

Experiences with an interactive boardgame that teaches elements of a basic automatic control course

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Abstract: Games are key pedagogical activities that engage students in problem-solving, critical thinking, and analytical ways of thinking. This paper introduces how we integrated Zendo, a game of inductive logic, into our teaching practices. To explore the impact, we collected the data from students in their active engagement with the interactive boardgame learning environment. Using a quantitative survey as well as an open-ended questionnaire, 16 students documented their in-context experiences, perceptions, and responses. We analysed the quantitative data through descriptive analysis while inductively coding the qualitative data to reveal the impact of the game on the students. The quantitative analysis showed a positive impact of the game on five different constructs related to learning, such as affective factors, collaborative learning, higher order thinking, and metacognition, while the qualitative data revealed four categories - low-stakes learning environment, collaboration and sociocultural influences, awareness of one's own inductive learning, and inspiration for learning - all of which support traditional classroom teaching. These appeared to be aligned with the sociocultural perspective, based on the idea that social interaction plays a crucial role in learning. The collected experiences show that games may supplement traditional homework, providing a learning environment that triggers students' cognitive (reflect and internalize) and social (interact and socialize) processes, an essential supporting element of learning. Through the lens of sociocultural theory, it not only enhances student engagement but also facilitates collaborative learning experiences. Additionally, within the framework of socio-constructivism, gamification serves as a powerful learning tool to foster active participation, social interaction, and the co-creation of knowledge among students.

Keywords:

Control education, educational games, logic game, pattern recognition

1 Introduction

1.1 Active learning elements in automatic control courses

Automatic control systems are sets of devices that command the behaviour of other devices using feedback loops. They are ubiquitous, as they appear practically everywhere in our homes, in the industry, in communication systems, and in scientific instruments, just to name a few (Åström, 1999). Notably, the underlying theoretical concepts find applications even in the design of quantitative-based personalized education (e.g., Knorn & Varagnolo 2020). For this reason, a basic automatic control course is included as part of the standard curricula of many engineering programs, such as electrical, mechanical, and aerospace. However, since the theoretical aspects of automatic control system design, i.e., the so-called *Control Theory*, are strongly grounded in mathematics, many students perceive this course as challenging. For this reason, many instructors have tried to incorporate active learning elements in their teaching practice, given the evidence that complementing traditional lectures with activities that stimulate problem solving can increase the learning and engagement of the students (Knight & Wood, 2005). Among active learning elements successfully implemented in a basic automatic control course, there are digital interactive tools (Koch et al., 2020; Costa-Castelló et al., 2018), virtual and remote laboratories (de la Torre et al., 2020), educational videogames (Munz et al., 2007), and escape rooms (Axelson-Fisk et al., 2022). However, to the best of our knowledge, no board games have been proposed so far to complement the traditional teaching of automatic control.

1.2 Game-based learning in higher education

“Serious games” find applications in different fields like education, healthcare, and military, offering novel ways to engage users for emotional purposes (Ma et al., 2011). New generations of students learn differently from the previous ones and want to be exposed to new information in a way that is not only useful, but also fun (Garcia-Iruela & Hijón-Neira, 2020). For this reason, the interest in using games as a teaching and learning strategy has increased in the last years, as educators search for opportunities to interact with their students and ensure that they achieve the appropriate learning outcomes (Menon & Romero, 2020). The socio-cultural approach to game-based learning emphasises the significance of social interactions and cultural contexts. Games become collaborative tools, enabling learners to co-construct knowledge through shared experiences, discussions, and interactions. This approach recognises the role of the environment in shaping learning dynamics and promoting meaningful engagement within diverse contexts.

Learner motivation is one of the key determinants of the learning process. Creating the game-based learning environment where learners engage with games and other players can lead to enhanced performance outcomes, as heightened enthusiasm and active participation contribute to more effective learning and skill development (Brusilovsky et al., 2009). A study by Hartt et al. (2020) explored the efficacy of game-based learning by using an immersive game-based approach that incorporated newly designed gamified tasks and activities in a higher education context. Their findings highlighted enhanced engagement, critical thinking, and collaborative skills. However,

challenges related to game design and integration into curricula are noted. In game-based learning, student interaction develops through dynamic engagement with virtual environments and peers. Collaborative problem-solving, communication, and strategic decision-making foster active participation, enhancing comprehension and knowledge retention. This interactive mechanism cultivates a conducive learning atmosphere that promotes both individual growth and collective learning outcomes.

Identifying the crucial factors that lead to successful learning represents a central focus in the research pertaining to the socio-cultural approach within the area of game-based learning. Three features – incentives, personalised agents, and navigation – were identified as key in considering how an instructional game should be designed (Sun et al., 2023). Findings from the study reveal the significance of community, peer interactions, and instructor support in fostering positive attitudes. Furthermore, the study discusses that both negative and positive feelings of game-based learners are contingent on the degree of control they have over the tasks and how relevant they perceive the tasks and games to be to their learning. Notably, some recent studies have pointed out that games can be tools for student co-creation in higher education (Zarandi et al., 2024).

Co-creation involves students participating in the learning process and constructing understanding and resources alongside academic staff, fostering positive relationships and shared endeavours in education, where both teacher and students learn from each other (Bovill, 2020). Co-creative elements that manifest in game-based learning activities comprise, among others, information seeking, information sharing and helping behaviour (Yi & Gong, 2013).

1.3 Inductive reasoning and the Zendo game

Inductive reasoning is the process through which we gather and analyse evidence to make predictions and formulate conclusions (Hayes et al., 2010). Felder & Silverman (1988) mention that “induction is the natural human learning style”, as it is the natural approach through which children discover the world, whereas “deduction is the natural teaching style”, since stating a principle and working down to its consequences empowers the teacher with more control over the organization and presentation of the topics. However, some works have highlighted the potential of inductive reasoning strategies to improve the students’ higher-order thinking skills, see, e.g., Low (2010), Misrom et al. (2020) or Pásztor et al. (2022). Zendoⁱ is a game of inductive logic designed by Kory Heath in 1999, in which one player (the master) must guide the other players (the students) so that they can correctly guess a hidden rule. In the original game, this is done by building and studying structures that may or may not satisfy the hidden rule, using a set of game components comprising pyramids, wedges, or blocks, that come in different colours, such as blue, red, or yellow. The game was adapted by DeOrsey et al. (2021) to teach mathematical concepts such as functions, numbers, sets. In their study, the authors provided examples of games and rules that have proven to be engaging during testing with students and teachers and discussed best practice for implementation. A survey was distributed to each student that participated in the organized activities, and a 97.6% rate of positive feedback was received.

