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A Gamification Framework for Exploratory Learning in Higher STEM Education

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Abstract:

One important objective of higher education is to foster a lifelong learning mindset in students. This is often achieved by encouraging them to delve into topics and techniques that go beyond the basics of a course. However, instructors often find it challenging to motivate students to engage in this type of exploratory learning. In this paper, we present a gamification framework specifically designed to promote exploratory learning in STEM (Science, Technology, Engineering, and Mathematics) courses while also enhancing inclusion and student engagement. The framework provides a comprehensive guide on how to turn a course into a role-playing game (RPG), including recommendations for intriguing story lines, the design of a game store with motivating rewards, and various types of quests with different exploratory learning objectives. To demonstrate the feasibility of the framework, we include three detailed case studies of gamifying STEM courses from different disciplines: Software Engineering, Mechanical Engineering, and Computer Science. We also analyze student feedback, summarize common findings, and propose potential areas for improvement.

Keywords:

Gamification, Exploratory Learning, STEM education, higher education, engineering education.

1. Introduction

Have you ever faced similar difficulties as described in the following scenario? As an instructor, you taught a critical subject and wanted your students to try a beneficial activity. This activity was related to the topic discussed in class, but not covered during lectures or included in the course objectives. You made it a bonus assignment, but later found that only a small number of students actually completed the activity and thus learned something new.

Many STEM courses cover important technical content. Students usually need to work on different assignments to reinforce their learning. Sometimes instructors find students not motivated enough to finish the assignments, especially bonus assignments and after class readings/practices aimed at encouraging student exploratory learning. One possible solution to this problem is gamification.

In the context of education, gamification is a pedagogy of using game elements and/or game designs to motivate student learning and promote a growth mindset [1][2][3]. Gamification can be done in either large or small scopes. Small scope gamification activities usually involve designing an individual class activity or assignment in a certain game format, which is very context specific. On the other hand, large scope gamification refers to gamifying an entire course. Many STEM courses share similar structure (lectures, labs, assignments, projects, etc.), which makes a generic course gamification framework possible.

This paper provides a generic framework to gamify a college-level course. Even though the framework can be implemented to turn all course components into game elements, the focus of the paper is on gamifying non-mandatory course assignments/activities with an intent to motivate students to learn and explore course-relevant subjects beyond required course work.

The rest of the paper is organized as follows: Section 2 describes related work on gamification and exploratory learning; Section 3 defines the gamification framework; Section 4 presents and analyzes three case studies on customizing the proposed gamification framework in different courses; and Section 5 concludes the paper with possible future improvements.

2. Related Works

"Gamification" was coined for the first time by game developer Nick Pelling in 2002. It was used to describe the use of a game-like user interface for electronic transactions applications [4]. The concept soon gained its popularity in business and marketing field [5], as well as user experience design. For example, Nah et al. proposed a framework for gamification of enterprise systems to enhance training and user experience with enterprise systems [6]. Noorbehbahani et al. provided an overview on how to map gamification to e-marketing [7].

There have been many research works and applications of gamification in the field of education. Much of the work has focused on gamifying individual learning activities. For example, Prasetya et al. proposed an idea to use gamification to make learning formal specification fun [8]. Singh et al. discussed a gamified approach to learn the concept of mathematical fraction [9]. Brown et al. designed some game-based learning methods to promote a culture of laboratory safety [10]. Some gamification platforms to gamify classroom activities such as quizzes and surveys have also become popular; a good example is Kahoot.

In addition to gamifying individual learning activities, researchers have also been working on enhancing gamification theories in education. Denny examined the effect of virtual achievements on student engagements in his study [11] and discovered significant positive effect. Inchamnan et al. discussed gamification workflow for growth mindset processes [12]. Su evaluated the cognitive load and possible learning anxiety caused by gamification in education [13]. As part of the European Horizon 2020 project NEWTON, an innovative NEWTON-enhanced gamification model was developed [14].

Exploratory learning traditionally mainly focuses on K-12 educations. There have been many good exploratory learning platforms for K-12 students such as Khan Academy Kids. During the last few years, some researchers have started exploring the application of exploratory learning in Higher Education, partially due to the increased online teaching needs incident to the COVID-19 pandemic. Garcia developed a real-time operation system tool to promote exploratory self-learning during remote learning [15]. Zuo et al. established some learning organization in exploratory learning based on social software [16].

