The Atomic Intrinsic Integration Approach: A structured methodology for the design of games for the conceptual understanding of physics

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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. 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.

Key words: *simulations; improving classroom teaching; interactive learning environments*

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. Game design and analysis

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.

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

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

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

The specific learning objectives of the game were:

1. To understand the interaction between objects with positive, negative and neutral charges.
2. To understand the relation between charge intensity and electrical force.
3. To understand the relationship between the distance between charges and electrical force.
4. To conceptually apply Coulomb's Law in order to predict the magnitude and direction of the force generated between two charges.
5. 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 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 1).

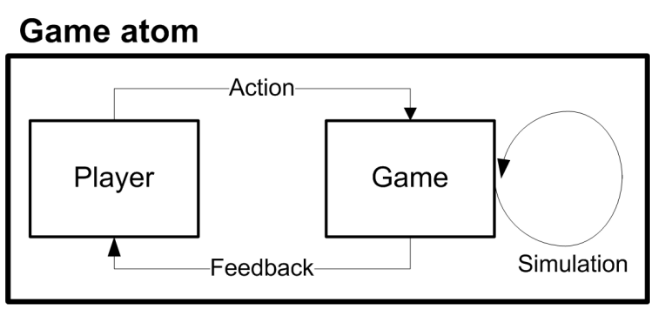

Figure 1: A game atom represents a feedback loop in the game, where the player executes an action and the game performs a simulation, and provides feedback to the player.

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).

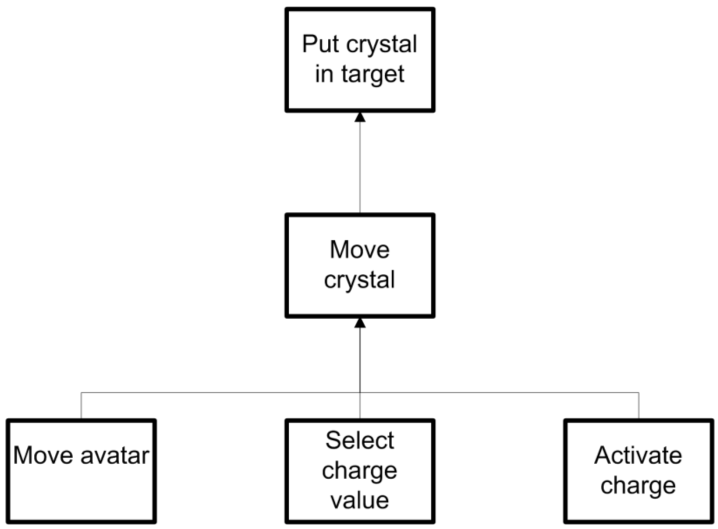

Figure 2: Structure of the original version of First Colony

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).

From the atomic analysis performed on the original videogame, and considering the principles of the intrinsic integration approach, we are interested in studying two research questions: (1) does an atomic analysis of videogames combined with the 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? For this purpose, the original videogame was redesigned according to these principles. The redesigned process is detailed in the following section.

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 3).

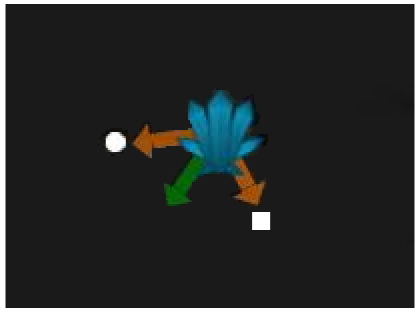

Figure 3: Arrows were shown next to the crystal to provide an external representation of individual forces and the total force.

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.

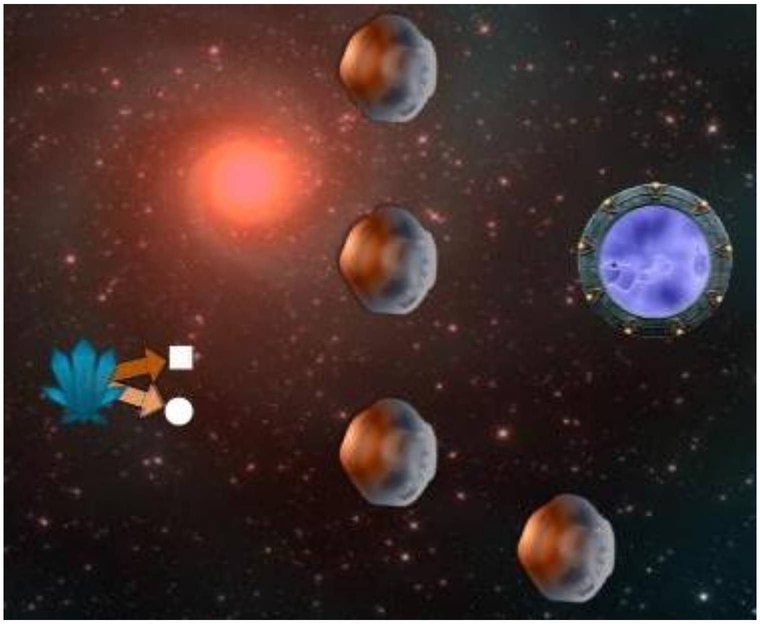

Figure 4: Static and moving obstacles were added to increase the flow experience and force player reflection on the concepts.