1.4 Research contribution

Motivated by the above discussion, a variant of the Zendo game, referred to in the following as *Control Zendo*, has been developed, implemented and tested in the Spring 2022 basic Automatic Control course (*ELE320 – Reguleringssteknikk*) at the University of Stavanger, Norway. This paper discusses our experiences with the game, supported by a critical analysis of the available quantitative and qualitative data about the students' opinions, collected through a questionnaire, and processed by means of descriptive analysis and inductive coding to reveal the impact of the game on the students. Instead of providing explicit instructions, the game encourages players to uncover the hidden rule through hands-on engagement. By immersing learners in problem-solving scenarios, this inductive game promotes critical thinking, pattern recognition, and deep understanding. This methodology allows players to construct their knowledge while fostering a sense of ownership over the learning process. In essence, *Control Zendo* turns the learning process into an interactive environment that motivates learners to explore, hypothesize, and construct knowledge through the process of playing the game. We intended for the game to be a learning environment that would help to strengthen course concepts and principles through their application in a different context. Further, we intended *Control Zendo* to impart comprehension of the interconnected nature of different course topics that might have previously seemed unrelated (Claypool, 2013).

1.5 Organization of the paper

The remainder of the paper is structured as follows. A description of how to integrate *Control Zendo* in teaching, covering the game rules, a gameplay example, and our experiences with using the game in the classroom is provided in Section 2. Results obtained from a questionnaire survey are provided in Section 3, along with the analysis of quantitative and qualitative data. Section 4 discusses the efficacy of the boardgame in teaching theoretical content through inductive logic. It discusses participant satisfaction and effectiveness in enhancing learning, particularly in affective factors, collaborative learning, higher-order thinking, metacognition, and potential future use, as supported by both quantitative and qualitative survey responses. Finally, Section 5 draws the main conclusions of this study.

2 How to integrate Control Zendo in teaching

2.1 Overview and summary of play

In *Control Zendo*, there is one player who is the *Master of the Sacred Loop*. This player is required to be knowledgeable about the topic under consideration and is the only one to know the hidden rule. Their role is to guide all the other players, a.k.a. *Disciples of the Sacred Loop*, towards the revelation of the hidden rule. Note that the *player* is not necessarily a single person, as this term can correspond to a team without significant modifications in the way the game is played.

Setup – Each disciple receives sheets to write down the equations as well as their personal annotations. Also, they receive two answering tokens, one black and one white. The *Master of the Sacred Loop* receives green and red marker pens. The Master of the Sacred Loop draws a card from the deck corresponding to the topic under consideration (see Figures 1-2) and marks it with the provided paperclip, selecting a subset of

statements to form the hidden rule that other players must guess. It is important that the Master of the Sacred Loop understands the hidden rule and can tell if an equation written down by a disciple satisfies the rule. If this is not the case, they are allowed to draw cards from the deck until they feel confident with the chosen rule. At this point, the Master of the Sacred Loop writes down two equations *Eq1* and *Eq2* on a publicly visible surface, for example the whiteboard. One of the equations must follow the hidden rule, while the other must violate at least one of the statements that define it. The former gets marked with the green marker pen, whereas the latter gets marked with the red marker pen.

Gameplay – The remainder of the game involves the disciples taking turns until the hidden rule is guessed correctly. In their turn, the disciple (in the following referred to as *active*) performs the following actions:

1. They write down an equation on their sheet, which gets marked by a progressively increasing number, i.e., *Eq3*, *Eq4*, etc.
2. They choose *tell* or *challenge* (read below)
3. Optionally, they can use Laplaceⁱⁱ coins to make guesses about the hidden rule (one guess per coin). Laplace coins are earned by winning a *challenge* (read below). After the active disciple has made their guess about the hidden rule, the Master of the Sacred Loop will tell whether the guess is right or wrong. In the first case, the active disciple wins the game. In the second case, the Master of the Sacred Loop will provide a counterexample that disproves the active disciple's guess. Note that partially right rules are considered to be wrong.

Tell – If the active disciple has chosen *tell* at step 2 of their turn, the Master of the Sacred Loop will look at the equation written down at step 1 of the turn, and will tell whether it follows the hidden rule or not, marking it with the green or red marker pen, accordingly. Note that this information is supposed to be available to all players, so it is recommended that the equation and colour marking are also shown on a publicly visible surface.

Challenge – If the active disciple has chosen *challenge* at step 2 of their turn, then every disciple secretly picks one of their answering tokens. If they think that the equation written down by the active disciple follows the hidden rule, then they will pick the white token. On the other hand, if they think that the equation does not follow the hidden rule, then they would pick the black token. Once every disciple has chosen their answering token, they reveal them simultaneously. At this point, the Master of the Sacred Loop reveals whether the equation satisfies the hidden rule or not, marking it with the green or red marker pen (as already described in *Tell*). All the disciples who picked the correct answering token earn a Laplace token which can be used in step 3 of their turn to try to win the game by making an official guess of the hidden rule. Note that the active disciple can immediately use their Laplace coin at step 3 of their turn.



