics. Section 2.1 refers to the state of the art. Section 2.2 describes the game and its learning objectives. Section 2.3 presents the original game design, analyses the redesign process based on an intrinsic integration approach and describes the fantasy and non-fantasy versions of the game. Section 2.4 refers to the experimental study, presenting the experimental setup, results and statistical analysis. Section 2.5 discusses the results and procedures of this study, while proposing multiple principles for the game design process. Section 2.6 presents the conclusions of this work. This chapter was submitted to the Computers and Education journal.

1.5   Game Brief

1.1.4   Game Description

First Colony 2D is an educational game about physics, in which players must learn the concepts of electrostatics to solve a series of puzzles that involve moving test charges to specific points of a map (goals) while avoiding obstacles. Students play in groups of three, so team communication and collaboration are vital for completing every level successfully. Each level is completed when the team manages to move every test charge to the goal.

First Colony 2D implements a model that is a combination of face-to-face Computer Supported Collaborative Learning (CSCL) (Zurita & Nussbaum, 2004) and a Classroom Multiplayer Presential Game (CMPG) (Susaeta, 2010), where three students share one

computer and work as a team. The game can handle multiple inputs, so each player controls his/her character through the use of a mouse.

As stated in section 1.3, two versions of the game were constructed. Both iterations implemented the same game mechanics and objectives, but differed in their amount of fantasy. The first version was dispossessed of all fantasy, so, players controlled electric charges and interacted with star-shaped test charges in order to move them to specific zones while avoiding spiked balls. The second version incorporated a fully-fledged story (characters, plot, etc.), causing the game elements to change: players instead controlled astronauts that had to collect electrically-charged crystals by moving them to portals. The hazards came in the form of asteroids that surrounded the collection site.

1.1.5   Learning Objectives

First Colony 2D was developed to teach electrostatics to 12th graders. The game includes three main topics: Coulomb's Law in its vector form (Equation 1a), the principle of linear superposition of forces (Equation 1b) and Newton's 3rd Law of Motion, applied to electric forces (Equation 1c).

$$\overrightarrow{F_{12}} = k\ \frac{q_1 q_2}{r^2}\hat{r} \qquad \text{(a)}$$

$$\vec{F}_j = \sum_i \overrightarrow{F_{ij}} \qquad \text{(b)}$$

$$\vec{F}_{12} = -\vec{F}_{21} \qquad \text{(c)}$$

Equation 1: Coulomb's Law (a), the principle of linear superposition of forces (b) and Newton's 3rd Law of motion (c).

These topics are part of the physics curriculum established by the Chilean Ministry of Education (MINEDUC, 1998).

The learning objectives of the game are:

- Understand the interaction between objects with positive, negative and neutral charge.
- Understand the relation between charge intensity and electric force.
- Understand the relation between the distance among charges and electric force.
- Understand the relation between the electric forces produced on two charges that are interacting.
- Apply Coulomb's Law to predict the magnitude and direction of the force generated between two charges.
- Apply the principle of linear superposition to predict the magnitude and direction of the net force over a charge in a system with multiple charges.

1.6   Game Mechanics

Mechanics are the procedures and rules of the game. They describe the goal of the game, how players can and cannot achieve it, and what happens when they try it (Schell, 2008). First Colony 2D incorporates multiple mechanics that define the core gameplay experience. These mechanics can be divided in two categories: Game-related and Player-related. The first group includes the mechanics that define the victory and defeat conditions of the game. On the other hand, the second group includes those that originate from the player's actions and his/her interactions with other game elements.

1.1.6   Game-related Mechanics

1.1.6.1   Victory Conditions:

The players' main objective in First Colony 2D is to move test charges to objective zones in the map. If a test charge enters an objective zone, the team is given a score (based on their completion time) and the level is marked as "completed". Figure A shows a test charge (star) going into an objective zone.
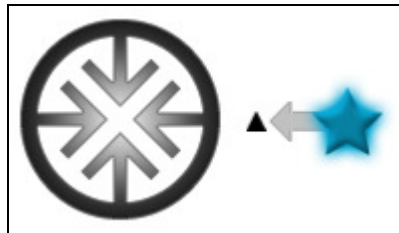
Figure 1-2: Victory condition

1.1.6.2   Defeat Conditions:

The team is defeated if their test charge is destroyed. This happens if:

- The test charge collides with a hazard.
- The test charge collides with a player's avatar.
- The test charge leaves the boundaries of the screen.

If any of these conditions are met, the test charge will be reset to its initial position; forcing the players to restart the level.

1.1.7   Player-related Mechanics

1.1.7.1   Moving the avatar

Every player can change the current position of their avatar by left-clicking on any position on the map. Once this is done, the avatar will move on a straight line from its current location to the new one.

1.1.7.2   Select charge value

At any point of the game players can select the charge value of their avatar; this can be done by using the mouse wheel. Scrolling upwards will cause the charge to increase, while scrolling downwards will cause it to decrease. A "charge meter" located at the left of the player's avatar will show the current value of the charge. Figure 1-3 shows this meter.
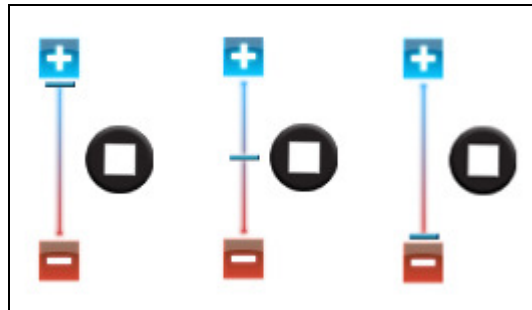
Figure 1-3: Charge meter for a positive, neutral and negative value.

1.1.7.3   Activate the electric charge

Players can activate their electric charge by pressing the mouse wheel; this will cause the following changes to the gameplay:

- ▪ The player will be marked as "ready to interact" (this will be fully explained in the "Move test charge" mechanic).
- ▪ The color of the player's avatar will change to that of the selected charge.
- ▪ The avatar's moving speed will be heavily reduced.

The electric charge can be deactivated by pressing the mouse wheel again, thus, returning the player's state back to normal. Figure 1-4 shows an avatar activated with three different charge values.
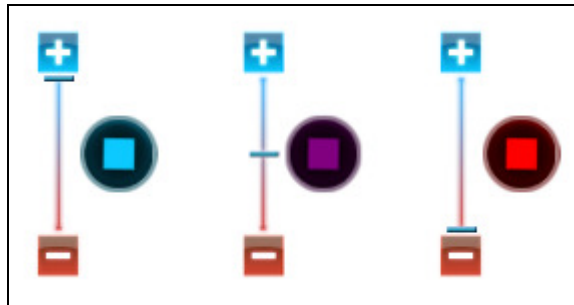
Figure 1-4: Active charge for a positive, neutral and negative value.

1.1.7.4 Move test charge

A test charge will only move if every member of the team is "ready to interact". If this is the case, each player will apply an electrostatic force to the test charge (calculated using Coulomb's first law of electrostatics) and the test charge will move in the direction defined by the sum of all players' forces.

A visual cue will be provided to the players in order to help them move the test charges; each individual force will appear as an arrow on top of the test charge, showing its direction and magnitude (a longer arrow will mean a bigger value). Figure 1-5 shows the arrows on a test charge.
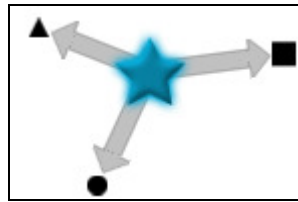
Figure 1-5: Force visual cue.

1.1.7.5 Divide test charges

Players can shoot a projectile in order to divide a test charge into two smaller fragments. This is done by right clicking on any test charge on the map. The new test charges will have the same polarity of the initial charge, but their charge value will be lower and not equal (a higher value this will be represented as a brighter color). In Figure 1-6 two fragments can be seen.

Figure 1-6: Divided test charge.

1.1.7.6 Crash with hazards

If a player's avatar collides with a hazard, the avatar will be "defeated", disappearing from the map. After a few seconds, the player will reappear on a fixed location (that depends on the map). There is no limit to how many times the player can be defeated.

1.7   Game Narrative

1.1.8   Game narrative design process

The use of stories in games is a fundamental part of game design. A game without a story becomes an abstract construct (Rolling and Adams, 2003). The role of narrative in adventure games is to provide initial and ongoing motivation for the game (Dickey, 2006).

In First Colony 2D the game narrative had to provide a cognitive framework for solving problems about physics. To do this, the game-narrative design process for First Colony 2D followed the heuristics proposed by Michele D. Dickey (2006) which described key components that should be implemented in order to integrate a narrative into a game-based learning environment.

This section is formed of two parts: The first will describe how Michele Dickey's heuristics were used to create a game narrative for First Colony 2D, while the second will show the graphical changes that the game experienced due to the integration of narrative.

1.1.8.1   Create a backstory

The backstory will likely outline the environment, ethical, physical, emotional, and temporal dimensions of the narrative as well as including a profile of the protagonist(s). The central challenge or initial call to action may be introduced at this time (Dickey, 2006).

Considering every aspect of Dickey's definition, an initial narrative was developed for First Colony 2D. The backstory is the following:

At the end of the 21st century, planet Earth plunged in chaos. Human population exceeded 12 billion, causing natural resources to become scarce. War raged throughout the globe, as nations battled for controlling the remaining energy sources.

In a desperate attempt to restore order, the U.N. initiated an emergency mission called "First Colony". The main objective of this mission was to establish a human colony in outer space to search for new natural resources that would solve all energy needs.

A glimpse of hope emerged as many nations supported the enterprise. Scientists and engineers from all around the globe worked together to construct the most technologically advanced spaceship and the best astronauts were trained to fulfill this quest.

After several years of preparations, the ship took off and ventured into space. The mission left the solar system and traveled through the darkest corners of the galaxy. Decades passed and the spaceship made its first discovery: a gargantuan green planet surrounded by a thick ring of asteroids. The planet was named "Second Earth" and the crew established multiple settlements throughout the surface.

Scout parties explored the planet in search for natural resources. However, very few were found and the colony began to struggle as its energy reserves grew thin. If no source was discovered soon, the settlers would perish and all hope for humanity would be lost.

An unexpected event brought hope to the colony: huge electromagnetic waves were detected in the planet's vicinity. Scientist soon discovered that the ring surrounding "Second Earth" was also formed by crystals that could store electrical charge. They were named "Quarks" and brief studies determined that one of these crystals could provide enough energy to sustain humanity for a hundred years.

A reconnaissance mission uncovered that "Quarks" were extremely fragile and that any form of physical interaction could easily destroy them. Considering this, the settlers decided to test other ways to move the crystals.

Engineers discovered that "Quarks" responded to electrostatic interactions and invented the EMAD (Electromagnetic Activation Device), a personal gadget that allowed its user to create an electromagnetic field around him. By using this new technology, astronauts could move the crystals and guide them to nearby collection centers.

A special squad of astronauts will be rigorously trained in order to fulfill the dangerous task of collecting the "Quarks" and saving humanity from extinction.

