Designing physics board games: a practical guide for educators

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Abstract
Board games can be a highly engaging and motivating resource to support physics teaching at all educational levels. However, the development of board games to facilitate the communication of complex science subjects may not be an easy task for those with no prior experience in designing games. For instance, the various classification of educational game features, proliferation of game mechanics and lack of scholarly guidance for designing and on their efficacy in formal learning may hinder the game development process. To address this issue, this study presents a hands-on game development framework for science educators and researchers on how to design educational science games. The framework is divided into five steps with simple exercises that build upon each other to create a student-centred educational resource as well as providing a means of evaluation.

Keywords: game-based learning, science board game, game development

Supplementary material for this article is available online

1. Introduction
Game-based learning (GBL) has gained increased attention in formal education [1, 2] as it can create realistic situations within a game and incorporate gaming elements, such as competitiveness, challenges, motivation and fantasy [3] into science lessons. Educational games can also employ a narrative thread to get students immersed in the story and learn from it [4]. However, there is very little guidance on how to design such materials to best support the learning of physics. For instance, non-digital games, whether for education or entertainment purposes, can have a plethora of mechanics, shapes, elements and sizes [5–8]. In addition to the...
abundant variation between games, multiple evaluation frameworks have been proposed to classify and identify the efficacy of different types of GBL practices as well as the learning outcomes that one is trying to achieve [9]. Hence, game design process plays a crucial role in ensuring that educational games can balance entertainment elements, educational content and the seriousness of gaming.

An important aspect of any educational game is the focus on creating engaging experiences for players to mitigate traditional teaching problems, such as increasing interactivity between students in the classroom [1, 10]. In order to achieve this, identifying an appropriate game development framework is key to ensure that an educational game experiences are ‘translated to a variety of mediated forms with each form capturing the essentials of the gameplay while leveraging the strengths and minimizing the weaknesses’ [11, p 1]. Furthermore, Klopfer et al [12] also describes that many educational games often fail to achieve learning goals due to meaningless and simplistic game designs, leading to a perception that educational games are not fun to play or ineffective to support learning [13].

In the context of physics education, there are specific constraints that may add a new layer of difficulty in the development and implementation of educational games in formal education [4, 14]. Particularly, learning new and complex material in physics lessons can be intimidating [15, 16]. Physics is often described as subject that is difficult to comprehend with a strong mathematical tendency and male-dominated [17, 18]. Further, physics and science-themed educational games often include a great deal of complex information for students to master while solving the game [19]. Moreover, the previous experience of the target audience with games should also be considered during design to ensure that all players can glean the same skills and knowledge from the educational game in the same way [20], which is not an easy task given the pluralistic environment of a classroom. Besides this, teacher familiarity with educational games, classroom management during gameplay, and connection with the curriculum, also influence the likelihood that science educational games are adequately developed and adopted as part of their regular practice [12, 21].

In this way the development of educational games to support formal physics teaching and learning require careful design choices to embed ‘play and learning in meaningful contexts’ [12, p 48].

2. Game design framework
The lack of scholarly guidance on how to design educational board game experiences may prevent the implementation of GBL teaching practices in physics formal education, and thus hinder an opportunity to use GBL to remove the intimidation inherent in the learning process of complex subjects [12, 22]. To tackle this issue, authors identified six design principles that are essential to create meaningful and effective educational games to support the formal instruction of science. This work is grounded in the initial work of de Freitas and Oliver [21] and Djaouti et al. [23] for classifying educational games. The proposed game design framework starts from identifying the target audience, who are the central piece of the next steps of game development. This is also in line with Klopfer et al [12] who states that gameplay design should connect players, i.e. educators and students, with the game from the start to support better learning experiences.

Figure 1 shows a visual summary of the design principles and the central questions that guides the discussion at each step of game development. The framework involves five main steps with associated exercises that build upon on each other to create the basic structure of a game, resulting in a prototype ready for gameplay. The exercises are simple in nature allowing anyone, regardless of their prior experience in playing or designing board games, to create an educational game. Each step of the framework is described in the next sections. It should be noted that previous published and scholarly validated games will be used as examples throughout the text [24, 25].