The redesigned structure of the game is shown in figure 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.

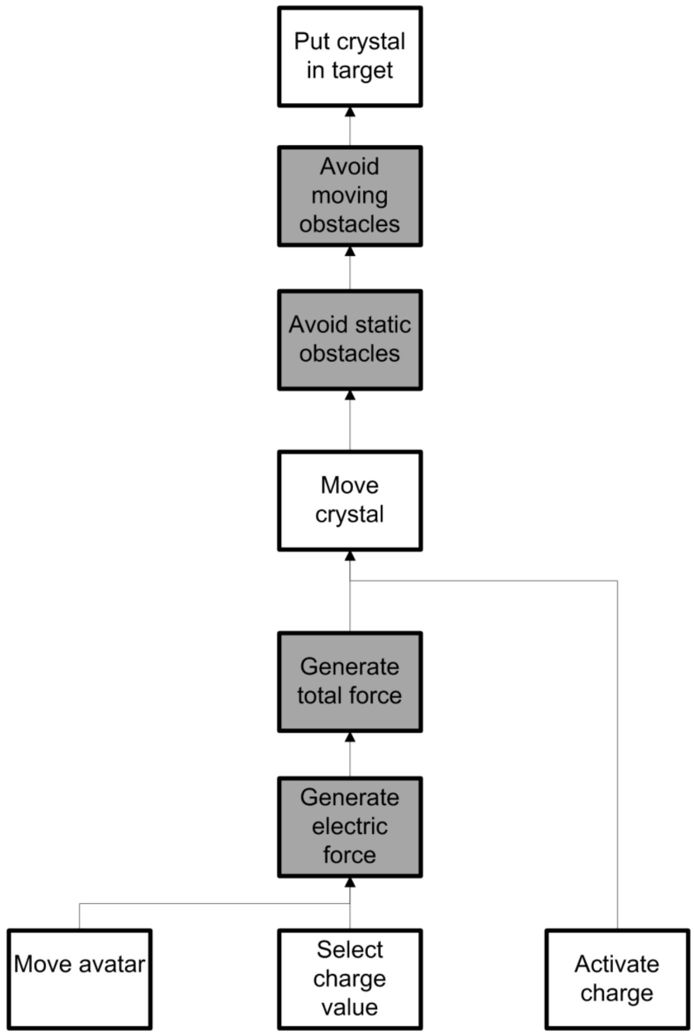

Figure 5: Structure of the redesigned version of First Colony. Colored blocks represent new game atoms added to fulfill the intrinsic integration principles.

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 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.