The major concern when creating the backstory for First Colony 2D was to include the game's main mechanic (moving test charges using electrostatic interactions) in a way that would be consistent to the game's narrative. This was achieved by inventing the EMADs and the Quarks, they would represent the electrically-charged particles and the test charges respectively. Establishing that Quarks could store electric charge and that they would break at contact, explained the use of electrostatic interactions as a collecting method.

1.1.8.2   Present the initial challenge

At the core of the quest is a major challenge; it is the apex or climax of the narrative. In a learning environment, the central challenge may be a problem or project that will serve as the catalyst of the story line and the goal for learning (Dickey, 2006).

In First Colony 2D, the major challenge consists in collecting electrically-charged crystals (or "Quarks") in order to save humanity from extinction. This challenge is

established during the backstory and serves to motivate the action throughout the game. To answer this call, players must venture into the ring of asteroids and resolve numerous puzzles while avoiding different kinds of hazards.

In order to complete the main challenge, player will have to learn the concept of electric charge and Coulomb's first law of electrostatics. This knowledge will be evaluated through several levels that will present different scenarios that the players will have to overcome. In addition, students will play in teams of three, so this test will require team collaboration and communication.

1.1.8.3 Identify potential obstacles and develop puzzles, minor challenges, and resources

Leading up to the main challenge are smaller obstacles and challenges. In a learning environment these could be procedures, skills, and content knowledge that will help learners complete the central challenge (Dickey, 2006).

The game has two minor challenges prior to the major engagement: the training exercises and the missions.

The training exercises are a set of eight tutorial levels in which players are taught the fundamental concepts of electrostatics (electrically charged particles, Coulomb's first law, electrical force, etc.), basic game controls (movement of the avatars, charge selection, charge activation, etc.) and team mechanics (player interactions, team coordination, etc.). These levels will provide players with the necessary knowledge to complete the game, and will allow them to experiment without failure before the real stages begin.

The missions include the four levels that precede the final stage. Each stage provides a different puzzle that will test the players' knowledge and the team's coordination. The difficulty increases with every level, as the behavior of the asteroids will change with every level; starting as static obstacles, changing to strange-moving comets and ending as a rain of fast moving meteors. The levels will be fully described in section 1.6.4.

1.1.8.4   Identify and establish roles

Throughout the journey, the hero encounters many characters and situations which play certain roles in the journey. These roles serve a particular function. In a learning environment the following roles might correspond to the following functions: the Hero, the Mentor, the Threshold Guardian, the Herald, the Shape-shifter, the Shadow and the Trickster (Dickey, 2006).

The role of the **Hero** will be assigned to the players, who will take control of the astronauts of the "First Colony" mission, a group that must explore the galaxy to discover new energy sources for mankind. The heroes will encounter the journey once they are given the task to collect "Quarks" in the dangerous asteroid field that surrounds the planet. The heroes' mission is crucial for humanity's survival because the crystals will provide enough energy to resolve Earth's energy needs.

The role of the **Mentor** will be taken by the teacher that controls the experience. The teacher will personify the astronaut commander that will assist the players throughout the game. During the training exercises the teacher will explain the basic concepts of electrostatics and encourage the analysis of the formula proposed by Coulomb's first law of electrostatics. Also he/she can emphasize learner reflection by pausing the game and encouraging team planning and evaluation of different resolution strategies. During the mission levels, the teacher will be able to see the number of victories and defeats of each team and provide guidance to those with low performance.

The **Threshold Guardian** might be a situation that tests the learner's content knowledge (Dickey 2006). In First Colony 2D this role is taken by the first mission level, in which players get to explore the asteroid field for the first time and must use all the skills acquired during the tutorial levels to achieve victory. This stage also symbolizes the start of the heroes' definite journey, because they leave the safety of the planet in order to face new and more difficult challenges. Once the Threshold Guardian is defeated, the players will finally become "collectors".

The **Herald** signals change and new information (Dickey 2006). The role of the herald will be taken by the graphic user interface which will provide players with useful information about the team's performance and the objective of the current level. This data will be presented to the players as "Mission messages" sent by the command center and will be showed to the team through a heads-up display (HUD) and a goal panel. Each of these elements will be fully described in section 1.8.

The **Shapeshifter** represents doubt (Dickey 2006). In First Colony 2D doubt is presented in the form of unknown hazards and shifting challenges. Throughout the game players will collect huge amounts of Quarks and disrupt the electromagnetic balance of the asteroid field. This will cause the asteroids to acquire strange behaviors and become more dangerous for the astronauts. Tension remains high until the final mission takes place.

The **Shadow** may be the main challenge or conflict (Dickey 2006). The role of the shadow is assigned to the last level of the game, which represents the major challenge and the ultimate barrier that players must overcome before achieving total victory. In this stage, the astronauts will experience the highest level of difficulty and will be assigned to collect the last remaining Quarks while a fierce meteor storm rages around

them. If the Shadow is defeated, all Quarks will be transported to Earth and humanity's safety will be assured.

The **Trickster** could also be envisioned as both comic relief and self-reflection (Dickey 2006). In First Colony 2D, the role of the trickster was not implemented.

1.1.8.5   Establish the physical, temporal, environmental and emotional, and ethical dimensions of the environment

A large part of the game-play experience is the setting. A game setting can be defined by physical, temporal, environmental, emotional and ethical dimensions (Dickey, 2006).

The **physical dimension** defines the physical space in which the player's character or game pieces move around (Rollings & Adams, 2003). First Colony 2D was developed to support traditional teaching, so the game will take place in the classroom and the teacher will control the flow of the experience.

The **temporal dimension** of a game world defines the way that time is treated in that world and the ways in which it differs from the real world (Rollings & Adams, 2003). First Colony 2D implements a variable time structure, i.e. time runs much faster than in reality, makes jumps and skips periods when nothing interesting is happening (Rollings & Adams, 2003). The story establishes that the astronauts must be trained for months, but the players can complete the tutorial levels in minutes. The narrative omits the space travel (that took several years) and the preparations before the missions, because they are not important to the plot.

The **environmental dimension** not only defines the game setting appearance, but also characterizes the game setting as fantasy or realism, the historical context and the geographical location (Rollings & Adams, 2003). First Colony 2D unfolds in a futuristic

setting where space travel and technologically advanced devices are common. The game narrative combines realistic elements (planet Earth, asteroids, space travel) with a fantasy plot (lack of natural resources, quest into space). The objective of the game narrative is to establish a fantasy setting while staying believable to the players.

The **emotional dimension** of a game world defines not only the emotions of the people in the world, but, more important, the emotions that the designer hopes to arouse in the player (Rollings & Adams, 2003). The narrative in First Colony 2D aims to amuse the players by giving a sense of greatness and importance to the quest that has to be fulfilled. Furthermore, the story focuses on creating tension and doubt as the astronauts have to overcome new challenges.

The **ethical dimension** of a game defines what right and wrong mean within the context of the world (Rollings & Adams, 2003). In this story, the ethical dimension centers on the sense of duty. Players receive the call to action and must complete the task in order to save humanity from extinction. Considering this, right is defined as fulfilling the quest, and wrong will be to refuse or fail the mission.

1.1.8.6   Develop cutscenes to support the development of the narrative story line:

Cutscenes provide the ongoing narrative. They may be used to deliver key information or plot hooks and could provide feedback about whether learners have successfully accomplished a task or aspect of instruction (Dickey, 2006).

Cutscenes are the main mechanism by which narrative is incorporated into First Colony 2D. They are used frequently throughout the experience and establish the setting, present the characters, describe the journey, show plot twists and reveal useful information.

The cutscenes in First Colony 2D are comprised of three elements: video, sound and text. The videos consist in pre-rendered 3D animations that were created through the use of the game's 3D engine. The sound includes several orchestrated pieces that help to set the mysterious, yet epic, mood of the game. The text is a recurring tool and communicates a huge part of the game narrative, so special care was taken into choosing the color, size, location and length of each message, so no information would be lost.

Four cutscenes where created for the game: introduction, mission start, meteor storm and ending. All cutscenes provide different information to the player and are vital for understanding the game's story. Figure 1-7 shows how each cutscene was incorporated into the flow of the game.
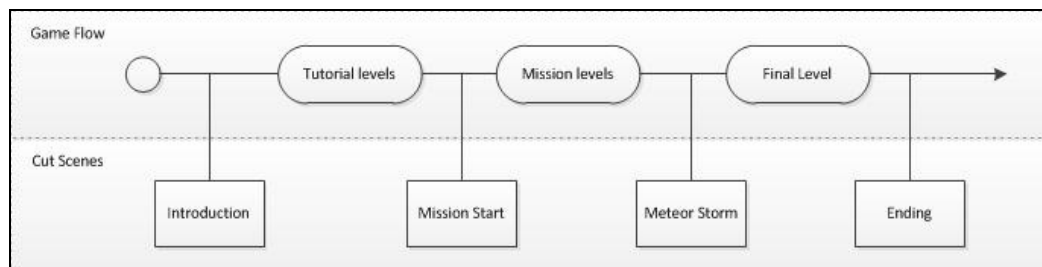
Figure 1-7: Cutscenes in game flow.

The **introductory cutscene** presents the game's backstory; i.e. it describes the context, plot, location and key story elements. This non interactive movie starts by showing planet Earth and describing the dire situation that humanity is facing. After this, the "First Colony" mission is explained to the players and the scene shows how the space ship leaves Earth and arrives to the new planet. Figure 1-8 shows some fragments of the first part of the cutscene.

Figure 1-8: Introductory cutscene: first segment.

The second part of this cutscene tells the players about the "Quarks" and who they were discovered by showing the field of asteroids that surround "Second Earth". Afterwards, the main characters of the game are presented; a scene shows the astronauts and describes their quest. Figure 1-9 shows the second part of the cutscene.
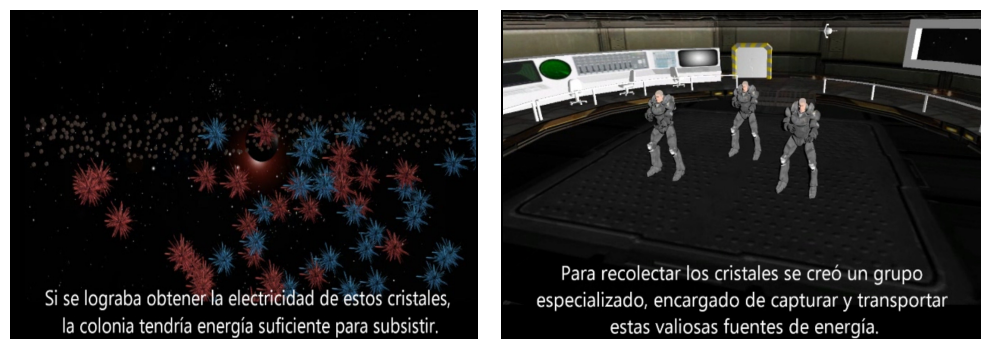
Figure 1-9: Introductory cutscene: second segment.

The introductory cutscene ends with a title screen. This can be seen in Figure 1-10.

Figure 1-10: Title screen.

The **"mission start" cutscene** congratulates the players for completing the tutorial levels and shows how the astronauts aboard the spaceship and venture into the asteroid field. This scene is displayed in figure 1-11.

Felicitaciones reclutas, han completado su entrenamiento!