2.1. Step 1: empathise
Borrowing the term from design thinking methodology [26, 27], empathise involves understanding the needs of the intended target audience. However, unlike design thinking, educational games are not designed to solve a teaching problem; instead, they focus on the best strategies to
support students’ learning of a given topic through problem-solving situations in a social network [14, 28]. As noted by Williams [11, p 7], ‘games are not played in isolation, so understanding the scenario of play can be as important as knowing the player’. Thus, the first action in the empathise step involves describing the teaching context in which the game will be implemented as well as the intended audience.

In order to understand the teaching context, it is necessary to describe five key aspects of any game namely:

(a) considering time logistics for students to play games that can be easily implemented within the school class time [29]. This involves identifying the length of the gameplay from beginning to end, which can vary from fast-paced games (less than 20 min) to full class games. Note that evaluation of the game should also be factored in.

(b) identifying the game’s intended audience is also crucial to ensure that game complexity is appropriate to maintain students’ involvement with the game and the content embedded in it. A study conducted by Cira et al [30] showed that adapting game complexity to different audience needs resulted in increased motivation, enjoyment and effort. For instance, the Valence card game took into consideration their target audience to design the aesthetics and balance the scientific information given in each card.

(c) identifying curriculum requirements, i.e. assess curriculum flexibility for non-traditional pedagogy and potential areas from the curriculum that could be covered through gameplay. Research has shown [28, 31] that a major barrier for the adoption of games in the classroom is linked to lack of curricula alignment and attitudes towards learning through games, therefore it is key to determine these points from the beginning.

(d) selecting a rubric assessment, which includes anticipating different forms of evaluation since regular tests may not assess the knowledge or skills developed during gameplay. This could involve presentations after gameplay, group discussions, reflective writings, concepts maps and knowledge diagnostic assessments.
establishing the designer’s previous familiarity playing non-digital games, is worthy of attention, as it could allow the designer to decrease development time by adapting existing game mechanics into their school context [12]. In this step, the designer should list board games that they have previously played and liked. This will save time in the next phase of development.

2.2. Step 2: define

Despite the fact that the name of this step is also imported from design thinking methodology [26, 27], this step does not involve defining a problem or a challenge to be solved [29]. Rather, it focuses on the learning outcomes that the designer aims to include in the game guided by the information created and gathered in the empathise step.

During this phase, the game designer considers the game’s learning goals, i.e. what the intended learning outcomes for the target audience or the skills that players should have developed by the end of gameplay. Note that this is a common aspect of any game development process, regardless of its type or medium [32].

In addition, this step also involves selecting other crucial elements of the game that influence how students experience the content embedded in the game. As previously mentioned, game complexity is one of the determinants of game success and adoption in the classroom [12]. However, choosing the appropriate game mechanics for achieving the intended learning outcomes is a laborious task. Although the authors have a privileged previous experience with board games, in this game development framework, it is suggested that the game designer should start creating their educational game by adapting existing mechanics. This is also supported by Illingworth and Wake [14], in which the authors recommend ‘adapting a commercially available off-the-shelf games’ (p 4) entity to communicate scientific ideas as a simple way for creating an educational gaming resources.

Thus, this step involves three main actions: define the learning outcome of the game, select game mechanics and identify challenges and constraints that influence game movements and rules, which are described in more details below.

2.2.1. Setting learning outcomes and action verbs.

Similar to any other teaching intervention, the learning outcomes should be specific, well defined and taken into account from the beginning of the development. When designing a game, the learning outcomes of a game are essentially the details of what students should have learnt on their completion of the game. Further, learning outcomes can also be used to help educators assess student learning from the game.