Figure 1. Deck "Classification of Systems"

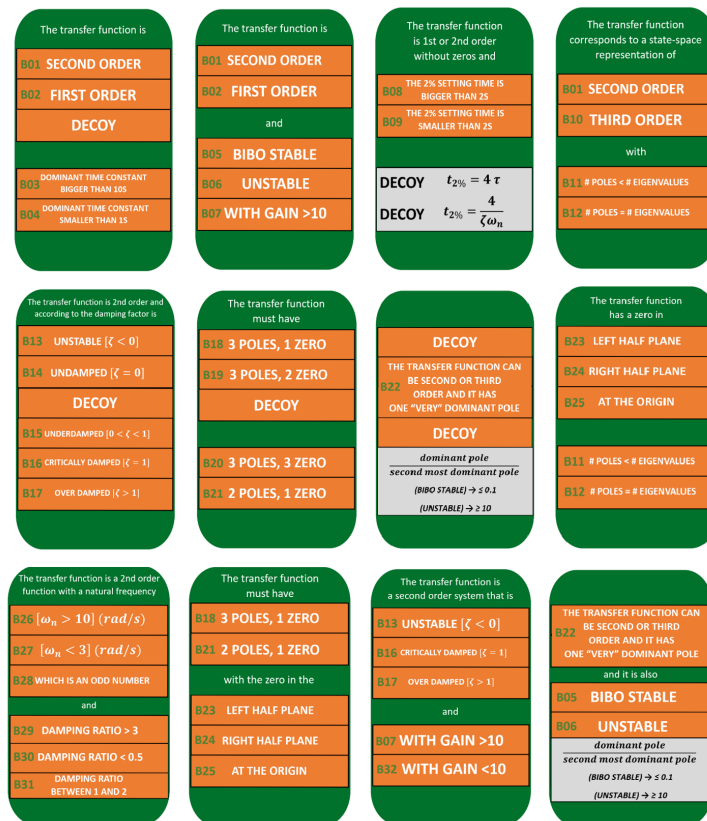


Figure 2. Deck "Transfer functions"

2.2 Gameplay Example

This section describes an example of gameplay using the deck *Classification of systems* shown in Figure 1. The reader who is not familiar with the concepts and terminology used in the cards is referred to Appendix A for a concise and game-oriented summary of the topic.

Imagine a scenario where the teacher or an experienced student plays the game as Master of the Sacred Loop (referred to as **MSL**) together with three students acting as Disciples of the Sacred Loop (**D1**, **D2**, and **D3**, respectively), each receiving a white and a black token along with blank sheets to take notes as necessary. **MSL** shuffles the deck and draws a random card or, alternatively, picks a card containing statements they feel familiar with. Let us imagine that the selected card is the top-left one in Figure 1, so **MSL** proceeds at putting two paperclips on the card, one on the statement A01 and the other on one of the decoys. Hence, the rule to be guessed becomes “A system must have exactly one input variable”. **MSL** writes down two equations, one adhering to the hidden rule and the other one not adhering to it, marking them with the appropriate colour:

$$\begin{cases} \dot{x}(t) = \begin{bmatrix} 7x_1(t) + 4x_2(t) + 8u(t) \\ 3x_1(t) + x_2(t) - 2u(t) \end{bmatrix} \\ y(t) = 2x_1(t) + x_2(t) \end{cases} \quad (2.1)$$

$$\begin{cases} \dot{x}(t) = 3 \sin(t) x(t) + u_1(t)u_2(t) \\ y(t) = x(t) + 2u_1(t) \end{cases} \quad (2.2)$$

At this point of the game, the statements A02, A05, A07, A09, A12, A13, A14, A16, A18, A20 can be already discarded because otherwise Eq. (2.1) would have been marked in red instead. Hence, statements A10 and A11 are also discarded because they appear on the same card as the statements A13 and A14, so they would produce a hidden rule incompatible with the fact that Eq. (2.1) satisfies it. It is now **D1**'s turn, who wants to assess whether the combination of A06 and A08 can be the hidden rule. To achieve this goal, **D1** should formulate an equation representing a nonlinear system with a single input. If this equation is flagged in red, then A06 and A08 would continue being potential candidates for the hidden rule. Conversely, the equation being marked in green would indicate that the linearity/nonlinearity property is not relevant, allowing the players to exclude A06 and A08 from consideration. **D1** writes down Eq. (2.3) and chooses “Tell”, so **MSL** marks it with the green marker:

$$\begin{cases} \dot{x}(t) = \begin{bmatrix} x_1(t)x_2(t) + u(t) \\ x_1(t) \end{bmatrix} \\ y(t) = x_1(t) \end{cases} \quad (2.3)$$

Given that both statements A08 and A09 have been ruled out, the players can infer that A15 is also eliminated, which leaves three feasible options: i) A01; ii) A04; iii) A17+A19. It is now **D2**'s turn. **D2** has a gut feeling that the hidden rule is the statement A04 but needs a Laplace coin to make the official guess. **D2** writes down Eq. (2.4) on their sheet and decides to “Challenge” the remaining players to guess whether Eq. (2.4) satisfies the hidden rule or not. Hence, each player chooses secretly the white or the black token, accordingly, then they reveal the chosen tokens simultaneously. **MSL** reveals that Eq. (2.4) does not satisfy the hidden rule, so it gets marked with the red colour:

$$\begin{cases} \dot{x}(t) = x(t) + u_1(t) + u_2(t) \\ y(t) = \begin{bmatrix} x(t) + u_1(t) \\ x(t) + u_2(t) \end{bmatrix} \end{cases} \quad (2.4)$$

D2 had chosen a white token, so no Laplace coin for them. Both **D1** and **D3** had selected a black token, so they receive a Laplace coin each. It is now **D3**'s turn. Eqs (2.1)-(2.4) are not sufficient to assess which one among A01 and A17+A19 is the hidden rule. Hence, **D3** proceeds at writing down Eq. (2.5), which corresponds to a single input time-variant system, and asks for "Tell":

$$\begin{cases} \dot{x}(t) = \sin(t) x(t) + u(t) \\ y(t) = x(t) \end{cases} \quad (2.5)$$

The fact that Eq. (2.5) has been marked with green colour by MSL indicates that A17+A19 is not the hidden rule (otherwise, Eq. (2.5) would have been marked with red colour). **D3** proceeds at spending their Laplace coin to make the official guess that the hidden rule is A01, thus winning the game.

2.3 Using the game in the classroom

During Spring 2022, two gaming sessions were organized. In the first session, which made use of the deck *Classification of Systems* shown in Figure 1, the students were split into different tables, each of which played the game independently. The second session used the deck *Transfer functions* (see Figure 2) and had the students collected into two-player teams that competed against the others while supervised by the lecturer of the course, who participated in the game as the sole *Master of the Sacred Loop* for the entire duration of the session.