3. Gamification Framework for Exploratory Learning

For a typical college-level STEM course, there are three essential elements: lectures, assignments, and tests. The types of assignments vary from individual problem-solving homework to group projects and presentations. Since the goal of this work is to encourage student learning outside class time and required assignments, our focus is on how to structure these extra learning activities into a game format, and then use a reward system to motivate students to participate in these extra learning activities.

According to Werbach and Hunter's game elements model [9][18], gamification is driven by **Mechanics**, rooted in **Dynamics**, and implemented by **Components**. Dynamics are big-picture aspects of the gamified system that should never enter into the game; Mechanics are the basic processes that drive the action forward and generate player engagement; Components are the specific instantiations of mechanics and dynamics. The proposed gamification framework follows this model. Our gamification framework focuses on major game components including quests, virtual currency, virtual goods, store, rules, and leaderboards. On top of those, we also need to define win states and create a good narrative to engage students in the game.

To summarize, here are the 5 general steps to gamify a course:

Step 1: Set up a game structure.
Step 2: Create a narrative (story) to engage students.
Step 3: Define game rules and win state.
Step 4: Identify game activities (quests).
Step 5: Design a reward mechanism.

Figure 1. Gamification Framework Elements based on Werbach and Hunter's Model

The rest of this section gives detailed explanations of each step.

3.1 Game Structure

A gamified course should look like a game. There are several game genres that can be applied to a course setting. In this framework, we decide to use a pseudo-sandbox role-playing game as our basic game structure.

A role-playing game (RPG) is a game in which players assume the roles of characters in a fictional setting. In a sandbox RPG, players have almost full control of their own actions and are free to explore. Minecraft and Valheim are both good examples of this format. Sometimes a sandbox RPG may lack objectives and thus cannot provide enough motivation to progress. Therefore, we create a pseudo-sandbox RPG that will keep the freedom for players but at the same time set clear objectives such as win states and a leaderboard to engage students.

Here are the basic components in our game structure. They are all listed as "components" in Figure 1.

Quests:
Quests are special tasks for players. Completing quests will allow players to earn various amounts of in-game currencies to purchase rewards. In our gamification framework, quests are different learning activities that are not mandatory lectures, assignments, and tests. Section 3.3 will give detailed discussions on typical learning activities that can be converted to quests.

Virtual Currency:
The format of virtual currency varies depending on the narratives. It is used to standardize points earned by players once they finish certain quests. Examples of virtual currency can be banknotes, golden coins, or different types of diamonds. Players can use earned points to purchase virtual goods in a game store.

Game Store:
A game store contains different types of rewards, A.K.A virtual goods. To motivate students to engage to further learning and exploration of course related knowledge, these rewards should have direct or indirect positive impact on their grades. Detailed reward mechanism discussion is in Section 3.4.

Virtual Goods:
These are different types of rewards available for students to purchase with virtual currency. Detailed discussion on designing virtual goods is in Section 3.4.

Game Rules and Win State:
The game rules for education purpose should be simple and straight forward so that they do not distract students from the learning goals. Depending on the story narrative of the game, certain win states should be identified. For example, if the narrative is to build a magic castle, the basic game rule would be to collect enough coins to purchase necessary building materials to build the castle. Naturally, the win state would be a built castle.

Please note that cooperation among students may be introduced to the game if desired. For example, the game rule may require the whole class's effort to collect enough material for building the castle.

Leaderboard:
Competition is another effective driving mechanism to generate player engagement. A leaderboard is a good implementation for that. Students may create their unique player ID to be

listed on a leaderboard. Player IDs should be different from student names to avoid any unnecessary negative impact from competition. A typical leaderboard can rank the rewards (in virtual currency or virtual goods) acquired by different players.

3.2 Narrative

Any RPG game should have a comprehensive narrative to tell the background story and assign relevant meanings to the players, quests, win states, virtual currency and goods. For example, in the case study described in Section 4.1, the background story is in a fantasy magical land where an evil dragon is damaging to the kingdom. The players are warriors who want to defeat the dragon and bring peace to the kingdom. The win states would naturally be defeating the dragon, which requires enough weapons and/or spells. The narrative of quests should conform to the magical land context and rewards can be weapons and/or spell scrolls that have certain positive impacts on students' grade.