Figure 1-11: Mission Start cutscene.

The **"meteor storm"** cutscene is played at the beginning of the fifth mission and shows how a huge number of meteors have entered the asteroid field and threaten to destroy the last remaining Quarks. The text messages emphasize the direness of the situation and motivate the players to act swiftly. Figure 1-12 shows this cutscene.
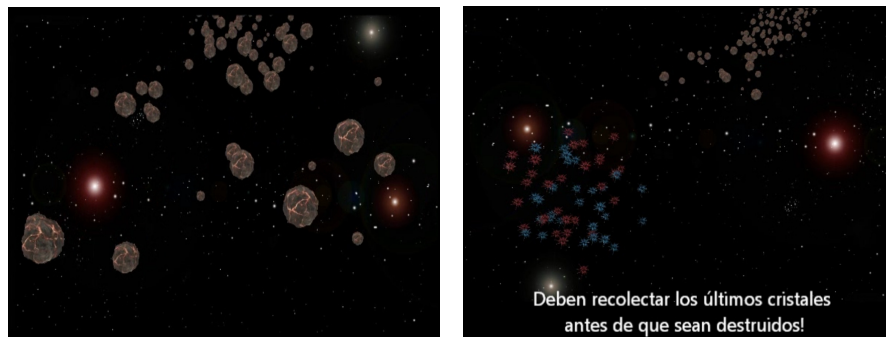
Figure 1-12: Meteor Storm cutscene.

The **ending cutscene** shows the Astronauts returning safely to the planet carrying the precious Quarks that were collected throughout the missions. A victory song plays and the scene ends as the credits roll in the background. Screenshots of the ending cutscene are displayed on figure 1-13.
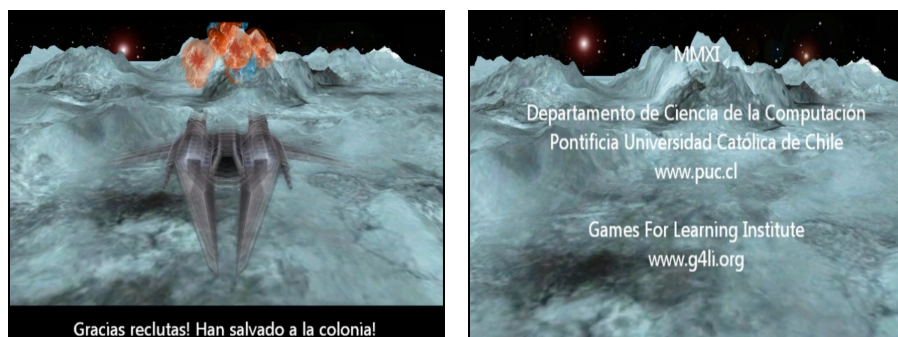
Figure 1-13: Ending cutscene.

1.1.9 Aesthetical and graphical changes

Games that include fantasy show or evoke images of physical objects or social situations not actually present. Non-fantasy games involve only abstract symbols (Malone, 1980).

To fully incorporate narrative into First Colony 2D, all game elements had to be visually modified to fit the setting. Table 1-1 shows the changes made to each game object.

Game Element	Without Narrative	With Narrative
Players		
Test Charge		
Objective		
Hazards		

Table 1-1: Aesthetical changes of game objects.

Both versions can be seen in Figure 1-14.
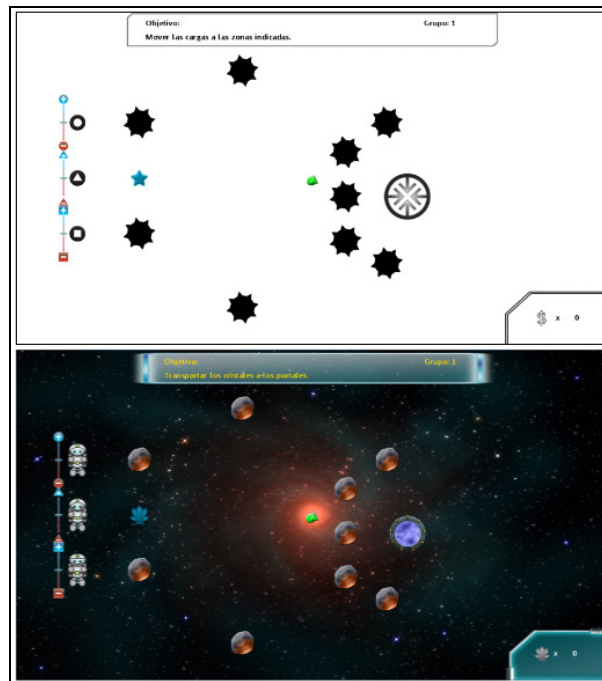
Figure 1-14: Fantasy and non-fantasy versions.

1.8   Graphic User Interface

The Graphic User Interface (GUI) of First Colony 2D includes several elements that serve to communicate information to the students. This section will start by defining the general layout of the GUI, followed by a description of its components, showing how they vary due to the integration of narrative.

1.1.10   General layout

The graphic user interface of the game includes five major components: three player heads-up displays (or HUDs), one Team HUD and one Goal board. The location of each of these elements can be seen in Figure 1-15.
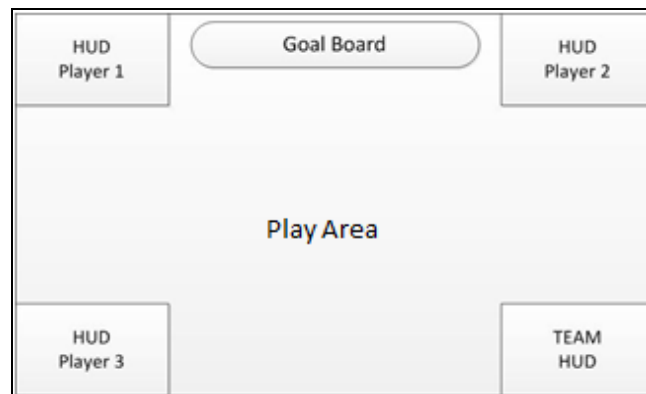
Figure 1-15: GUI general layout.

The general layout of First Colony 2D was designed with the intention of displaying information in a clear and efficient way. In addition, the components' distribution aims to maximize the play area of the game.

1.1.11   GUI elements

1.1.11.1   Player HUD:

Each player has a HUD that is only available during the tutorial levels and provides information of the player's personal performance. In addition, this component includes two elements: the player identifier and the score marker. Figure 1-16 shows the non-narrative and narrative versions of a players HUD, as well as the player identifier (1) and the score marker (2).
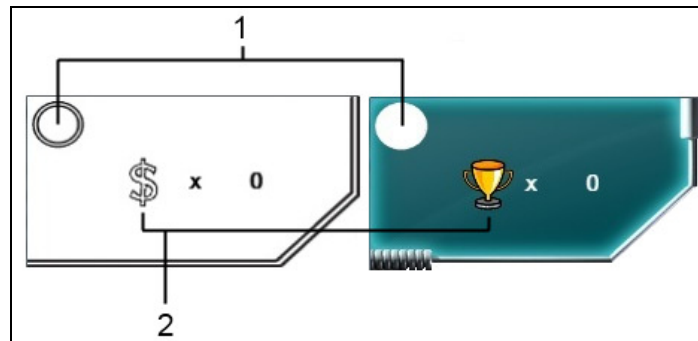
Figure 1-16: Player HUD.

Different symbols were utilized to represent the number of victories for each player (2) in each version. A currency icon was utilized for the non-fantasy version and a trophy for the fantasy iteration.

1.1.11.2   Team HUD:

The Team HUD will be shown during the mission levels and will provide information of the team's performance in the current level. The HUD includes a score marker that displays the number of points that players have accumulated throughout the level. Figure 1-17 shows the non-narrative and narrative versions of the Team HUD, as well as the score marker (1).
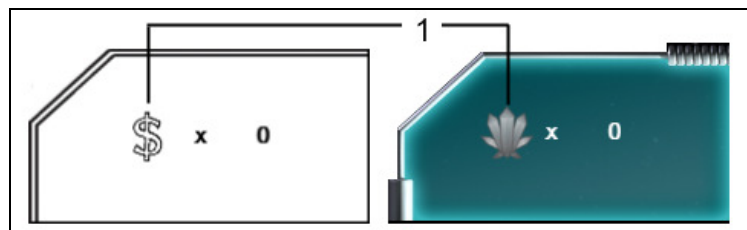
Figure 1-17: Team HUD.

1.1.11.3   Goal board:

The goal board displays a brief description of the task that the players must fulfill in the current level and the team's identification number. A screenshot of the goal board can be seen in figure 1-18, which displays the goal description (1) and the team identifier (2).
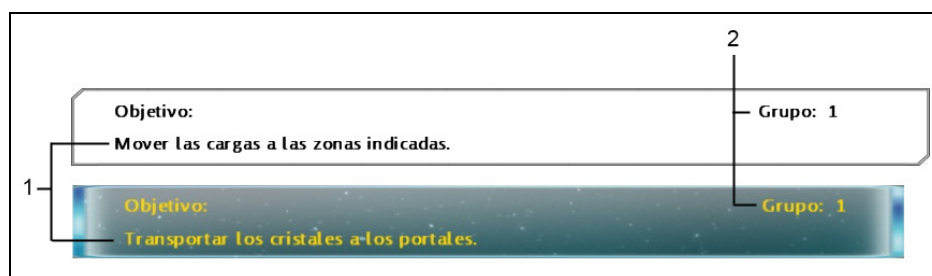
Figure 1-18: Goal Board.

1.9   Level Design

First Colony 2D was conceived as an educational tool for the traditional learning environment. Because of this two main challenges had to be solved. Firstly, the game should allow students to progress at their own pace, while allowing the teacher to guide the experience. Secondly, the game should provide challenges that encourage the practical application of the concepts of electrostatics. A crucial element for resolving these matters was the Level Design, which can be defined as arranging the architecture, props and challenges in a game in ways that are fun and interesting – that is, making sure there is the right level of challenge, the right amount of reward, the right amount of meaningful choice, and all the other things that make a good game (Schell, 2008).

The current section will discuss how the level design process contributed to solve each of the previously mentioned necessities. To do so, the game's level structure will be described, follow by an in-depth analysis of the most relevant levels.

1.1.12   General Level Structure

One of the major concerns during the Level Design process was to define a level structure that would support multiple learning rates and allow the teacher to control the overall progress of the game. To solve these issues, the levels followed an activity-based structure and implemented an iterative goal system.

The activity-based structure specifies that each level must deal with an exclusive learning topic and define a fixed objective. These aspects will contribute to the student's learning process by allowing them to focus on a unique task, while permitting the teacher to explain each concept systematically and solve questions more precisely.

The iterative goal system allows a stage to be played multiple times by defining a sequence of respawn points for the test charges. Each time the level is completed, the test charge will reappear on a different location with a different charge value. This system encourages students to progress at their own rate by providing an ongoing challenge for advanced players that will keep them entertained once they have completed the level.