However, designing a learning outcome is not a simple task and requires careful consideration and reflection before implementation. For instance, since the authors’ previous research has taken place in the Irish context, the learning outcomes of the post-primary junior cycle science curriculum’s Earth & Space strand were used to guide the game development [33]. If the game designer is not familiar with developing learning outcomes nor has a curriculum to guide development, [34] provides a list of action verbs for each dimension of learning (following Bloom Taxonomy [35]) that could be used to inform game development. Once the learning goal of the game has been defined, the next step involves selecting the game mechanics or players movement in the gameplay.

2.2.2. Mechanics.

This refers to the players’ actions in the game, i.e. how they move and interact with the game [29]. Depending on the game designer’ previous experience with games, this step may add a new layer of difficulty for educational game development [19]. However, adapting popular commercial games into an educational game could reduce the game development time and costs significantly [14]. See table 1 for a list of commercial off-the-shelf board games with varied mechanics which have been implemented in other science educational games. For instance, the Dalton Centre at Manchester University implemented the game mechanics employed in Top Trumps to design an energy database card game, in which players compare and discuss different energy sources. Similarly, NASA also developed a card game in which players need to compare planetary data, and the order and relative size of the Solar System objects. It should be noted that...
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**Table 1.** List of popular board games in which the mechanics can be implemented in educational games.

| Board game       | Mechanics description                                                                 | Overview                                                                 |
|------------------|-----------------------------------------------------------------------------------------|--------------------------------------------------------------------------|
| **Pandemic**     | In this game, players are scientists and specialists trying to find a cure and treat disease hotspots for the four plagues listed in the game. This is a commercial off-the-shelf game involving multiple mechanics to engage players in the narrative, including action points (each player receives a number of points to spend on each turn), cooperation, hand management (cards with rewards when played in a certain sequence), point to point movement (game board with different areas in which players move pieces into and out of each area), set collection (collect cards in the game to make a set of them), trading and variable player powers. | The game has several expansions, mainly changing the location where the game takes place. Similarly, the game is not an educational or serious game, however, the actions players need to take during gameplay encourage role-playing of scientists’ work to research cures for diseases. In addition, other games such as periodic: a game of the elements also implement the same mechanics in which players advance in the game by collecting sets of elements and moving through the periodic table. Chiarello and Castellano (2016) created a series of educational physics games which uses point to point movement to discuss quantum physics principles and relativity. |
| **Top Trumps**   | This is one of the most popular card game. Each game contains different values, and players compare them in order to trump and win an opponent’s card and thus win the game. The first player to get all the cards wins the game. The mechanisms in this game are straightforward and involve memory, trick-taking (i.e. cards are played and evaluated in each round or trick to determine the winner) and intransitive mechanics where there is no single dominant strategy (e.g. rock-paper-scissors is based on this mechanics). | Top Trumps has several card decks with different themes, such as cars, books and popular characters. Interestingly, the mechanics implemented in this game, i.e. trick-taking, have been implemented in several educational or serious games as it allows students to analyse, discuss and make decisions based on the numerical information given in the cards. |
| **Terraforming Mars** | Terraforming Mars is a ‘modern board game’ that involves changing Mars environment to make it similar to Earth, i.e. a habitable planet. The process includes changes in the atmosphere, temperature and surface. The game has a hexagon grid game board, and involves several mechanics to engage players in the mission and topic, such as hand management, income (gain resources throughout the game), set collection, tile placement, progressive turn order, and variable player powers. In addition, the game requires players to actively engage in strategic thinking throughout the gameplay. | Despite the astronomy theme and a large amount of planetary data, the game may not be suitable to align with a regular science lesson given the duration of the gameplay (approximately 120 min). However, this is a commercial off-the-shelf game that has several mechanics which have been used in smaller educational games to convey scientific information. For instance, NASA Space Voyeurs card game is an educational game with income mechanics in which students earn research points by completing different actions in the game. Although these are not the only mechanics involved in the game, it is a great example of how the mechanics are used to engage players in space manoeuvres and overcome research challenges in outer space. Moreover, Planet, a commercial board game, employs tile placement mechanics to form environments on different planets. |
Fluxx Fluxx is a card game which includes three types of cards that change the game rules, goals and dynamics, e.g. how to draw and play cards, and winning conditions. The game mechanisms involve two well-known mechanics in board games: hand management and set collection.