3.3 Game activities

Game activities are in the format of quests in this gamification framework. Table 1 shows a template for quest design.

Table 1: Quest Design Template

Quest Name	*A few words summarizing the activity*
Narrative	*Relevant to the game's background story*
Description	*A detailed description on what students should do to complete the quest*
Learning goal	*List related learning objectives.*
Reward	*Virtual money. In special cases it can be virtual goods directly.*

The design of quests is the most customizable component in this framework. Design quests that accommodate the overall gamification objectives. For example, if the main objective is to motivate students' exploratory learning, any exploratory learning activities (such as supplemental reading/video watching/exercise) could be designed as quests. If the instructor mainly wants to reinforce topics learned during the course, preview quizzes or extra exercises could be good candidates for quests. If the major goal is to improve interactions between students and the instructor, small quests can be designed to reward students visiting office hours and asking questions inside and outside class.

3.4 Reward Mechanism

Reward mechanisms are designed in the format of a game store. There are rewards (virtual goods) in the store that can have either direct or indirect impact on students' grades. The key to developing a successful store is to listen to students. Use your experience on the "I wish" comments or requests from students during your past semesters and design them into virtual goods that can be purchased with virtual money. Table 2 provides a template for developing a reward item.

Table 2: Reward Item Template

Reward Name	*The name should be related to the game narrative*
Description	*The effect of using the reward item (relate to the game narrative)*
Result	*What a student can do/get in a course*
How to Use	*Instructions on how to use this reward in the course*
Cost	*How much virtual money it costs*
Total Counts	*How many items are offered to the entire class*

4. Case Studies

Three gamification case studies were conducted at University of Wisconsin-Platteville during the fall semester of 2022. These case studies all followed the proposed gamification framework. However, they were customized for different STEM courses with slightly different objectives.

4.1 A Software Engineering Course Case Study

A dragon slayer game was implemented in a junior level software engineering course (SE3730 Software Quality). The course consisted of two sections with a total of 52 students. The final goal in the narrative is to become strong enough to Slay the evil dragon. Students were able to undertake 6 different quests, each with their own rewards. Upon completion of each quest, students would earn a certain number of magic crystals, which could be used to purchase magic items from the game store. There were 5 different magic items available for purchase. An adventurer's leaderboard was also posted and updated throughout the semester. Tables 3 and 4 provide a brief summary of the quests and magic items.

Table 3. Dragon Slayer Game Quests Summary

ID	**Quest Narrative**	**Description**	**Quest Type**
1	Explore the map of the black forest where the dragon lives	Visit career fair and ask employers about Quality Assurance (QA) positions in their companies	Free exploration: explore the market need for QA skillsets
2	Get magic training to strengthen your power on time manipulation magic	Finish 4 additional modules on a visualized learning tool for Git Branching	Topic reinforcement
3	Study an old master wizard's works and get inspirations	Watch a documentary about Dr. W. Edward Deming	Additional Reading/Video Watching
4	Win a warrior tournament	An in-class QA process improvement contest	Competition and challenge.
5	Practice a magic spell you learned from a book	A coding exercise to practice test driven development steps	Topic reinforcement
6	Win a wizard tournament	Use RapiTetris to strategically play the Tetris game to achieve maximum MC/DC testing coverage	Competition and challenge.

Table 4. Dragon Slayer Game Store Items Summary

ID	Name	Narrative	Effect
1	Memory Spell Scroll	Enhance your memory for casting spells during a battle	Bring one extra one-sided letter-sized hand-written cheat sheet to your exam
2	Regeneration Spell Scroll	Regenerate a part of your wounded body	Resubmit one exam question after it is graded
3	Chronos	The magical hook-style sword can drag time back	1-day extension on any assignment
4	Hypno	The sword can hypnotize your opponent.	The professor will forget ONE mistake in your assignment. You can resubmit your assignment to correct ONE mistake.
5	Dragon Slayer Halo	Congratulations! You have collected enough powers to defeat the dragon! You have the option to wear a Dragon Slayer halo, which will increase your power permanently.	'Your final grade will increase 1%.