1.1.13   Level analysis

First Colony 2D is composed of 13 levels: 8 training exercises and 5 mission stages. Each level is defined by a layout that specifies key locations for players (starting and respawn positions), test charges, goals and hazards (starting point and trajectory). In this section the layout for the most relevant stages will be described. Figure 1-19 shows the legend used for each outline.
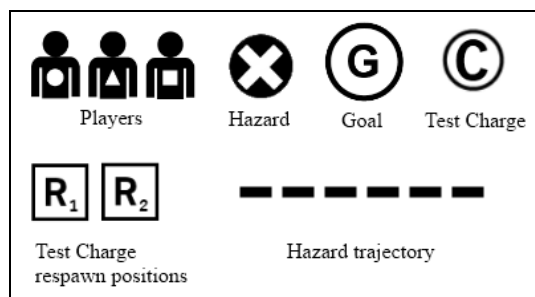
Figure 1-19: Layout legend.

1.1.13.1   First Mission: Hazards

In this mission, the game introduces static hazards to the students. The objective of this level is to guide the test charge to the goal without colliding with the hazards. In addition, players must navigate the stage carefully, because if they touch any of the hazards their avatar will die and their team will lose a point. Figure 1-20 shows the layout for this level.
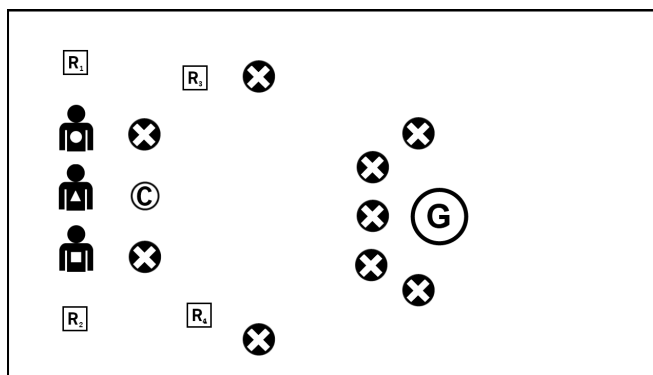
Figure 1-20: First Mission Layout.

The first mission was designed for students to practice Coulomb's First Law of electrostatics, while establishing minor movement restrictions. This encouraged the team

to discuss the route they wanted to take and the charge values they would have to use in order to do so. The locations of the respawn points were designed to force the team to assign new roles to each player and guide the test charge through different trajectories.

1.1.13.2   Second Mission: Trapped

In the second mission every player is surrounded by static hazards; being unable to move. In this level, students must guide the test charge only by modifying their charge intensity and polarity. This allows them to understand the relation between charge intensity and electric force when the distance has a fixed value.
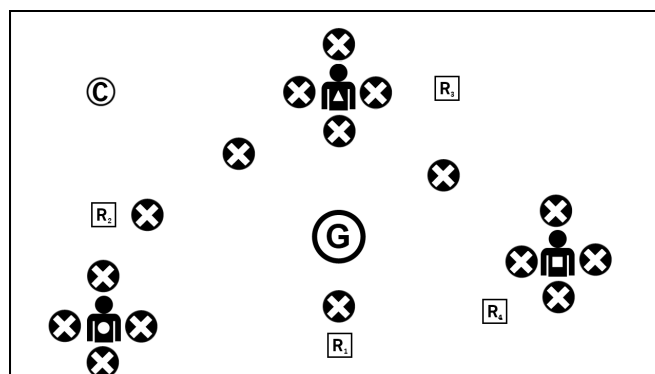
Figure 1-21: Second Mission Layout.

In every iteration the test charge respawns close to a player (R2, R4 and R5). This was done to encourage the closest player to assume the lead role in moving the test charge (because, according to Coulomb's law, the effect that his charge will have on the electric force will be greater than that of his teammates'). Figure 1-21 shows the initial layout for the second mission.

1.1.13.3   Fourth Mission: Circles

The fourth mission introduces a new game element: the moving hazard. This new threat travels in circular patterns and can leave the level, appearing afterwards from the opposite side. These hazards were included in the game to encourage students to plan and execute their decisions faster. In previous levels this was not an issue because hazards where static and students had more time to make their decisions. The layout of this level can be seen in figure 1-22.
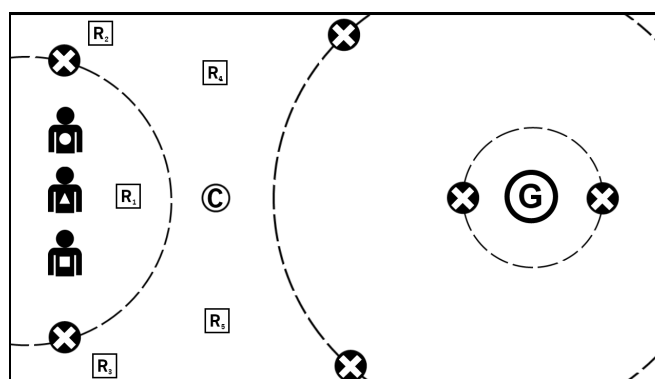
Figure 1-22: Fourth Mission Layout.

1.1.13.4   Final Mission: Hazard Rain

As stated in section 1.7.1 the final mission represents the major challenge of the game. In this level players must guide the test charge while avoiding moving hazards that have horizontal (H1 and H2) and vertical (V1, V2 and V3) trajectories. Once a hazard reaches the edge of the screen it will disappear for a few seconds, after which it will reappear at the starting point of the trajectory. In addition, all hazards move at the same speed, with the exception of the hazards in lane V2 that move slower.
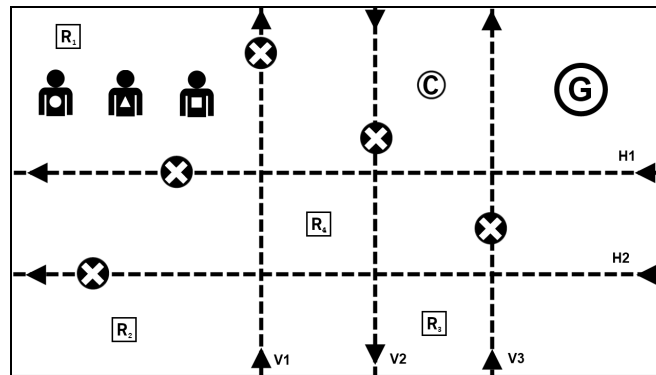
Figure 1-23: Final Mission Layout.

An easy first location for the test charge was selected in order to avoid student frustration. The following respawn points where located in increasingly difficult positions with the intention of challenging the team to the extent of their abilities.

1.10   Experiment

The experiment was carried out in a public school in Santiago, Chile with 36 Twelfth grade students (27 boys and 9 girls). The experience included 4 sessions; in the first two students played the non-fantasy version of the game, while in the last two they played the fantasy version. Each session was one and a half hours long, allowing 9 students to play the game. One member of the research team acted as teacher to guide the experience.

The experiment required the use of four laptops; three for the students and one for the teacher. The three student computers were located on individual tables, used three mouses (one for each player) and were located close to the white board. The teacher's computer was connected to a projector to show the game's cutscenes (if the fantasy version was being played) and the score of each team. A Wireless router was utilized to connect the student computers to that of the teacher that acted as a server.

The teacher's computer provided information about the number of times a student had completed or failed a certain stage. This allowed the teacher to assist players that were performing poorly by encouraging conceptual analysis and proposing new strategies for solving a level.

Figure 1-24: The teacher controlled the experience.

The flow of the experience was controlled by the teacher (as shown in figure 1-24). The game permitted the professor to pause or restart a stage, as well as advancing all students to the next level. The teacher waited until all groups had completed the level in order to move on to the next one. However, students would frequently finish a level and continue playing, asking for more playtime. Because of this, an additional five minutes per stage were granted to allow the players to experience the different iterations of each level. Figure 1-25 shows a group of students playing the game.
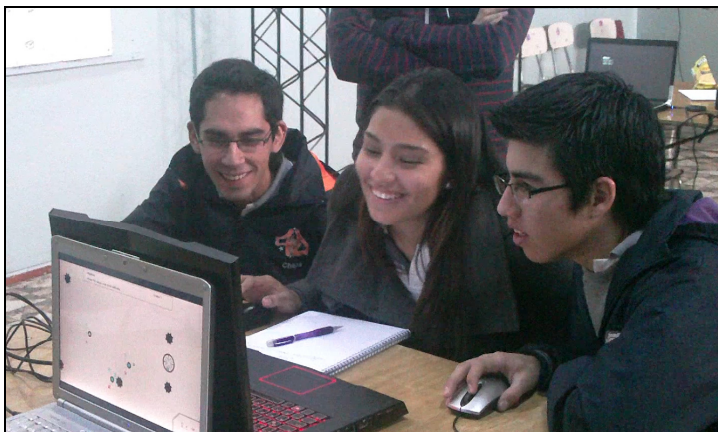
Figure 1-25: Students playing the game.

Throughout the experiment students would often take specific roles in their group. The three most common tasks were: pusher, puller and moderator. In the first one, the student activated his charge with the same polarity as the test charge in order to "push it" to the goal. In the second role, the student chose a charge value whose polarity was opposite to that of the test charge with the intention of attracting it to the goal. In the last one the student was responsible of deciding when the test charge was going to move. This player always activated his charge after his teammates and controlled the timing of the charge's movement. As the game unfolded the students reassigned their roles to solve each level more efficiently.

Another interesting behavior was that advanced students would use the game to explain the concepts of electrostatics to their teammates. If a student had a doubt about the subject, the other members of the group would stop playing and address the issue; generally through a brief in-game explanation that relied on the movement of the test charge or on the graphical representation of the electric force (the arrows).

1.11 Conclusions and future work

The research team managed to develop a redesigned version of the game done by Garcia-Campo et al (2010), incorporating changes to the game mechanics, level design, narrative and technology.

The integration of narrative into an educational game is a complex process that must consider multiple components. Each of these elements were successfully integrated in the fantasy version of First Colony 2D in order to give motivation to the players. On the other side, the non-fantasy adaptation was stripped of all these components in favor of an abstract aesthetic.

The level design was an important component of the game design process. Through the implementation of an iterative goal system and an activity-based structure, the game was able to support multiple learning rates and allow the teacher to control the overall progress of the game.

The results of the experiments showed that the redesigned version of the game permitted students to obtain more correct answers than the previous version. In addition the outcomes obtained from the game experience questionnaire revealed that, for this kind of educational games, students favored the non-fantasy version. Because of this, the game development process should focus primarily on creating engaging game mechanics, rather than incorporating a full-fledged story.

In conclusion, through the development of this game it is possible to define a methodology for the design of games for the conceptual understanding of physics. These principles can be applied to many physical laws and processes, but further experimental work should be carried out to validate them.

2.   **THE ATOMIC INTRINSIC INTEGRATION APPROACH: A STRUCTURED METHODOLOGY FOR THE DESIGN OF GAMES FOR THE CONCEPTUAL UNDERSTANDING OF PHYSICS**

2.1   **Introduction**

The conceptual understanding of complex processes and models is essential to the learning of science. In physics in particular, many educators advocate the prioritization of the conceptual and qualitative understanding of basic principles, over the use of mathematical formulae (diSessa, 1998; Forbus, 1997; Hewitt, 2002). However, engaging students in complex thinking about models and processes is not easy, and traditional methodologies for teaching may not be well suited to this end (Bransford, Brand & Cocking, 1999).