We observed that the first mode of playing presented some issues that were solved in the second mode, which is thus the one we recommend to use with students who are approaching the game for the first time and who are not familiar enough with the topics covered by the selected deck of cards. More specifically, we observed that splitting the students into different tables would often create tables of students with mixed performance. If there were high-performing students at a table, they would quickly understand the game and dominate it, thus spoiling the fun for the remaining students, those who may require this activity the most. On the other hand, tables without high-performing students were often unable to advance with the game, thus requiring more hints and suggestions by the lecturer. Notably, some of these tables spontaneously gave up the competition and engaged in cooperation; namely, the students collaborated to figure out the hidden rule. These issues were all mitigated during the second team-based session, which featured more communication among the players of the same team. Based on these observations, we think that a first approach to the game should preferably happen with teams of two or three players, possibly selected according to established group formation strategies, as discussed in the literature about *cooperative learning* (e.g., Van der Laan Smith & Spindle 2007). In other words, we think that team competition should be preferred over individual competition, as it fosters a better learning experience by reducing frustration and bridging gaps in understanding among students with different skill levels. This setup was found to encourage collaborative problem-solving and enable all students to contribute meaningfully while enjoying a supportive environment (Møgelvang & Nyléhn, 2023). However, for students with strong inductive thinking and a high level of understanding, individual competition may still be beneficial.

3 Results

Data about the in-context experiences, perceptions, and responses during the organized activities were collected using a questionnaire survey created by the authors. This survey comprised both items rated on a five-point Likert scale (quantitative data) and open-ended questions (qualitative data). The questionnaire was sent to all students who participated in the organized sessions, with a total of 17 completed questionnaires returned. It is important to note that the fact that the questionnaire has not undergone statistical construct validation, think-aloud interviews, or similar validation methods, and the small sample size are limitations of this work that the reader should keep in mind. Hereafter, we summarize the main findings from analyzing the quantitative and qualitative data.

3.1 Analysis of the quantitative data

The items rated on a Likert scale in the questionnaire (see Table 1) have been categorized into five different areas, or constructs, related to learning: i) affective factors, ii) collaborative learning, iii) higher-order thinking, iv) metacognition and v) projected future use.

Affective factors – The items related to affective factors are #1, #6, #14, and #15. The students reported their learning experience with playing *Control Zendo* to be fun (M=4.8), motivational (M=4.4), inspiring (M=4.4) and confidence-boosting (M=4.1). Compared to traditional learning in the classroom, most students did not mind making mistakes while playing the game. Competition through trial and error brought the satisfaction of managing to figure out the hidden rule.

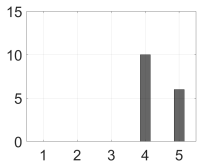
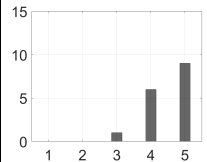
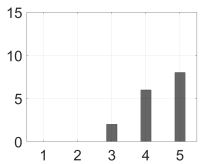
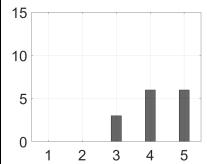
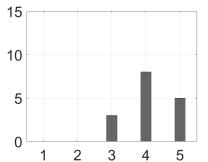
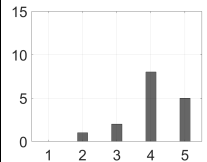
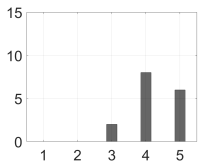
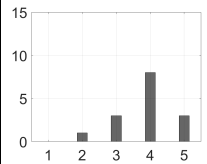
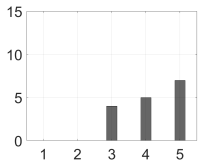
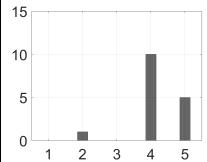
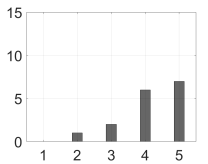
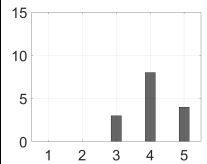
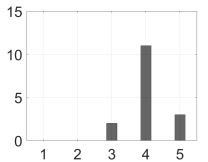
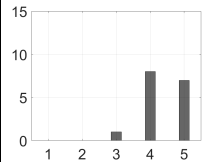
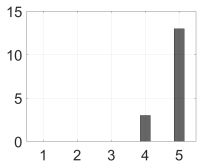
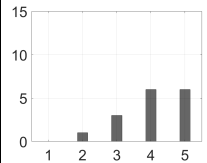
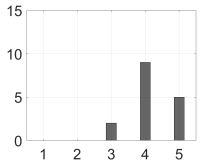
Collaborative learning – The items related to collaborative learning are #5, #8, and #12. The students stated that the game offers opportunities to collaborate with their peers in learning (M=4.1). While playing the game, they acquired social skills related to communication with their peers (M=4.1). The game also trained them to observe their peers (M=3.9), as the students had to wait for their turns, plan while waiting, and accept their loss as well as enjoy their victory.

Higher order thinking – According to items #4, #10, #11, and #17, the game could enhance the students' thinking skills, as it involved them to think about the statements in the cards actively. Hence, it can be used to develop higher order thinking skills among students. The students reported that the game helped them to think about the subject more critically (M=4.2), facilitated a deeper understanding of the topic (M=4.2) and allowed them to exercise problem-solving skills (M=4.2).

Metacognition – According to items #2, #3, #7, #9, and #13, the students use learning processes to plan, monitor, and assess their understanding and performance while playing the game. The boardgame was designed to integrate learning with game play, so that the goal of finding out the hidden rule is integral to the game, which is an integral part of the learning process. Playing the game helped the students be creative in their learning (M=4.5), increased their awareness in the topic they were learning (M=4.4), and allowed them to discover the knowledge they needed to learn (M=4.3). They thought that playing the game helped them develop relevant skills (M=4.2) and focus on their learning (M=4.1).