This game received very positive feedback. At the end of the semester, a comprehensive survey was conducted, and 28 students responded. The majority of students agreed that the game is fun to play, motivated them to learn more outside the class, and helped with their learning in the course. Most of them also indicated interests to play similar games in other courses. Figure 2 shows the detailed results.

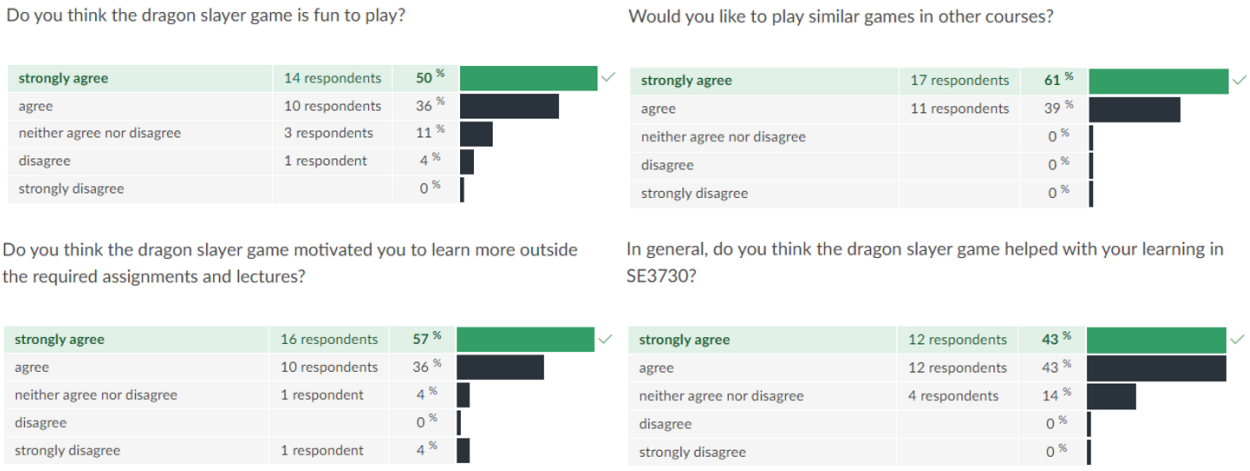

Figure 2. Student Survey Results on Overall Satisfaction of the Dragon Slayer Game

Figure 3 shows the detailed results of students' feedback on their favorite quests and magic items.

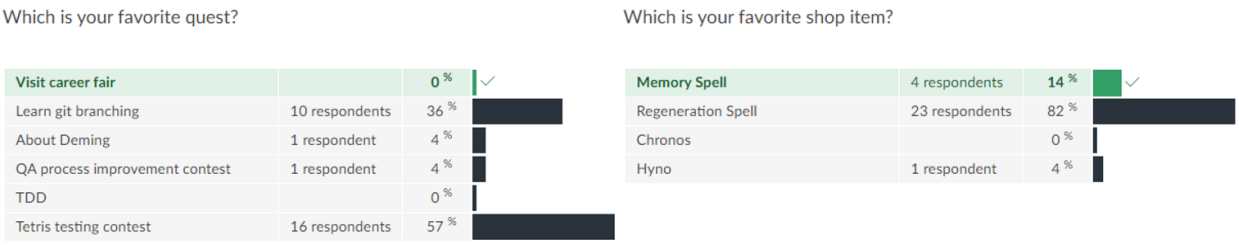

Figure 3. Student Survey Results on Favorite Quest and Shop Item

In terms of students' favorite quest, "Tetris testing contest" was the winner, followed closely by "Learn git branching". It is worth noting that these were the two quests that had game elements in the activities themselves. Moreover, "Tetris testing contest" also had a competition element in it. The student who achieved the highest MC/DC coverage won the contest and got extra crystals as the prize. These findings confirm that entertainment plays a crucial role in the success of any gamification effort, and that competition provides greater motivation.

There is no doubt that the Regeneration Spell Scroll was the most popular magic item among the students. Throughout the semester, 4 tests were given in the course and all students collectively purchased and utilized the Regeneration Spell Scroll more than 50 times. In the course game design, it is important to design desirable virtual goods so that they can motivate students to finish quests.