Photosynthesis This game also employs an abstract board game with a science theme which aims to grow a woodland as the Sun moves around the board. Players are required to use strategic thinking to place trees in locations where there is Sun to gain points or ‘sunlight’ which can be used in a variety of ways during gameplay. Other mechanisms that are designed to engage players in the gameplay are action points, area of influence (i.e. multiple players may occupy the same space in the game board and gain rewards), income and progressive turn order.

the list provided here includes a limited number of science board games that may be of interest to the reader. The list of games provided in table 1 provides examples of games with simple mechanics which might be familiar to both teachers and students, therefore reducing the complexity of gameplay. However, [36] provides a comprehensive list of game mechanics for different types of audience that may be helpful to those with little, or no experience in playing or designing non-digital games.

Thus, it should be noted that mechanics is an important aspect of any game as it determines how one will interact with the game and between players. However, selecting game mechanics is only the first step in designing players actions and should be coupled with challenges that keep the player engaged in the game.

2.2.3. Constraints and challenges. Constraints refer to rules or movements that enable or restrict play in different ways to maintain enjoyment and motivation to continuing playing. For instance, constraints could include obstacles or challenges placed in the players’ way to make the journey to the winning goal fun and interesting [38]. However, there should be a balance in the number and level of challenges, based on the intended audience described in the empathise step, to prevent the game becoming boring or decreasing in flow [23, 39]. The constraints could include a gameplay time limit, and number of players, cards and/or moves per turn. For instance, Fluxx is a card game in which the game constraints changes during gameplay with the card New Rule, by limiting the number of card that can be drawn, played or held for each player. In addition, challenges might include actions or moves that players need to perform to progress in the game.

2.3. Step 3: ideate

Building on the previous steps, the ideate phase aims to gather information about the elements that the game will have and the story in which students will be immersed during gameplay. This is in line with [40], in which the authors describe that ‘this
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phase is to obtain a good set of ideas for what the new pedagogical model will be’ (p 177). In sum, this step focuses on three key aspects of games: components, rules and theme.

2.3.1. Components. Components refer to the materials and pieces needed to create a physical version of the game [41]. Note that the game designer must select items that align with the chosen game mechanics to maximise player immersion in the game [21, 42]. Components of non-digital games may include a board game, dice, playing cards, pawns, timer or props [14]. In the literature [37, 43, 44], educational board games involve a game board, playing cards and a timer. For instance, Dziob [45] developed a board game which has a game board, dice and playing cards. Chiarello and Castellano [37] uses game boards with paths similar to Snakes and Ladders in which players move around completing actions to win the game. Moreover, Coil et al [44] designed an educational board game in which uses a game board, playing cards with different information related to microbes and a player sheet. Thus, educational board games can involve different components to convey the scientific information.

2.3.2. Rules. Rules are defined as statements and directions that players must follow within the game to be played correctly [11]. This is one of the most important aspects of any game, as noted by [46, p 160] ‘rules provide the structure out of which the play emerges. It’s also important to realize that rules are essentially restrictive and limit what the player can do.’. Hence, it is also important to consider the target audience, defined earlier in the empathise step, as this will influence the rules that constrain their interaction with the game and between players during gameplay [12]. Moreover, rules also describe the conditions for the game to end or the method of winning, game set up, and the components of the games and how they can be used during gameplay. Figure 2 presents an example of a rule book included in an astronomy board game developed by the researchers [25].

2.3.3. Theme. This game element refers to the scenario or story in which players are immersed in the game [46]. The theme provides a context to help players remember the game rules and make better and more informed decisions in the game [11]. Also, the theme should relate to the educational content of the game. For instance, the narrative of the game could ‘allow students to take on certain identities and associated points of view’ [12, p 24]. In fact as noted by [47] narrative-centred learning environments, such as educational games, ‘have been shown to contribute to situational interest’ (p 30). An example of the game theme employed in previous research [24, 25] is shown below.