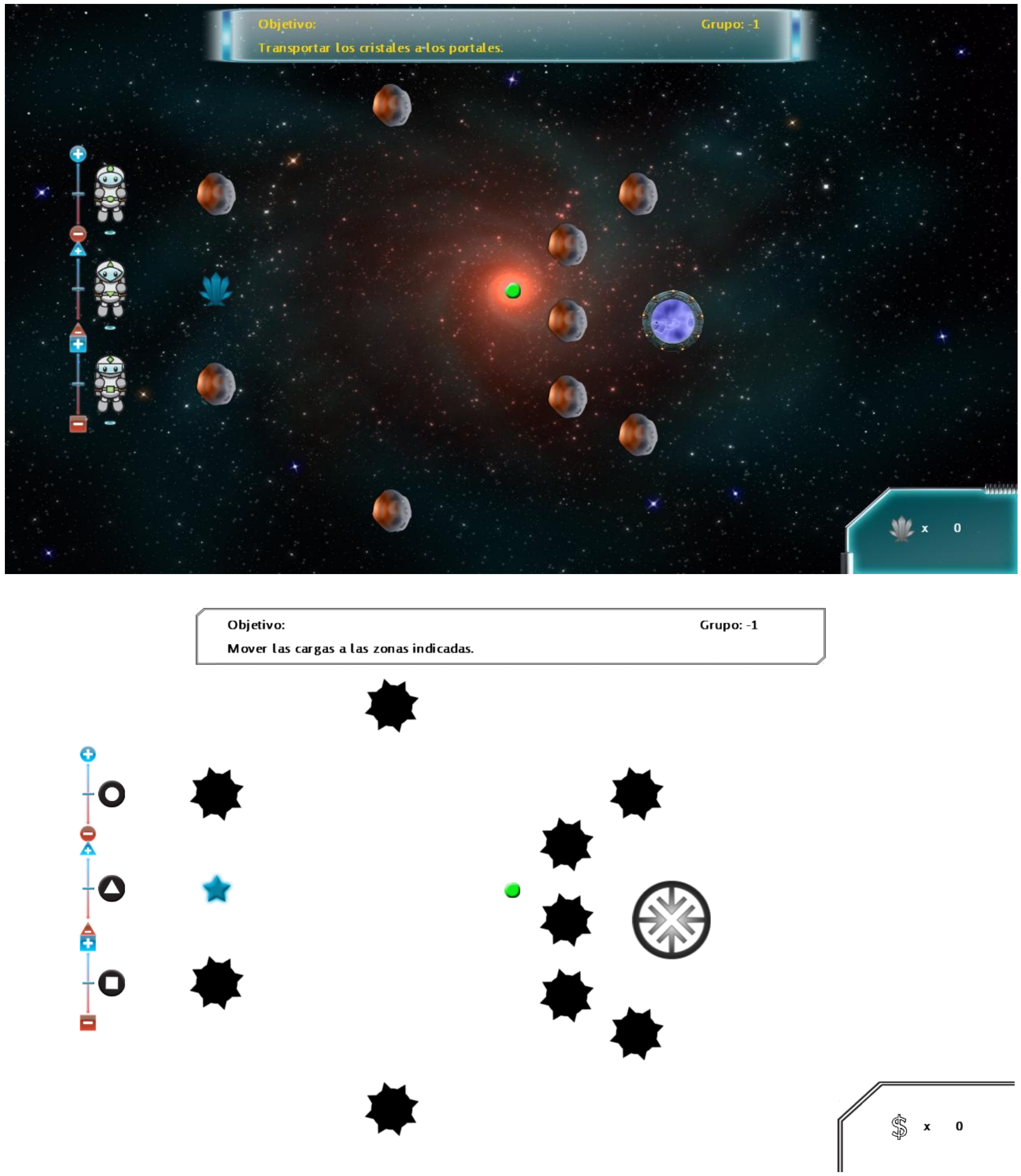

Figure 6: Screen shots of the same level viewed in the fantasy version of the game (top) and the non-fantasy version of the game (bottom).

3. Experimental study

3.1 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 12^{th} 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 that were randomly assigned, 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. To form these two groups, students were randomly sampled from the original 36 and assigned to one of the versions. 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 12^{th} 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 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 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.

3.2 Session Description

Each session was structured using a script that detailed the flow of the complete videogame-based class. This same script was used in all the sessions and for all version of the videogame, including the original version and the redesigned versions with and without fantasy. One of our researchers acted as the teacher for the session, carrying out this script. Each session started with the teacher giving an introduction to the topic to familiarize students with the general ideas and terminology. This introduction was carried out interactively, asking the students about the basic knowledge on the subject to assess what they already knew. Throughout this introduction the students were already with their corresponding groups and devices, however they could not interact yet with the game because it was paused.

After finishing the introduction, the teacher explained the basic idea of the game, how students should interact with their devices, and its relation to the concepts introduced. The teacher then proceeded to send a message through his laptop to resume the student devices and start the tutorial part of the game. Each tutorial level added a new game element which corresponded to a conceptual element explained by the teacher. The teacher received the results of the student performance in real-time and could pause the game to make specific clarifications. The teacher controlled the flow of the game, advancing to the next tutorial level only when every student had accomplished the minimum requirement. This allowed the teacher to keep the whole class working on the same concepts simultaneously.

After the tutorial phase of the game, the students then played the mission part. This part was collaborative and included different, increasingly difficult levels that encompassed all the relevant instructional concepts, and added additional gameplay challenges. In this part, there was no general explanation provided by the teacher, rather he moved around the room to observe the different groups and answered questions when the students were confused. Similar to the tutorial levels, the students controlled the flow of mission levels, advancing only when all groups had accomplished the minimum goal for the level.

3.3 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 dependent 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 a one-way analysis of covariance (ANCOVA) with the original experiment's results and the new results, using the pre-test results as co-variable (Table 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.

	Gender	Original Game		Atomic Intrinsic Integration Game	
Test		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: 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 a one-way ANCOVA with the results of both the fantasy and non-fantasy groups, using the pre-test results as co-variable and the game played as factor (Table 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 ($F = 0.30$; $p = 0.58$).

	Gender	Endogenous Fantasy Game		Non-Fantasy Game	
Test		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 3: Test results of comparison between fantasy and non-fantasy versions of the game

To analyze possible gender effects in the comparison between fantasy and non-fantasy versions, a two-way ANCOVA was performed, using both the game played and gender as factors, and the pre-test results as co-variable. The analysis showed no statistically significant differences between genders ($F = 0.17$; $p = 0.67$) and no significant interaction between gender and the version of the game played ($F = 0.95$; $p = 0.33$).