Projected future use – Item #16 shows that the students found that the game generated meaning towards the topic they were studying (M=4.1), so that the game-based learning seemed a promising possibility which could benefit their learning in the future.

Table 1. Quantitative data from a five-point Likert scale on boardgame experience (n= 17).

Item #	Participating in the boardgame has...	Histogram	Mean	Item #	Participating in the boardgame has...	Histogram	Mean
1	motivated me to learn		4.4	2	helped me learn in a creative way		4.5
3	increased my awareness in the topic I was learning		4.4	4	helped me think more critically		4.2
5	encouraged me to collaborate more with my peers		4.1	6	boosted my confidence in learning the topic		4.1
7	allowed me to discover the knowledge I needed to learn		4.3	8	helped me observe my peers while playing the game		3.9
9	helped me develop relevant skills		4.2	10	facilitated my deeper understanding of the topic		4.2
11	encouraged me to develop problem solving skills		4.2	12	helped me communicate with my peers more		4.1
13	helped me focus on learning		4.1	14	inspired me to play more such games in my courses		4.4
15	been a fun experience		4.8	16	generated meaning towards my study		4.1
17	helped with my thinking process		4.2				

3.2 Analysis of the qualitative data

The survey allowed participants to reflect on their boardgame experience through both quantitative ratings and written responses. The Likert-scale questions captured levels of engagement and learning, while the open-ended questions provided additional insights into the game's impact. These reflections help to better understand participants' experiences and perceptions of the learning process.

The findings discussed hereafter were obtained through a process of reading the answers to the following open-ended questions:

Q1. How did you feel about participating in the boardgame?

Q2. What was interesting and relevant to you and your learning?

Q3. Tell us your experiences while playing the game?

Q4. How did the boardgame influence your learning?

Q5. How was playing the game different from traditional learning/solving exercises in your typical courses?

then applying codes to excerpts, various rounds of coding, grouping codes according to categories and subsequently themes, and then interpreting them from a sociocultural perspective, based on the idea that social interaction plays a crucial role in learning (Vygotsky & Cole, 1978).

Friendly low-stake learning environment – The students reported that the boardgame activity created a motivating and encouraging environment in which they competed in a friendly manner.

Student 1, Answer to Q1

Very fun, good way of learning about the topic. Felt welcome right away, and comfortable learning environment.

While they were playing the game with each other and against each other, they made the game a rich learning experience. The hands-on nature of board games created a memorable experience and boosted their confidence and made it easier for players to tackle the mathematical equations throughout the game without the fear of losing.

Student 2, Answer to Q1

I very much enjoyed participating in the board game, it built up my confidence with the course material, as well as being a fun way to interact with my classmates and the lab assistant.

Student 3, Answer to Q1

I was scared I did not have sufficient background knowledge to participate in the game.

Student 4, Answer to Q5

It was okay to fail. It did not feel tiresome.

Developing good relationships between players and academic staff was also mentioned as an important element in their learning experiences.

Student 5, Answer to Q1

It was fun, and I feel like I did learn much more about that specific topic we was working on. Also like that you are closer to lecturer, and developing relationship with lecturer and student assistants.

Student 13, Answer to Q1

Very fun, nice to hang out with people and learned a couple new things. Got more familiar with some concepts in control theory.

Collaboration and socio-cultural influences – The participants highlighted the importance of interdependence and sharing individual knowledge, strengths, and perspectives during the control board game.

Student 6, Answer to Q2

What was most interesting and relevant to my learning was being allowed to discuss with my fellow students the course material, committing to writing certain things down and getting immediate feedback on whether I had an understanding.

Critical thinking in interactive environment – We can also see that the game challenged the students to analyse information, make decisions, and solve problems within a dynamic and interactive environment. As the students navigated the scenarios, they had to evaluate options, anticipate results, and adapt their strategies, which in turn develops their ability to think critically and apply knowledge.

Student 12, Answer to Q2

Method that we used. Like try different options, who knew was wrong, and try to eliminate different options to finally come to right answer. And then go through why the right answer, is right. That did help me get a better understanding about transfer-function, in our case.

Student 11, Answer to Q2

The method we used. By eliminating options we actually got a true understanding of how a transfer-function really works.

The boardgame environment requires reflective and analytical thinking that engages students with varied learning styles and keeps them actively involved in the process of trying out equations that disprove some of the statements to arrive at the correct answer.

Student 14, Answer to Q2

It was interesting to get a more free view of the state space system and to get to play around with the different rules.

Inductive approach to learning – The students were given a set of statements to interpret, and they attempted to analyze the data to discover the hidden rule. The instructions were familiar to the students, so they could make connections to their prior knowledge.

Student 8, Answer to Q5

Most similar experience: Exercises in learning a programming language, e.g. building a simple game in Python or similar. This was more social, which is a good thing these days.

Student 6, Answer to Q2

To be game master you need to have a good understanding of the subject, and forced you to think differently.

The content of study was presented in the context of its intended applications through the boardgame within Vygotsky's concept of *zone of proximal development*, the level that they can work independently on and in collaboration with their peers. Higher order thinking skills, such as 'thinking about learning', were expressed as a product of this learning environment.

Student 15, Answer to Q2

Interesting to learn how the game worked, and how it clearly illustrated the difference between types of systems, and forced you to reflect on the correct way to classify.

Student 16, Answer to Q5

Very different in most ways. Fun and mildly competitive, while forcing you to evaluate key concepts of the subject in order to play the game. It did not “feel” like studying.

Inspiration for learning, supporting traditional approaches – The participants reported that the board game provided them with a better understanding of the subject, and improved their learning.

Student 5, Answer to Q4

I think my learning was influenced in a positive way. It was easier to learn in a way where you are having fun at the same time as you learn.

Student 10, Answer to Q4

It made it much more easy to find out what I needed to know. Competition also helped motivate me.

The learning environment stimulated them to create their own systems (rather than just answer questions about systems), with specific characteristics, ensuring that they properly understood the target subject matter they had discussed with peers.

Student 7, Answer to Q4

It influenced my learning by exploring the rules and to get a better understanding of how to classify a system.