One methodology that has been used to teach physical phenomena conceptually is through computer simulations - programs that contain a model of a system or process (de Jong & van Joolingen, 1998; Perkins, Adams, Finkelstein, Dubson, LeMaster, Reid et al 2006; Wieman & Perkins, 2006). Computer simulations can be used for science learning by giving the learner the task of inferring the characteristics of the model underlying the simulation (de Jong et al, 1998). One advantage of using simulations is that they can potentially lead to kinds of knowledge that are qualitatively different from the knowledge acquired from more traditional instruction (Swaak & de Jong, 2001).

However when computer simulations are used for discovery learning without any additional instructional support, they show no better results than traditional methods (Gredler, 2004). The reason for these poor results is that learners encounter several problems when only using simulations: they have difficulty finding new hypotheses to test, they design inconclusive experiments, and do not exploit the whole range of possibilities provided by the system (de Jong et al, 1998).

The integration of computer simulations with games has been shown to be one possible solution to these problems (de Jong et al, 1998; White, 1984). Adding specific goals and challenges within the simulation and structuring its progression through game levels has shown marked improvements in the learning outcomes in comparison with non-game simulations (de Jong et al, 1998). Games are useful in this context because they emphasize the process of reflection: unlike a linear process, learning with games follows a cyclical pattern of experience, reflection on that experience, drawing of conclusions based on these reflections, and the formation of a plan for a new action based on those conclusions, before acting once again (Paras & Bizzochi, 2005).

The idea of combining games with simulations has been successfully applied to the design of games for the conceptual understanding of physics. Games for teaching both Newton's laws of motion (White, 1984) and Maxwell's laws of electromagnetism (Squire, Barnett, Grant & Higginbotham, 2004), have been developed and tested with successful results, demonstrating that they improve the learning outcomes when compared with other approaches, such as inquiry-based learning (Squire et al, 2004) and unguided discovery learning (White, 1984).

Although previous research on physics games has validated their use as an effective tool for achieving conceptual understanding, it is not clear how to generalize their results for the design of other physics games. An important research question that remains is how to transform a physics simulation into an educationally effective and engaging game.

In this article we present a structured methodology for the design of such games. To formulate this methodology we started with a pre-existing and tested game for teaching conceptual physics (Section 2.1) and performed an analysis to improve its learning outcomes (Section 2.2). Based on that analysis we redesigned the game, applying our proposed methodology (Section 2.3), and validated it experimentally in a classroom setting (Section 3). Based on this experience we generalized the methodology for it to be

applied to other games in the discussion section (Section 4). Finally, we present relevant conclusions regarding this experience (Section 5).

2.2   Game design and analysis

2.2.1   Original design and experimental study

The original game which we developed was called "First Colony", and its goal was to teach electrostatics to 12th graders (Echeverria, Garcia-Campo, Nussbaum, Gil, Villalta, Améstica et al, 2011). Electrostatics is an interesting area for instructional games as the nature of the interactions is non-intuitive and invisible. For this reason, it has been used in several research projects that designed games and virtual environments for the topic, obtaining successful learning outcomes (Squire et al, 2004; Salzman, Dede & Loftin, 1999).

The scope of our game was more limited than in previous games: we focused only on point charges and static electricity forces, which studies show to be difficult topics to grasp conceptually (Maloney, O'Kuma, Hieggelke & Van Heuvelen, 2001). The basic physical laws that were simulated in the game were Coulomb's Law (Equation 1a) and the principle of linear superposition of forces (Equation 1b). Coulomb's Law states that the force between two static point charges is proportional to the magnitude of both charges, and inversely proportional to the square of their distance. The principle of linear superposition states that the total force exerted on an object is the vector sum of all the individual forces affecting it.

$$\overrightarrow{F_{12}} = k \; \frac{q_1 q_2}{r^2} \hat{r} \quad \text{(a)}$$

$$\vec{F_j} = \sum_i \overrightarrow{F_{ij}} \quad \text{(b)}$$

Equation 1: Coulomb's Law (a) and the principle of linear superposition of forces (b).

The specific learning objectives of the game were:

- To understand the interaction between objects with positive, negative and neutral charges.
- To understand the relation between charge intensity and electrical force.
- To understand the relationship between the distance between charges and electrical force.
- To conceptually apply Coulomb's Law in order to predict the magnitude and direction of the force generated between two charges.
- To conceptually apply the principle of linear superposition to predict the magnitude and direction of the net force exerted on a charge in a system with multiple charges.

The game was integrated as part of a class, where the teacher first introduced the basic concepts related to electrical force, and then allowed the students to play. The game was played in groups of three students, where each student controlled one mouse and worked collaboratively in groups of three. The teacher had control of the computer that ran the game, and could pause the gameplay when necessary in order to reinforce any concept that was not clear.

In the game, players assume the role of astronauts from the first human colony on an extra-solar planet. They have been sent on an important mission to bring back a precious crystal found in space. The colony has limited energy resources and the crystal has the unique quality of storing electrical energy. The crystal is fragile, however, so the astronauts can only interact with it from a distance using electrical force.

The game was experimentally tested with 27 12th grade students, from a public school in Santiago, Chile (Echeverria et al, 2011). A pre-post test experimental design was developed in which the students took a conceptual survey of electrostatics before and after the one hour session. The test scores increased from an average of 6.11 correct answers in the pre test, to 10.00 correct answers in the post test, a statistically significant result with 99% confidence ($p < 0.00001$) and a large effect size (Cohen´s D = 1.58).

Although the general results of the game were positive, a more detailed analysis showed that not all students were learning from the game. The percentage of students that improved after playing the game was only 66.66% in questions related to Coulomb's law, and only 62.07% in the ones that related to the principle of linear superposition. These results implied that more than a third of students were not increasing (or even worse, were decreasing) their conceptual knowledge of both laws after having played the game. This suggested that the methodology used to design the game was incomplete, and that a better design approach was required.

2.2.2 Game analysis

To understand how best to modify the original game and improve the learning outcomes of the students who played it, we initially performed an analysis of the game to identify its core structure. There are different approaches for analyzing the structure of games (Cousins, 2005; Cook, 2007; Koster, 2005), however one common aspect of most approaches is the description of games as collections of *game atoms*, which are "the activities enacted by a player in a game as mediated by an underlying set of rules, mechanics and affordances" (Koster, 2005). These game atoms, also called *ludemes* (Cousins, 2005) or *skill atoms* (Cook, 2007), represent the building blocks of the game, and combine to create the core gameplay structure. Each game atom represents a feedback loop between the player and the game (Cousins, 2005), involving three elements: an action performed by the player, a simulation or computation performed by

the game in response to the action, and feedback provided by the game to the player as a result of the simulation (Figure 2-1).
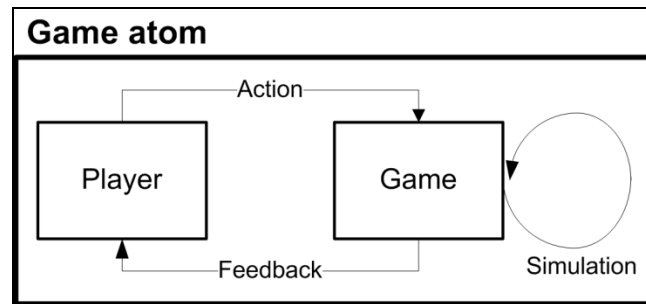
Figure 2-1: A game atom represents a feedback loop in the game, where the player executes an action and the game performs a simulation, and provides feedback to the player.

Game atoms are combined recursively to build the structure of a game: low-level atoms represent the basic actions that the player can perform using the input devices, and by successively combining these, higher level atoms are formed, which represent higher level activities that the player can perform in the game, when the lower level atoms are mastered (Cousins, 2005; Cook, 2007). In the original version of First Colony, the lower-level atoms of the game were the three actions that the player could perform directly with the mouse: move their avatar on the screen, select the value of their charge, and activate the charge to allow its interaction. By combining these three atoms, the player could interact with the crystals, applying an electric force that moved them, with different accelerations depending on the values of each player's charges and their locations. Finally, by moving the crystals the players were able to achieve the goal of the game by placing them in specific targets located on the screen (Figure 2-2).
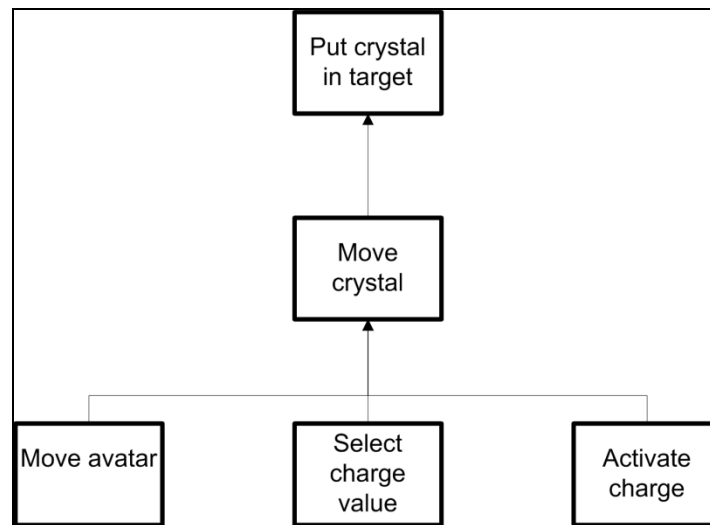
Figure 2-2: Structure of the original version of First Colony

This diagram does not fully describe the game interactions or all the possible sequences of actions to win the game, but it does provide a useful tool for analyzing what the core activities in the game are and how each of the higher level activities depends on mastering the ones at lower levels.

Although the atomic analysis of the game provides a useful way of understanding its core structure, it does not give any guidance on how this structure should be changed to improve the instructional value of the game. One general approach that has been successfully used to design instructional games is "intrinsic integration" (Habgood, 2005). This approach is based around the idea that the learning content should be completely integrated with the core game structure (Habgood & Ainsworth, 2011), defining the subset of activities that the player will undertake most frequently during the game experience, and those that are indispensable to winning the game (Fabricatore, 2007). The intrinsic integration approach identifies two principles that should be included in order to create an educationally effective and engaging game. The first is to incorporate the learning material into the structure of the gaming world and the player's

interactions with it and provide an external representation of the learning content that is explored through the core mechanics of the gameplay. The second is to deliver learning material through the parts of the game that are the most fun to play, riding on the back of the flow experience (Csikszentmihalyi, 1990) produced by the game and not interrupting or diminishing its impact (Habgood et al, 2011).

A secondary aspect of the intrinsic integration approach is that the fantasy element of a game cannot be justified in itself as a critical means of improving the educational effectiveness of digital learning games (Habgood, 2005). The intrinsic integration approach suggests that there is a logical hierarchy when designing an intrinsically integrated game. This hierarchy firstly prioritizes the learning content, then the game mechanics and finally the fantasy context (Habgood et al, 2011). Fantasy in instructional games, therefore, is only important in terms of its motivational value, and not because it improves the educational effectiveness of the game. This idea contradicts previous research done on instructional game design (Malone & Lepper, 1987; Rieber, 1996).