To analyze the effects of previous experience in videogames in the comparison between fantasy and non-fantasy versions, a two-way ANCOVA was performed, using both the game played and frequency of videogame usage as factors, and the pre-test results as co-variable. The frequency of videogame usage of the students was obtained through a questionnaire delivered before the experience, were students chose their gameplay frequency from one of five options: everyday, some days a week, some days a month, rarely or never. The analysis showed no statistically significant differences between gameplay frequency ($F = 0.19$; $p = 0.90$) and no significant interaction between gameplay frequency and the version of the game played ($F = 0.10$; $p = 0.90$).

The results of the Game Experience Questionnaire for students that played the fantasy and non-fantasy versions (Figure 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.

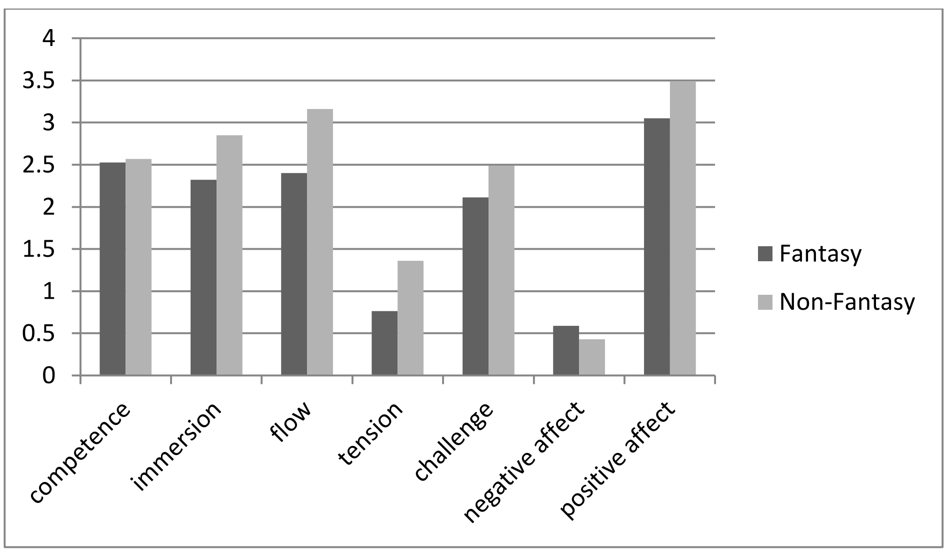

Figure 7: Game experience questionnaire results of comparison between fantasy and non-fantasy versions of the game

4. 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 8, showing the generic structure of a game that is designed using the principles.

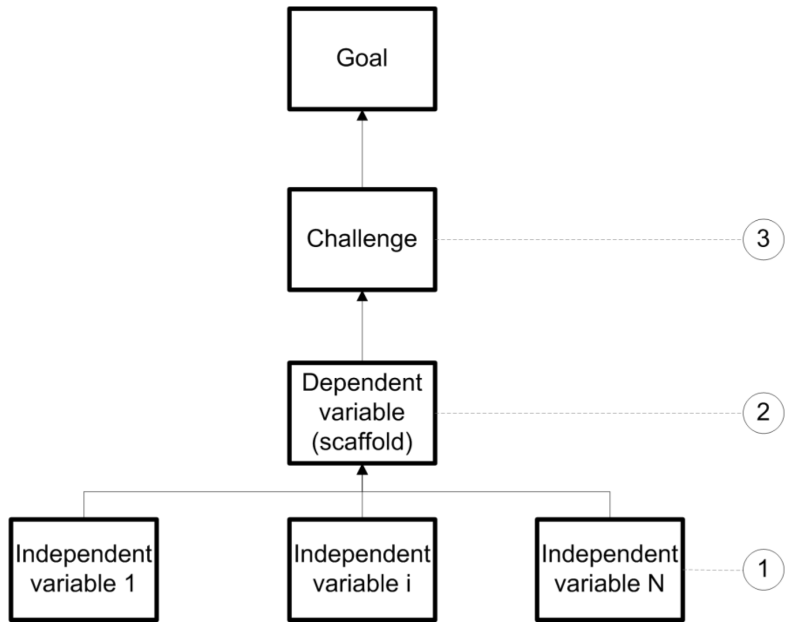

Figure 8: Generic structure of a game for the conceptual understanding of physics applying the three principles of our methodology: (1) the independent variables of the simulation are integrated as low-level game atoms, (2) the dependent variable of the simulation is integrated as a scaffolded game atom, (3) this connects to the goal through an additional game atom that provides an interesting challenge.

5. 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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