Many students also commented that they liked the idea that these quests were just "posted" without a deadline and they can finish them any time during the semester without time pressure. This flexibility helped many students to eventually being able to finish all or most of the quests.

4.2 A Mechanical Engineering Course Case Study

The proposed gamification framework was implemented in an upper-level Mechanical Engineering course (ME4750/6750 Computational Methods in Engineering). Gamification elements were added to the course with the goal of reducing dependence on points and grades as motivations for students to complete learning activities. A blended motivation scheme was adopted which uses both grades and game currency to reward activity completion.

Course content was divided up into modules, with each module consisting of **Inquiry**, **Investigation**, and **Solutions** activities. Each assignment included a rubric for both grading points and currency. Currency was awarded based on the overall assignment performance to additionally incentivize quality work. With each assignment, students accumulated currency as the course modules were completed. Before the course mid-term students were given a purchase order by which they could buy virtual goods to provide perks on the exam. Perks included the following, depending on the price of virtual goods:

- additional 50% time for exam
- access to student notes
- access to instructor notes
- 5-minute access to internet connection

- ask instructor a single true/false or multiple-choice question with answer posted for all to see
- ask instructor any question but receive no points for instructor's comments

Students were presented with reflection questions related to the course gamification at the end of the semester. Several questions were posed to gather general positive and negative replies, as well as recommendations for possible improvements which can be harvested for future ideas. Additionally, students were asked to unambiguously state whether the gamification should be retained or eliminated on the course's next offering. The majority of students had positive opinion about the gamification elements in the course and would like to retain them. Figure 4 shows the detailed results.

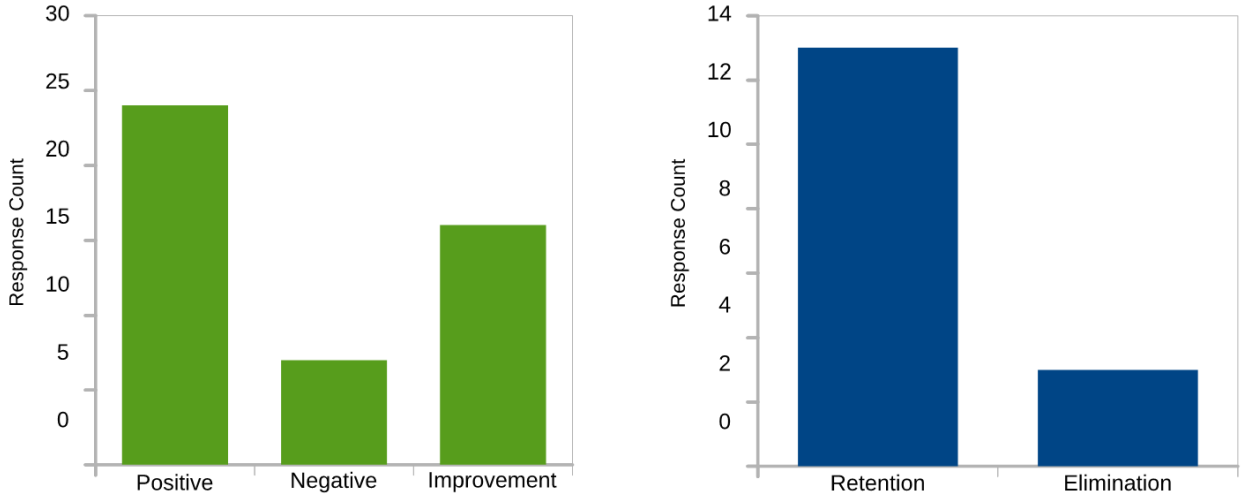

Figure 4. Student Survey Results on ME Course Gamification

Positive comments by students indicate partial success in the attempt to provide additional motivation for completion of learning activities and assignments. Examples of positive student comments include the following:

- "More gratification that works contributed to more than "just a grade""
- "Turn in every assignment when I otherwise might not"
- "Gave incentive to get work done and make corrections to provided materials"
- "Added strategy to getting work done; felt more important"