2.3   Game redesign

2.3.1   The Atomic Intrinsic Integration Approach

Combining intrinsic integration with an atomic analysis of the game provided us with a structured methodology for redesigning the game. We called this methodology the *Atomic Intrinsic Integration Approach.* The game was redesigned by modifying the original game's atomic structure according to the two guiding principles of the intrinsic integration approach:

(a) Incorporating the learning material within the structure of the gaming world and the player's interactions with it and provide an external representation of the learning content that is explored through the core mechanics of the gameplay

In the original version, neither the electrical force between two charges nor the total forces on one charge were directly represented by game atoms. The effect of the forces was only indirectly represented by the movement of the crystal, and because the movement of the crystal was affected by all the players, the effect of the force generated between one player and the crystal could only be seen when no one else was interacting.

To resolve this representation problem, we overlaid arrows on the test charge that directly represented the direction and magnitude of the force being applied between players and the test charge, based on Coulomb's Law. To differentiate the force applied by each player, next to each arrow we also showed the player's symbol (a square, circle or triangle). We added an extra arrow with a different color, which represented the added force generated by all players, applying the principle of superposition (Figure 2-3).
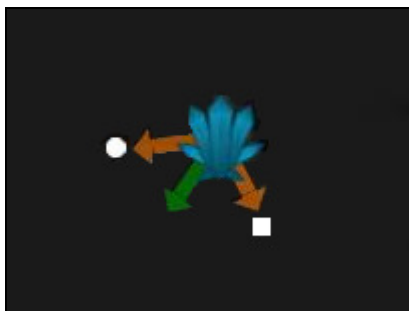
Figure 2-3: Arrows were shown next to the crystal to provide an external representation of individual forces and the total force.

With this modification we achieved two goals. Firstly, the effect of Coulomb's Law and the principle of superposition were integrated as separate game atoms, which provided specific feedback through their corresponding arrows. Secondly, by separating the representation of forces from the movement itself, the game allowed the players to conceptually separate the concept of force, which was essential to the learning objectives

of the game, from the movement of the test charges, which was merely an indirect representation of the forces.

However, in the initial testing sessions in which the game was played including these modifications, a problematic side effect appeared. Because the players were provided with direct feedback about the forces, they could achieve the goal of moving the crystal to the target by trial and error, never needing to reflect on how to generate a specific force, which defeated the main purpose of the game. To solve this issue, we decided to progressively remove the arrows as the player advanced in the game, completely hiding them in the final levels. In this way, the arrows acted as scaffolding for the first part of the game, and then, when removed, the players were forced to apply their acquired knowledge to finish the game.

(b) Delivering learning material through the parts of the game that are the most fun to play, riding on the back of the flow experience produced by the game and not interrupting or diminishing its impact.

Observations made during the gameplay sessions of the original version of the game showed that, although players enjoyed the game at the beginning, they lost interest in the game as the session progressed, which suggested a clear problem in the flow experience. In addition to this engagement issue, there was also an educational problem with the challenge structure of the game: there was no losing condition in the game and many students could win the game by mere trial and error, without having to reflect on the underlying concepts.

To solve both of these problems, we decided to create additional challenges by adding static and moving obstacles to the world (Figure 4). If the crystal collided with an obstacle they were destroyed, and the level started over, which forced the players to reflect on the physical concepts before trying to move the crystals. The addition of

obstacles also provided more variety in the levels of the game, with the aim of positively impacting the flow experience.
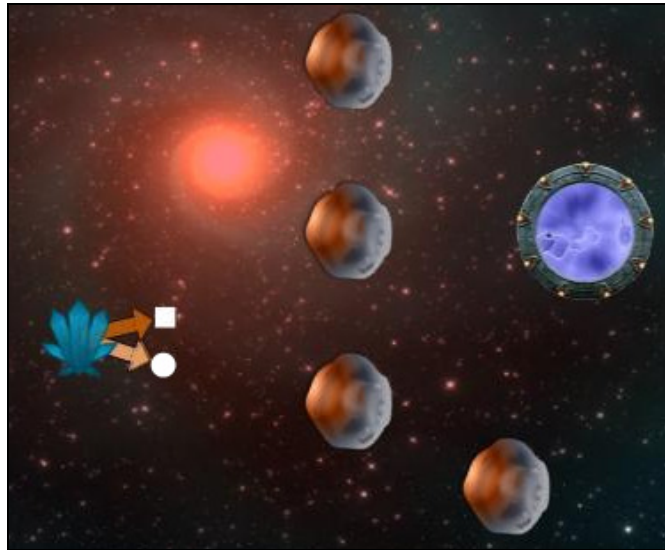
Figure 2-4: Static and moving obstacles were added to increase the flow experience and force player reflection on the concepts.

The redesigned structure of the game is shown in figure 2-5. Two game atoms were added in order to explicitly represent the forces through arrows ("generate electrical force", "generate total force"), and two additional game atoms were added to increase the challenge and force reflective strategies among players ("avoid static obstacles", "avoid moving obstacles").

The game atoms were introduced progressively into the game, starting with the basic atoms in the tutorial, and eventually adding the obstacle atoms to the mission levels. Also, as explained before, the force arrows were gradually removed from the game, in order to force a deeper reflection on the concepts.
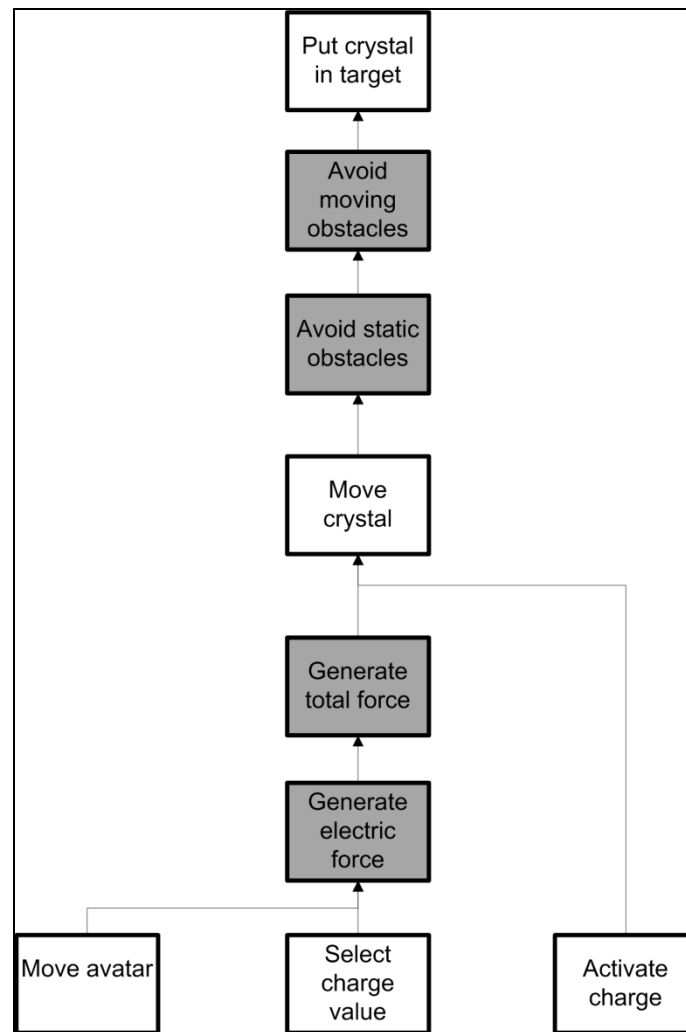
Figure 2-5: Structure of the redesigned version of First Colony. Colored blocks represent new game atoms added to fulfill the intrinsic integration principles.

2.3.2   Fantasy and non-fantasy versions of the game

To analyze how the fantasy context of the game affected the educational effectiveness and engagement of players in the game, we modified the game applying the endogenous fantasy approach for increasing the intrinsic motivation of instructional games (Malone et al, 1987), which is based on two principles: (a) the skill being learned and the fantasy

depend upon each other; (b) there is an integral and continuous relationship between the fantasy context and the instructional content being presented.

Our analysis of the original version of the game suggested that these two principles were already being satisfied: the story was centered on electrically charged crystals, and applying the physical laws to move these crystals was essential to fulfill the challenge presented by the story. However, we believed the fantasy aspect of the game, and especially how the narrative was presented, could be improved in order to enhance the endogenous fantasy. In order to improve the story, we applied Dickey's principles for game design narratives (Dickey, 2006) to analyze the game, and found that the only principle that was not considered was to "*develop cut scenes to support the development of the narrative story line*". We added four cut scenes to the game. At the beginning, the first cut scene presented the backstory of the game as well as the environment and setting, and the initial challenge of collecting crystals to save the colony. A second cut scene appeared at the end of the training levels, marking the end of the first part of the game and the beginning of the actual mission. A third cut scene was shown before the last level, where a climatic challenge was added - an asteroid field was approaching and the players needed to collect a certain amount of crystals before they were destroyed by the asteroids. The final cut scene showed the astronauts returning to the colony with the crystals, having accomplished the mission.

The non-fantasy version of the game, developed to compare the effects of fantasy in the effectiveness and engagement of the game, was designed to include the same atomic structure and level design as the fantasy version, but every fantasy element was removed (Figure 2-6). For this non-fantasy version we also used Dickey's principles, but now as a guide to define what should not be included:

- **Create a backstory:** there was no backstory in this version of the game; players took control of electric charges, and were told to move a test charge using the physical laws, without any story-based justification.

- **Establish the physical, temporal, environmental, emotional, and ethical dimensions of the environment:** the environment was visually modified to eliminate any relation with the original story. The players' avatars, the test charges and the obstacles were represented with abstract symbols, and minimalistic black and white graphics were used. All sound effects and music in the game were removed.

- **Present the initial challenge:** because there was no back story, an initial challenge was not presented. The players were only told what to do at each level, but with no far-reaching goal to achieve.

- **Identify potential obstacles and develop puzzles, minor challenges, and resources:** these elements were identified but only in the abstract context in which the objects were presented, and with no relation to a story or justification.

- **Identify and establish roles:** in this version, players did not take the role of astronauts, they directly controlled charges.