Student 11, Answer to Q4

It was a good repetition of the topic we had a couple of weeks ago. Easily more motivated to refresh topics in the course this way than sit down and read (which is something I don't do until the time before the exam).

Student 15, Answer to Q4

There were a few bits of information that were new to me, but mostly information I had already knew. Very good repetition/reinforcing of concepts I had already learned.

Student 17, Answer to Q4

The game targeted some key concepts about the respective control theory – subject (In this case, Transfer functions).

4 Discussion

The quantitative analysis of the data revealed valuable insight across five key learning-related constructs as shown above. This analysis underscores the multifaceted advantages of game-based learning in promoting positive affective experiences, collaborative skills, higher-order thinking, metacognitive processes, and the future utility of such educational approaches. Given the additional insights and implications emerged from the analysis of the qualitative data, we proceed at interpreting the numbers and the excerpts holistically, shedding light on how they relate to each other.

Affective Factors - The quantitative data underscored and reinforced the qualitative insights with high mean ratings across all affective factors. Such convergence evidently affirms that the game genuinely fostered a positive and motivating atmosphere for

learning. Students found the game to be enjoyable and highly motivational, boosting their confidence and reducing their fear of making mistakes, a sentiment seldom expressed in traditional classroom settings. The competitive element, where they explored the rules through trial and error, was a source of satisfaction and contributed to a positive learning environment. The game stimulated curiosity, fostered intrinsic motivation, and created a positive emotional experience. Player emotions, such as enjoyment and achievement, played a crucial role in shaping a favorable environment for effective educational experiences within the gaming context.

Collaborative Learning - The quantitative results indicated high mean ratings in favour of collaborative opportunities and the development of communication and observation skills. Together, both qualitative and quantitative findings emphasized that the game not only encouraged collaborative learning but also nurtured social interaction and observational abilities among students. The game facilitated collaboration by promoting communication, creating a sense of shared goals, and encouraging players to work together to solve challenges. The qualitative findings illuminated the collaborative nature of the game where students had the chance to collaborate with their peers and develop valuable social skills. From a sociocultural perspective, when students participate in collaborative mathematics discussions while playing a boardgame, they are engaging actively in the process of reasoning (Hunter & Civil, 2021) and negotiation of ideas. Moreover, the game encouraged them to observe their fellow players, as they were required to wait their turns, plan strategically while waiting, and gracefully accept both wins and losses. The sense of collaboration extended beyond the game itself, as students possibly developed effective communication skills when working together.

Higher-Order Thinking - Both qualitative and quantitative results underscore the significant influence of the game on fostering students' higher-order thinking skills. This highlights the potential of the game as a valuable tool for cultivating cognitive abilities among students, thereby promoting deeper understanding and problem-solving capacity. This game-based learning promotes critical thinking by requiring students to analyse situations, make decisions, and solve problems, strengthening their ability to apply knowledge in different scenarios. The qualitative data revealed that students actively engaged in rule-based thinking, resulting in higher-order cognitive skills like critical thinking and problem-solving as supported by the quantitative findings, where we can also observe high mean ratings for critical thinking and problem-solving, complementing these insights.

Metacognition - The results indicated high mean ratings across various metacognitive aspects. The results from the qualitative and quantitative data emphasize how the game, through its immersive mode, encouraged metacognitive thinking, making the learning process more dynamic and enhancing students' abilities in various aspects of learning and cognition. The qualitative data showed that the game encouraged students to engage in metacognitive processes, such as planning, monitoring, and assessing their understanding and performance. As an integral part of the learning process, the game provided students with an environment conducive to creative thinking, increased topic awareness, and knowledge acquisition.

Projected Future Use - The qualitative and quantitative findings also underscore the students' recognition of the capacity of the immersive game engagement to influence and enhance their future use of such learning. In both the qualitative and quantitative analyses, students viewed the game as a promising tool for future learning. Qualitative

data indicated that students found the game generated meaning and relevance toward the topics they were studying, implying its potential future utility. The quantitative data supported this perspective with a high mean rating for the game's ability to shape future learning experiences.

The insights presented in this section show the depth and richness of participant responses, achieved through the process of analysis of learning satisfaction. By employing a sociocultural lens, drawing on Vygotsky and Cole's foundational work on the pivotal role of social interaction in learning, we have identified emergent themes, which contribute to our broader understanding of the context of how students can learn and enjoy concurrently. The combination of quantitative and qualitative findings not only supports our interpretations but also underscores the interconnectedness of sociocultural factors in shaping the learning experiences recounted by participants. At the same time, these findings suggest that incorporating boardgames into the learning process can create a positive and engaging learning environment, foster collaboration, promote inductive learning, and inspire students, thereby supporting and enhancing traditional educational approaches.

Interestingly, the surveys revealed no negative feedback from students regarding the game-based activity. The only possible downside, in our view, is that, as with any activity, it demands resources that could potentially reduce time for other course activities. However, in our current approach, this is done infrequently (usually up to 6 hours in a 10 ECTS course), and participation remains voluntary.

5 Conclusions

This paper has described the experiences with the *Control Zendo* boardgame, which has been used successfully in the Basic Automatic Control course at the University of Stavanger, Norway. The game is an adaptation of the popular game Zendo, and it involves applying inductive logic to discover a hidden rule which is related to the theoretical content taught in the course.

The paper has described the rules of the game and has discussed the experiences during Spring 2022, supported by quantitative and qualitative data collected utilizing a questionnaire survey. Overall, the sixteen participants were satisfied and found *Control Zendo* effective for learning. The numbers from the survey provided evidence that inductive logic boardgames can impact positively the learning experience of engineering students. In particular, *Control Zendo* has a positive impact on areas such as affective factors, collaborative learning, higher-order thinking, metacognition, and projected future use.

The game-based environment made learning more entertaining and competitive with immediate rewards that made the students becoming more engaged in the subject matter. The focused content should be directed for students to regulate their thinking and improve the cognitive process around it. Learning took place without the strenuous labour compared with traditional approaches. It is worth recalling that several studies have suggested that game-based instruction can be integrated into traditional learning processes and can be as effective as traditional teaching methods (Vlachopoulos & Makri, 2017).