Space agencies, such as NASA and ESA, are continually sharing their information with the public using different methods. Recently, they published an article describing the puzzles that were used to test astronauts for a space mission. Solving puzzles is an essential part of the training to see if the astronaut is mentally capable of working on their own and finding solutions for any unexpected problems that may encounter in space. In the envelope, there is one of the puzzles mentioned in the article to identify grand challenges involved in space travel and to show a possible answer to these problems. Now, it is your job to solve the logic grid to recognise how a given challenge and its solution had a positive impact on our society. Be smart and work with your group to solve the challenges! Open the folder to see your first task. Good Luck!

2.4. Step 4: prototyping

This stage of the framework involves the development of a quick physical prototype based on all information selected for each game component [48]. Initially, the focus should be on testing the mechanics and verifying if the components selected align with the gameplay. It should be noted that the main goal of this step is to have a ‘quick version’ of the game to allow a playtest session with the intended audience. Therefore, the game aesthetics (i.e. artwork and graphic design of the game) can be preliminary and should only be finalised once the prototype has been tested.
and amended towards the successful intended outcomes [19, 48]. To have a truly ‘co-creative process’ [40, p 177], the prototype development should also include the target audience to understand how they will react to the game idea and enact design change accordingly [14]. In fact, the most important thing about this initial prototype is to run through the design ideas quickly and gather feedback to guide the refinement of the game.

Figure 3 shows the initial prototype of the board game employed that integrated the game elements described in the previous steps. The development of the prototype involved one physics expert and one science teacher to gather feedback about the learning outcomes of the game, evaluate the selected games components and check wording of the board and playing cards. After the initial prototype was finalised, the researcher invited other intended stakeholders (e.g. post-primary school students) to evaluate the game before moving to the playtest phase.

2.5. Step 5: playtest

The last part of the game development framework involves playtesting the games. Playtesting is an important aspect of the game development process. As noted by [48, p 38] ‘the fun and excitement of playing cannot be calculated in an abstract fashion: it must be experienced’. In addition, it is difficult to predict what will work without testing the prototype, regardless of the designer previous experience with developing or playing educational games [41]. As described in [14] playtesting is an iterative process which involves starting playing the game alone and then with a ‘trusted inner circle’ (p 10) to build confidence in design before moving to playtest with large groups.

For example, the games could be piloted with physics experts to review the game content, a game developer to analyse the proposed game mechanics, science teachers to verify the curriculum alignment and lastly, post-primary school students, and the target group of the
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Figure 3. Initial prototype developed by the researcher to gather initial feedback from the intended audience about the core idea of the game.

Figure 4. The final design of the board game created after playtest. Reproduced with permission from [25].
intervention. Evaluating the game idea by peers is extremely important to gather feedback about the game before moving into a final design. The feedback form employed by the authors in prior work is given in the supplemental materials (available online at stacks.iop.org/PhysEd/57/035006/mmedia).

Once the prototyping is concluded with the target audience, the designer should work on the visual aesthetics of the final game design. For instance, an evolution of the prototype described in the previous step is shown in figure 4. The board was designed to have strong visual elements and graphics that would immerse students in astronomy.

3. Conclusion
Research has shown that educators and researchers alike encounter many barriers in adopting games for teaching science due to procedural difficulties in designing games and lack of training on using games in the classroom [49, 50]. To address this issue, the game development framework outlined here provides a simple guide on how to apply learning principles in board game design that may lead to enhanced engagement and academic performance in Physics education. The framework involves five design principles: empathise, define, ideate, prototype and playtest, in which well-defined tasks are described, taking into consideration both essential features that any educational game should include such as rules, learning outcomes, and designing purposeful game mechanics, and the learning outcomes intended with the educational game resource. Thus, it is hoped that this five step framework will support the uptake of non-digital games in physics classrooms, from the standpoint of designer or user, and from novice to the more experienced game creators.

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No new data were created or analysed in this study.

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