- **Develop cut scenes to support the development of the narrative story line:** every cut scene was removed from this version.
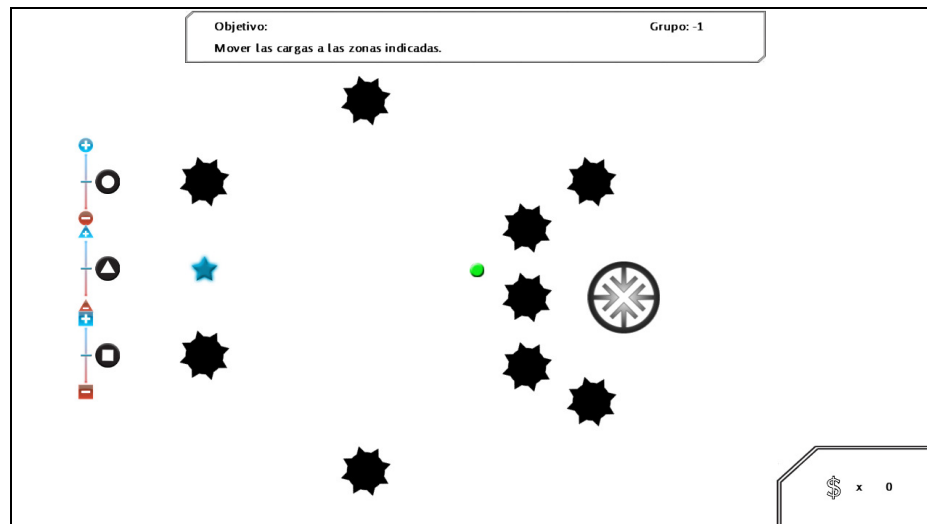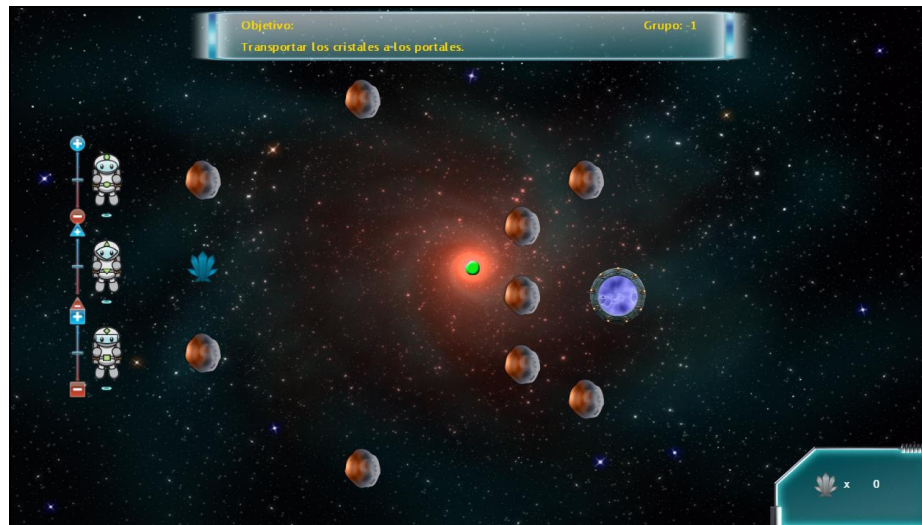
Figure 2-6: Screen shots of the same level viewed in the fantasy version of the game (top) and the non-fantasy version of the game (bottom).

2.4   Experimental study

2.4.1   Setup

We designed a two-part experiment in order to answer the two research questions at the heart of this study: (1) does the Atomic Intrinsic Integration Approach improve the educational effectiveness of a conceptual physics game? and (2) does the presence of a fantasy context in a conceptual physics game improve the educational effectiveness or the player engagement? The experiment was carried out in the same public school as the original experiment in Santiago, Chile. The game was tested with 36 12th grade students (27 boys and 9 girls) in one and a half hour long sessions. In each session 9 students played, divided into groups of three, and one of our researchers acted as teacher for the session.

The first part of the experiment was designed to answer the first research question. To accomplish this, all students in the sample (36 students) played the version of the game that had been redesigned applying the two intrinsic integration principles. The sample of students that played the original version was assumed comparable, considering that both groups were from the same school and same school year. To answer the second research question, we divided the 36 students into two groups - 20 students from the sample played the fantasy version of the game while the other 16 played the non-fantasy version. All experimental groups (original version, fantasy and non-fantasy) were in the same age bracket (17 to 18), and had similar previous experience with games. This experience was assessed through means of a questionnaire before beginning the experiments.

A pre-post test design was used to compare the learning achieved through the game. The instrument used to measure the expected learning outcomes was a specially designed conceptual evaluation that assessed each outcome by asking specific questions. The evaluation was based on the Conceptual Survey of Electricity (CSE) proposed by

Maloney et al. (2001), with certain modifications to ensure that all of the desired learning outcomes were covered and any questions on unrelated or more advanced subjects were excluded. The resulting instrument consisted of 21 questions, with 9 questions taken directly from the CSE, and the rest formulated by two 12th grade physics teachers. The test was validated with 20 students of the same school and year, yielding a Cronbach's alpha of 0.74, above the minimum value of 0.7 required to prove reliability.

To measure the engagement of players we used the Game Experience Questionnaire (GEQ) (IJsselsteijn, Poels, & de Kort, 2008), a questionnaire that has been validated as an effective tool for assessing experiences with both instructional and commercial games. For the purpose of this study, the GEQ was used mainly as a general metric to compare the game experience of the two versions (fantasy and non-fantasy), and not as a way to evaluate specific details of the games. We translated the English version of the questionnaire into Spanish, using the procedure specified by the developers of the questionnaire (IJsselsteijn et al, 2008), in order to maintain valid results for comparison. This questionnaire uses 42 Likert-type questions to measure seven relevant characteristics of the player experience: *competence*, *immersion*, *flow*, *tension*, *challenge*, *negative affect* and *positive affect*. Each one of these characteristics is associated to a subset of items, and is measured with a score from 0 to 4. A higher score is considered better for every characteristic, except for *negative affect* where a lower score is considered a better result. A representative item for each dimension is shown in Table 2-1.

Dimensions	Items
Competence	I was good at it
Immersion	I could use my imagination in the game
Flow	While playing, I forgot about everything around me
Tension	I was nervous during the game
Challenge	I had to put a lot of effort into the game
Negative affect	I found it boring
Positive affect	Playing the game was fun

Table 2-1: Representative items for each of the dimensions of the GEQ.

The experimental procedure was carried out over a three day period. On the first day, all students participating in the study were gathered in a classroom and completed the pre-test during a 30 minute period. On the second day, 4 groups of 9 students participated in the game-based class, which lasted 90 minutes, one group at a time. At the end of the class, students answered the GEQ questionnaire. Finally, on the third day, all students were gathered in a classroom where they had 30 minutes to complete the post-test.

2.4.2 Results and Statistical Analysis

The results of the conceptual evaluation pre- and post-tests (both of which had a minimum score of 0 and maximum of 21) showed an increase in the average number of correct answers from 7.36 to 12.36, with standard deviations of 2.69 and 3.77 respectively. To analyze the statistical significance of these results we performed a Student's t test for dependant variables, the null hypothesis being that the pre-test and post-test averages were equal and the alternative hypothesis that the post-test average was greater than the pre-test average. To reject the null hypothesis, a one-tailed test was used with a significance level (alpha) of 0.01 (1%). The results of the t test rejecting the

null hypothesis were statistically significant ($p < 0.00001$), meaning we can conclude with 99% confidence that the average number of correct answers in the evaluation increases after students are exposed to the game. Additionally, a power analysis was performed to measure the effect size, which resulted in a Cohen's d quantifier value of 1.68 indicating a large effect size. There were no significant differences between boys and girls, and between students with more previous experience with games.

To compare the effects of using the Atomic Intrinsic Integration Approach, we used an ANCOVA analysis with the original experiment's results and the new results, using the pre-test results as co-variable (Table 2-2). The analysis showed that in the enhanced intrinsic integration version of the game, students achieved an average score of 12.11 which was a statistically significant improvement ($F = 4.55$; $p < 0.05$) on the average score of 10.32 obtained with the original version. This implies that, on average, students learned more with the redesigned version of the game. Two additional ANCOVA analyses were performed per gender, also obtaining significant differences for boys ($F=4.22$; $p <0.05$) but no significant difference for girls ($F=0.69$; $p=0.41$). This suggested that the modifications were more useful for boys than for girls.

Test	Gender	Original Game		Atomic Intrinsic Integration Game	
		Mean	Std. Dev.	Mean	Std. Dev.
Pre-test	Boys	6.69	1.88	7.22	2.72
	Girls	5.57	2.47	7.77	2.72
	Total	**6.11**	**2.24**	**7.36**	**2.69**
Post-test	Boys	9.61	2.72	12.40	4.18
	Girls	10.35	2.81	12.22	2.33
	Total	**10.00**	**2.74**	**12.36**	**3.77**
Adjusted Post-test	Boys	9.92	-	12.35	-
	Girls	10.77	-	11.88	-
	Total	**10.32**	**-**	**12.11**	**-**

Table 2-2: Test results of comparison between original game and the atomic intrinsic integration version

To understand how well each physical law was understood by the students - a serious problem with the original version of the game - we measured the percentage of students who increased their test scores from the pre-test to the post-test, in questions related to each physical law. The percentage of students which improved after playing the new game in questions related to Coulomb's law and the principle of linear superposition increased from 66.66% to 83.33% and 62.07% to 81.56% respectively. This shows that the new version of the game increased the number of students that improved their performance after playing the game.

To compare the effects of the fantasy element in the game we used an ANCOVA analysis with the results of both the fantasy and non-fantasy groups, using the pre-test results as co-variable (Table 2-3). The analysis showed that there were no statistically significant differences between the results obtained by the students who played the fantasy and non-fantasy game ($F = 0.30$; $p = 0.58$). Two additional ANCOVA analyses were performed per gender, obtaining no significant differences for boys ($F=0.47$; $p=0.49$) or girls ($F=0.18$; $p=0.68$).

Test	Gender	Endogenous Fantasy Game		Non-Fantasy Game	
		Mean	Std. Dev.	Mean	Std. Dev.
Pre-test	Boys	6.87	3.05	7.61	2.36
	Girls	8.5	2.12	7.57	2.99
	Total	**7.06**	**2.95**	**7.60**	**2.52**
Post-test	Boys	11.64	4.03	13.23	4.34
	Girls	13	2.82	12	2.38
	Total	**11.81**	**3.85**	**12.80**	**3.75**
Adjusted Post-test	Boys	11.95	-	12.90	-
	Girls	12.92	-	12.02	-
	Total	**12.01**	**-**	**12.64**	**-**

Table 2-3: Test results of comparison between fantasy and non-fantasy versions of the
game

The results of the Game Experience Questionnaire for students that played the fantasy
and non-fantasy versions (Figure 2-7) show that students from both groups achieved
similar results in all of the dimensions measured. To analyze the statistical significance
of these results, for each dimension of the GEQ we performed a Student's t test for
independent variables, the null hypothesis being that the score of each dimension for
both versions would be equal and the alternative hypothesis that the scores would be
different. To reject the null hypothesis, a two-tailed test was used with a significance
level (alpha) of 0.05 (5%). The results of the t test for every dimension were not
statistically significant, meaning that we cannot reject the null hypothesis of the scores
being equal. Considering the GEQ scores in all dimensions as a general metric for the
player experience, these results suggest that there was no significant difference in the
player's experience of the fantasy version and the non-fantasy version.
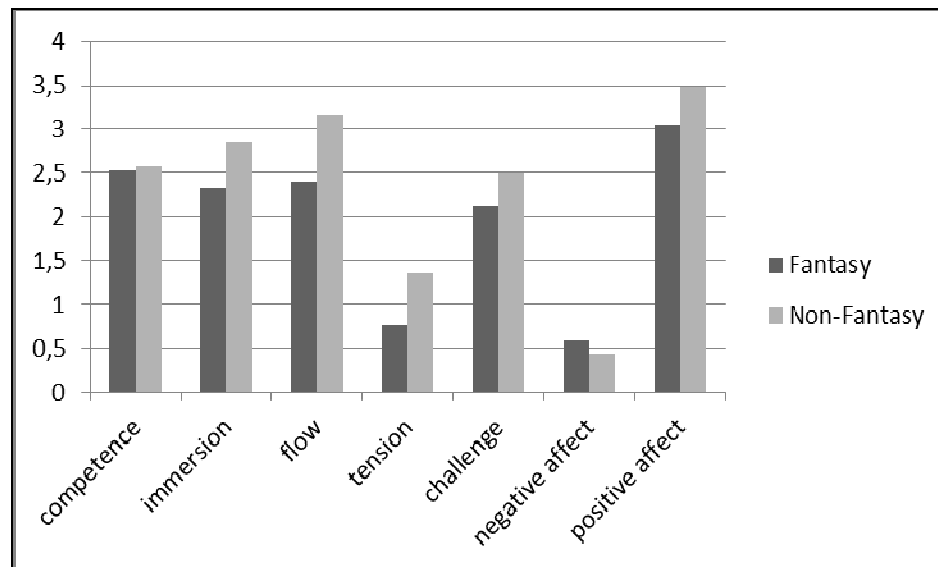
Figure 2-7: Game experience questionnaire results of comparison between fantasy and non-fantasy versions of the game

2.5   Discussion

The results of the experimental study show that applying the Atomic Intrinsic Integration Approach was useful for increasing the average test results and decreasing the number of students with conceptual problems. Intrinsic integration provided a useful methodology for understanding what elements should be improved in the game, while the atomic analysis helped visualize how the interaction was structured in the game, and how this structure should be modified to improve the game.