Due to the game's flexible rules, the proposed activity allows for various adaptations, aligning with the co-creation principles in higher education. By tailoring the game to fit

the needs and preferences of the entire group or class, students remain engaged with the content and continue to learn effectively, especially when they can participate in ways that feel most comfortable to them. This approach reflects the broader trend toward inclusive, student-centered learning environments (Bovill, 2020). Our study found a similar effect, emphasizing that an engaging and well-facilitated learning environment, where participants support each other through meaningful interactions, plays a crucial role in reducing frustration while fostering creativity and critical thinking (DeOrsey et al., 2021).

Integration of games into traditional lectures ensures that students can get a greater understanding of the subject. Games as an outside activity may be supplemented to traditional homework, which tends to be done mainly because it is required rather than to gain an understanding. On the other hand, the game-based learning environment places little demands or expectations. The students can relax, reflect, and gain an understanding of what they were learning together in small groups, which is an essential supporting element of learning in social constructivism.

In conclusion, the integration of *Control Zendo* as a serious game into the university curriculum has proven to be highly effective in fostering significant learning outcomes through social interactions. Drawing upon the sociocultural theory of game-based learning, the game creates an immersive and collaborative environment in which students co-construct knowledge through shared experiences and discussions. This approach recognizes the pivotal role of social interactions and cultural contexts in the learning process. Research studies underscore that game-based learning environments enhance motivation, active participation, and critical thinking, thereby yielding improved learning achievements. The dynamic engagement with virtual environments and peers leads to collaborative problem-solving and communication, elevating both individual growth and collective learning outcomes. The game's inductive design further accentuates its pedagogical value by promoting hands-on exploration, critical thinking, and deep comprehension.

By aligning game mechanics with essential concepts, *Control Zendo* bridges the gap between theory and application, offering a platform for learners to comprehend intricate automatic control principles within a contextual framework. In this way, the game facilitates a holistic understanding of interconnected subjects that might have previously appeared disjointed. Our experience with *Control Zendo* has shown that the mechanics from the *Zendo* game can be adapted to higher education settings, providing an avenue for comprehensive learning, meaningful social interactions and increased engagement. We hope that our study can help promote the integration of inductive thinking games in higher education, encouraging students to engage actively with course material and develop critical thinking skills. By incorporating games that require students to deduce rules and patterns from specific examples, we can make learning more interactive and effective. These games not only make learning more engaging but also foster deeper understanding and application of complex concepts across various disciplines.

We believe that this game-based activity and setup can be easily adapted to other disciplines, not limited to STEM, by simply modifying the set of statements. For instance, in language learning, students could explore vocabulary and grammar through contextual sentences, deducing rules such as "This sentence contains a feminine noun" as they advance, internalizing such rules naturally. In a history class, the rule could take

the form of “This king belonged to the Fairhair dynasty”. To assist teachers interested in adapting the Zendo game for their classroom, we have outlined the current rules in Appendix B. These rules are designed to be directly useful for teachers of automatic control and to serve as inspiration for other educators looking to adapt the game to their own subjects.

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Appendices

Appendix A Classification of systems

A state-space representation is a mathematical model used in control engineering and system identification which describes a physical system using input, output, and state variables related by a set of first-order differential equations or difference equations, referred to as the *state equation*, and a set of algebraic equations, referred to as the *output equation*. In the continuous-time case (the discrete-time is similar, thus omitted), this representation takes the following general form:

$$\begin{cases} \dot{x}(t) = f(x(t), u(t), t) \\ y(t) = g(x(t), u(t), t) \end{cases} \quad (\text{A.1})$$

where $t \in \mathbb{R}$ represents time, $x \in \mathbb{R}^n$ is the state vector, $u \in \mathbb{R}^m$ is the input vector, $y \in \mathbb{R}^p$ is the output vector, and $f: \mathbb{R}^{n+m+1} \rightarrow \mathbb{R}^n$, $g: \mathbb{R}^{n+m+1} \rightarrow \mathbb{R}^p$ are some generic functions that define the state and output equation, respectively. Rules A01, A02, A03, A05, A06, A07 all relate to the number of inputs in the system, i.e., the length m of the vector u , and they can be interpreted as $m = 1$, $m = 2$, $m \geq 1$, $m = 0$, $m = 1$, $m = 2$, respectively. Rules A04, A17, A18 also care about the value of m , but at the same time they relate to the number of outputs of the system, i.e., the length p of the vector y . A system is said to be *single-input-single-output (SISO)* if it has only one input and one output variable, and *multiple-input-multiple-output (MIMO)* otherwise. Hence, rules A04, A17, A18 can be interpreted mathematically as $m = p$, $m = p = 1$, $m + p \geq 3$, respectively. Rules A10, A11, A12 involve the number of state variables, i.e., the length n of the vector x , and can be interpreted in mathematical terms as $n \in \{1,2\}$, $n \in \{2,3\}$, $n \in \{3,4\}$, respectively. Rules A08 and A09 are mutually exclusive (for a given system, one of them is true, the other one is false) and care about the linearity of the system. A system is said to be *linear* if Eq. (A.1) can be rewritten in a compact matrix form, as follows:

$$\begin{cases} \dot{x}(t) = A(t)x(t) + B(t)u(t) \\ y(t) = C(t)x(t) + D(t)u(t) \end{cases} \quad (\text{A.2})$$

where $A(t) \in \mathbb{R}^{n \times n}$, $B(t) \in \mathbb{R}^{n \times m}$, $C(t) \in \mathbb{R}^{p \times n}$, $D(t) \in \mathbb{R}^{p \times m}$ are the so-called *state*, *input*, *output* and *feedthrough* matrix, respectively. In cases where this does not apply, the presence of trigonometric (e.g., $\sin(x_1(t))$) or exponential (e.g., $e^{u(t)}$) nonlinearities is used to determine whether A13, A14 hold. Rules A19-A20 are also mutually exclusive and concern the time-varyingness of the system. A system is said to be *time-invariant* if the functions in Eq. (A.1), or the matrices in Eq. (A.2), do not depend explicitly on time, i.e., Eqs. (A.1)-(A.2) take the following form:

$$\begin{cases} \dot{x}(t) = f(x(t), u(t)) \\ y(t) = g(x(t), u(t)) \end{cases} \quad \begin{cases} \dot{x}(t) = Ax(t) + Bu(t) \\ y(t) = Cx(t) + Du(t) \end{cases} \quad (\text{A.3})$$

whereas the system is said to be *time-variant* otherwise. Finally, the rule A15 holds (hence, the rule A16 does not hold) if $\dot{x} = 0$ when $x = 0$ and $u = 0$, i.e., $f(0,0, t) = 0$. Note

that the rule A15 always holds for a linear system, due to the fact that $\dot{x}(t) = A(t) \cdot 0 + B(t) \cdot 0 = 0$ no matter the specific values taken by the matrices $A(t)$ and $B(t)$.