When prompted for negative impacts of the gamification student comments were more diverse than when asked to indicate positive impacts. Students indicated adjustments to the economy and increased application would improve the merit of gamification. Reduced need to prepare for exams when able to rely on perks was also noted several times. Some example responses are included below:

- "I studied less for the exam because I knew I would have my notes"
- "Has some promising aspects, but not compelling enough in current form"
- "Economy needs work; some equipment is too cheap"

Students identified a number of potential improvements to the gamification system; most of these recommendations focused on wider and deeper integration of gamification into the course. Specifically, students requested more opportunities to earn and use class currency. Some example student recommendations include the following:

- More incentives to buy besides just exam perks
- Need more opportunities to spend currency
- Integrate more deeply with course; expand beyond just exams
- Use currency to eliminate minor aspects from assignments
- Create more diverse opportunities to earn currency

4.3 A Computer Science Course Case Study

Compared to the previous two case studies, the proposed gamification framework was implemented in a junior level Computer Science course (CS3830 Data Communications and Computer Networks) in a light-weight manner with one specific objective: improve student engagements in and outside class. With this goal in mind, example quests designed for this course include:

- ranking top during Kahoot! quizzes in class
- winning an in-class programming contest
- submitting "muddy paper" (clarification questions) to the instructor

Students would collect golden points by completing various quests. With enough points, they could make a wish and the instructor would decide if the wish could come true. Here are some example wishes that came true during the semester: one assignment deadline extension, one assignment resubmission, one quiz retaking, etc.

Figure 5 shows the positive impact of the gamification element on student engagement with a total of 96 students in class. The first two class activities were rewarded with golden points, while the last activity (final outcome survey) had no incentive. A significant difference can be observed.

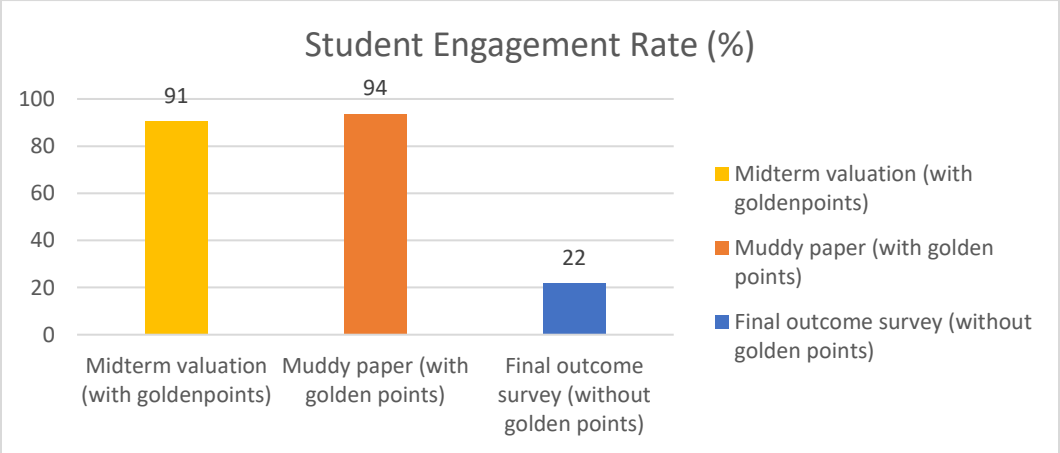

Figure 5. Student Engagement Rate for Different Activities

At the end of the semester, an open question survey was conducted in class. Most students listed some game quests as part of their favorite activities in the course and would like to see similar activities in future courses.

5. Conclusions and Future Works

In this paper, we proposed a generic gamification framework for Higher Education courses. Even though the proposed framework can serve as a template to design a course-wide game for any course, the focus of this paper was how to utilize it to motivate exploratory learning of students that go beyond the basics of a STEM course. Three cases studies were conducted in three different engineering and science discipline, all of which demonstrated positive impact on students learning.

The implementation of the proposed gamification framework requires a significant amount of upfront game design work and manual effort to maintain the game during the course, which may pose a challenge for instructors. To overcome this, we plan to explore the possibility of automating a portion of the gamification-related tasks, such as automated tracking of game statistics, game design tools, and virtual good management. Additionally, we aim to expand our gamification knowledge base by experimenting with new quest and virtual good concepts.

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