Fantasy did not play a relevant role in the educational effectiveness of the game, with no significant differences between the two versions of the game in the pre-post test comparison. A more surprising result was that in the game experience questionnaire there were also no significant differences between both games. This suggests that the fantasy element did not contribute to engaging the players. However, it is difficult to generalize these results for other contexts because of the different ways that fantasy can

be included in the game and also because the relative importance of the fantasy element will vary depending on the type of game.

Based on this experience, we outline some principles below that describe how the Atomic Intrinsic Integration Approach should be applied when designing games for the conceptual understanding of physics:

(1) Give the player control of every relevant independent variable in the simulation as a low-level game atom, and introduce them progressively throughout the game

Although this principle was already included in the original version, we believe it is an essential aspect when designing this type of game and is consistent with previous experiments with interactive simulations for physics (Adams, 2008). These should be combined with a progressive introduction of each variable, allowing the player to directly experience how each variable independently affects the results of the simulation. These relevant variables should be included as operative mechanics, by linking a player input with an explicit representation, which ideally should be tightly integrated within the game world, and not through external numeric displays.

(2) Provide appropriate explicit representations using a game atom for the simulated dependent variable integrated within the game world, which serve as scaffolding to increase the players understanding. Progressively remove these scaffolds as the game advances, to test the ability of the players to apply their knowledge by themselves without help.

One fundamental difference between the original and new version of the games was the inclusion of arrows to symbolize forces. The two physical laws represented in the game were related to the concept of force, and this was not directly represented in the original version. This was especially problematic for understanding the principle of linear

superposition, which involves vector addition, and it is very hard to understand without a clear representation.

The addition of the arrows helped the students to complete the feedback loop between their actions (which modified the independent variables) and the result (which simulated the dependent variables), and thus increased their conceptual understanding. It is also essential that the representation used is appropriate for the task: if we had used number values to represent the forces instead of visual arrows, the players would not as easily have understood the concept of vector addition applied to force. What is considered an "appropriate representation" should be analyzed case by case, depending on the concept.

It is also essential to eventually remove the scaffolding provided by this representation. If this is not done there is a real danger that the players will interact by mere trial and error and will not reflect on how the independent variables affect the simulation.

(3) Connect the dependent variables that result from the simulated principles with the goal of the game through a game atom that creates an interesting and fun challenge.

The main learning objective of the game was for the players to understand how the independent variable of each law affected its result. This is the main cognitive challenge for the players, but on its own it does not generate a fun game. Even when an additional but simple challenge is added, like in the first version of the game where they had to apply forces to move the crystals, it was not enough to create an interesting and engaging game.

Thus to create an engaging instructional game, it is essential to design a challenge structure on top of the instructional structure, by connecting the output of the simulation with an interesting challenge. In the case of this game, by adding different obstacles through increasingly complex levels we achieve the necessary engagement among

players. Because the challenge was interesting and it required the player to master the use of the electrical force, the students were motivated to reflect on the relationship between the different variables involved in all of the physical laws.

How to identify an interesting challenge is something that cannot be pre-specified, and must be play-tested for each specific game. This in essence is what game designers do best - carefully crafting interactions that are both engaging and fun for the player. What is different for this type of game is that the interesting challenges must be semantically linked to the simulated result, in such a way that the complete structure of the game feels natural and produces a successful flow experience. As our experimental results suggest, if the challenge provided is sufficiently interesting and fun, secondary elements of the game, such as a fantasy element, can be excluded without decreasing player engagement.

A summary of these three principles is presented in figure 2-8, showing the generic structure of a game that is designed using the principles.
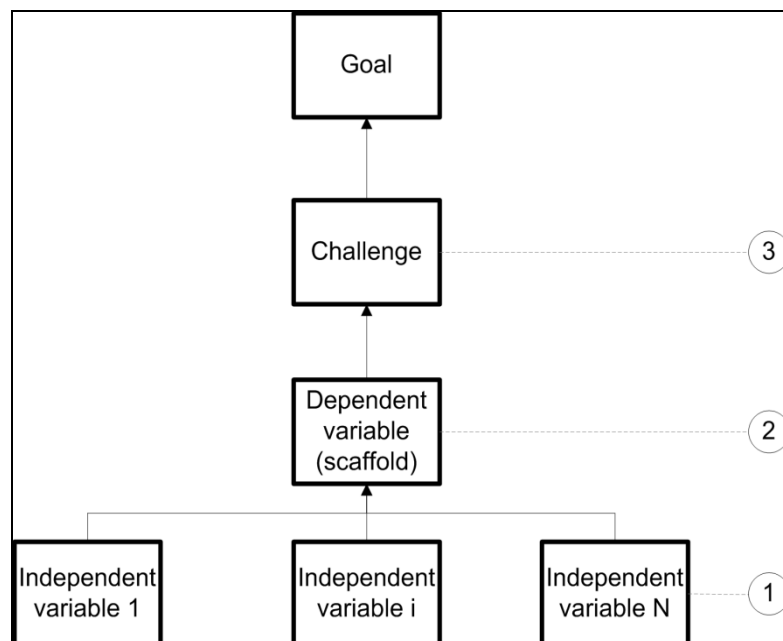
Figure 2-8: Generic structure of a game for the conceptual understanding of physics applying the three principles of our methodology: (1) the independent variables of the simulation are integrated as low-level game atoms, (2) the dependent variable of the simulation

2.6   Conclusions and Future work

Using the principles presented in the previous section, we have defined one possible methodology for the design of games to assist with the conceptual understanding of physics. We believe that these principles can be applied to many physical laws and processes, and that they provide a simple and useful guide. Further experimental work should be carried out in other physical domains in order to validate these principles.

There are many questions outside of the scope of this study that are left to be answered by future work. Firstly, it is not clear why the redesigned version significantly increased boys' results but not the girls'. Further analysis and experiments are needed to understand why this difference exists. Also, further analysis of the results from the GEQ

is required to understand how the scores of each specific dimension could be used to improve the game. Finally, the relevance of a fantasy component in this and other types of games should be further studied. Adding a story implies more effort in designing a good game, so it is important to know how relevant it is for different types of games.

One important difference between traditional game design and instructional game design is that in the former there are no initial restrictions beyond the budget and imagination of the designer. In instructional games, on the other hand, there are several restrictions regarding learning outcomes and instructional methodology. Principles such as those presented here facilitate the task of the game designer by providing a systematic way of incorporating these restrictions into the game design.

Although some of these principles could well be applied to other domains we think that this should be considered carefully beforehand. A general problem with instructional games is thinking that general principles can be applied undifferentiated to any type of instructional game and every domain. A goal for the instructional game community should be to define guidelines and principles that are appropriate to specific situations and domains, and validate them through continuous experiments in realistic conditions, in order to generate tools and methods that facilitate the design of more engaging and effective games.

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APPENDIX

E-mail of acknowledgement of submission

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■ El programa une el atractivo de los juegos comerciales con las necesidades del aprendizaje para lograr que alumnos de educación media se fascinen con los fenómenos físicos.

PAMELA ELGUEDA

La primera colonia humana en otro planeta se está quedando sin energía. Los únicos que pueden ayudarla son tres escolares que deben trasladar por un laberinto los cristales con carga eléctrica que salvarán a sus habitantes. Y eso no es todo: los héroes de la jornada deben conocer y dominar tres leyes físicas que les permitirán mover los cristales sin inconvenientes y a tiempo para salvar a los colonos.

"Es un videojuego colaborativo para alumnos de 3° y 4° medio, pensado para que los profesores puedan enseñar física en la sala", explica Alejandro Echeverría, miembro del equipo de alumnos de pre y posgrado de Ingeniería de la Universidad Católica, que trabajan en este proyecto bajo la guía del profesor Miguel Nussbaum.

"La física muchas veces se enseña más como una fórmula. Nuestra idea es que ellos entiendan los procesos que hay detrás de esos fenómenos, y las investigaciones han mostrado que los juegos son útiles para lograr eso", agrega.

Con el apoyo del Centro de Estudios de Políticas y Prácticas en Educación (Ceppe) y de Microsoft, los estudiantes están elaborando este juego que se desarrolla en un computador, que pone a prueba los conocimientos sobre fuerza eléctrica y que necesita del trabajo en equipo de tres alumnos.

"El juego va en su segunda etapa de diseño. La primera la probamos con alumnos del Chilean Eagles College, de La Florida, y el rediseño lo estamos probando con alumnos del Liceo San Francisco, de San Ramón", comenta Alejandro Echeverría, quien es alumno de doctorado del profesor Nussbaum. Junto a él trabajan Cristián García-Campo, Francisca Gil, Enrique Barrios, Matías Améstica y Sandra Leclerc, todos alumnos de magíster.

Lo diferente de este programa, agrega, es que une el atractivo de los juegos comerciales de computador con la enseñanza práctica de una materia compleja. "Está diseñado para que ellos se deban plantear hipótesis y en la medida que las van comprobando, van avanzando. Es un desafío interesante para ellos", asegura.

A la izquierda, alumnos del Liceo San Francisco que han probado el juego. Arriba, un detalle del videojuego.

Las evaluaciones les han demostrado que los alumnos efectivamente aprenden bastante acerca de las fuerzas eléctricas, independiente de sus conocimientos previos. "Hombres y mujeres aumentan por igual sus conocimientos y vemos que trabajan de manera distinta: ellas son más dadas a debatir acerca de lo que deben hacer para ir avanzando, mientras que ellos están más preocupados de la competencia y es eso lo que los fuerza a trabajar en equipo", dice Echeverría.

Los alumnos le han dado su aprobación al juego y le han pedido que lo suba a Facebook. "Así que una vez que esté concluida la investigación, lo cerraremos y lo pondremos en línea para que quienes quieran, lo puedan descargar gratis".