Appendix B Statements to create possible rules

This Appendix provides all the currently devised statements, which can be combined to create cards using the well-known logic connectors AND, OR, XOR, and NOT. Special care should be taken to avoid creating cards with contradictions (e.g., “The order of the system is an odd number” AND “The system has two state variables”) or tautologies (e.g., “The order of the system is an odd number” OR “The order of the system is an even number”).

B.1 Classification of systems

01	The system is strictly proper
02	The order of the system is an odd number
03	The order of the system is an even number
04	The system has two state variables
05	The system has one state variable
06	The system has only one input variable
07	The system has only one output variable
08	The system is SISO
09	The system is MIMO
10	The system has as many inputs as outputs
11	The system is linear
12	The system is nonlinear
13	The system is time-variant
14	The system is time-invariant
15	The state equation is linear and the corresponding state matrix is diagonal
16	The state equation is linear and the corresponding state matrix contains only non-negative functions
17	The state equation is linear and the corresponding state matrix has a 0 element in each row
18	The state equation is linear and the corresponding state matrix has a 0 element in each column
19	The state equation is linear and the corresponding input matrix has three columns
20	The state equation is linear and the corresponding input matrix does contains only non-negative functions
21	The state equation is linear and the corresponding input matrix is square
22	The state equation is linear and the corresponding input matrix contains at least one row with all 0s
23	The output equation is linear and the corresponding output matrix contains only 0s and 1s
24	The output equation is linear and the corresponding output matrix is square
25	The output equation is linear and the element in row 1 and column 2 of the output matrix is negative

B.2 Transfer functions

01	The transfer function is 1 st order
02	The transfer function is 2 nd order
03	The dominant time constant (τ or $\omega_n \zeta$) is bigger than 10 seconds
04	The dominant time constant (τ or $\omega_n \zeta$) is smaller than 1 second
05	The step response of this transfer function converges to some steady-state value
06	The transfer function has a DC gain bigger than 10
07	The 2% settling time (4τ or $4/(\zeta \omega_n)$) is bigger than 8 seconds
08	The 2% settling time (4τ or $4/(\zeta \omega_n)$) is smaller than 4 seconds
09	The (dominant pole approximation of the) transfer function is unstable
10	The (dominant pole approximation of the) transfer function is undamped
11	The (dominant pole approximation of the) transfer function is underdamped
12	The (dominant pole approximation of the) transfer function is critically damped
13	The (dominant pole approximation of the) transfer function is overdamped
14	The transfer function has three poles and one zero
15	The transfer function has three poles and two zeros
16	The transfer function has two poles and one zero
17	The transfer function has a zero in the left half plane
18	The transfer function has a zero in the right half plane

19	The transfer function has a zero in the origin
20	The dominant pole(s) of the transfer function correspond(s) to a natural frequency ω_n bigger than 10 rad/s
21	The dominant pole(s) of the transfer function correspond(s) to a natural frequency ω_n smaller than 3 rad/s
22	The dominant pole(s) of the transfer function correspond(s) to an odd value of the natural frequency ω_n
23	The dominant poles of the transfer function correspond to a damping factor ζ between 0.5 and 1
24	The transfer function has a DC gain smaller than 1
25	The transfer function blocks a sinusoidal signal with frequency equal to 5 rad/s
26	The step response of this transfer function contains a pure (non-decaying, non-growing) sinusoidal term
27	The step response of this transfer function contains a term that decays as e^{-2t}
28	The step response of this transfer function contains a term that oscillates at a frequency of 4 rad/s

B.3 Root locus

01	The root locus has an odd number of branches
02	The root locus has three or fewer branches
03	The root locus has no branch that converges to a point in the s-domain for high values of K
04	The root locus has at least one branch that converges to a point on the real axis for high values of K
05	The root locus has branches that converge to complex conjugate locations of \mathbb{C} for high values of K
06	One branch of the root locus diverges with an angle of 90 degrees w.r.t. the real axis
07	One branch of the root locus diverges with an angle of 60 degrees w.r.t. the real axis
08	One branch of the root locus diverges with an angle of 180 degrees w.r.t. the real axis
09	The closed-loop transfer function is unstable for all positive values of K
10	The closed-loop transfer function is stable for low values of K but becomes unstable for high values of K
11	The closed-loop transfer function is unstable for low values of K but becomes stable for high values of K
12	$s = -5$ belongs to the root locus
13	$s = -3$ does not belong to the root locus
14	The interval $[-10, -8]$ belongs to the root locus
15	The interval $[-5, -3]$ does not belong to the root locus
16	The asymptote(s) of the root locus radiate(s) from a point in the left half-plane
17	The number of branches of the root locus that start at a location on the real axis is equal to one
18	All the branches of the root locus start from locations on the real axis
19	The asymptote(s) of the root locus radiate(s) from the origin
20	The asymptote(s) of the root locus radiate(s) from $\alpha = 3$
21	One of the branches of the root locus starts from the origin of the complex plane
22	Two of the branches of the root locus start from points on the imaginary axis
23	The root locus is symmetric with respect to the imaginary axis
24	All the branches of the root locus start from points located on the unit circle

ⁱ <https://boardgamegeek.com/boardgame/6830/zendo>

ⁱⁱ The name of the coin is a homage to the French mathematician Pierre-Simon Laplace, who pioneered the mathematical tool nowadays known as Laplace transform, which is a core topic for the basic Automatic Control course.