JTK: Jurnal Tadris Kimiya 9, 1 (June 2024): 1-11
Website: http://journal.uinsgd.ac.id/index.php/tadris-kimiya/index
ISSN 2527-9637 **(online) ISSN** 2527-6816 **(print)**

Innovative Learning Approaches: Quantum Chemistry Board Games for Education and Computational Thinking Strategies

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Received: 27 April 2024; Accepted: 13 June 2024; Published: 30 Juni 2024

Abstract

Computational thinking (CT) learning is becoming increasingly important in today's education in developing critical thinking and problem-solving skills. The development of board games is one of the techniques used to hone problem-solving skills by integrating CT into the learning process. Through this innovative learning approach, abstract concepts in atomic structure and the periodic system of elements are integrated into components of the game. The research aims to improve students' critical thinking and problem-solving skills in challenging chemistry content such as quantum numbers. This research includes the design, development, and implementation stages of board games in learning. The N-gain score of 0.7 is achieved, indicating an improvement in the effectiveness of learning chemistry subjects on atomic structure and the periodic system of elements through the designed board games. In addition, students provide positive feedback regarding engagement and interest in learning through this interactive approach. These results indicate that the use of CT-integrated board games can be an effective tool for teaching chemistry materials at the high school level while promoting students' CT skills. Well-designed board games can be used as effective learning tools to improve student's critical thinking and problem-solving skills in quantum numbers.

Keywords: board games, computational thinking, electron card, proton card, quantum chemistry

DOI : https://doi.org/10.15575/jtk.v9i1.31609

1. Introduction

One crucial aspect of 21st-century skills, which include collaboration, communication, critical thinking, problem-solving, and creativity, is the development of critical thinking and problem-solving abilities (Kim et al., 2019). Unfortunately, the current state of critical thinking and problem-solving skills Indonesian students learning is subpar, this leads to students' underperformance in both numeracy and literacy assessments (Ekasari, 2021; Anggraini et al., 2023).

In 2021, the Minister of Education and Culture Indonesia released the competency-based national assessment, which measures the quality of learning. This national evaluation represents a new paradigm in education, capturing the intake, process, and product of learning in all educational institutions to improve academic quality. The national assessment uses three instruments: minimum competency assessment (literacy and numeracy), character survey, and learning environment survey (Rohim, 2021). According to the national assessment results in 2022, students' literacy and numeracy skills generally remain below 50% (less than 50% of Indonesian students successfully reach the basic competency requirements for literacy and numeracy).

This study aims to address the gap in educational strategies by integrating educational game development into chemistry learning, an area that has shown promise in enhancing student engagement and understanding but has not been extensively explored in the context of Indonesian education. Previous studies have shown the potential of educational games to improve learning outcomes in various subjects (Squire & Jenkins, 2003; Gee, 2003; Annetta et al., 2009; Papastergiou, 2009; Hamari et al., 2016). However, there is limited research on their application specifically in chemistry education within Indonesia, making this study novel and significant.

One suggested approach to improve problem-solving skills is integrating computational thinking into learning (Limbong et al., 2023). Computational thinking, as demonstrated in BBC Bitesize online learning (Mulyanto et al., 2020), helps students handle complex problems by mimicking how computers work. Computational thinking consists of four main steps: breaking problems down, simplifying them, recognizing patterns, and formulating step-by-step solutions (Martins et al., 2020). This approach includes skills vital for practical problem-solving, such as problem analysis, pattern identification, breaking tasks into manageable parts, creating orderly solutions, and concluding (Labusch et al., 2019; Ubaidullah et al., 2021).

The integration of computational thinking skills into education not only fosters logical problem-solving but also nurtures positive attitudes, enhances metacognitive abilities and social skills, boosts self-confidence in strategy planning, imparts fundamental computer concepts, and promotes creative and adaptable thinking (Doleck et al., 2017; Ozden & Tezer, 2018; Mendrofa, 2024). In the 21st-century, possessing these skills becomes indispensable for the younger generation, equipping them with valuable tools to navigate future educational challenges and the job market, particularly in Indonesia (Kusno & Setyaningsih, 2021).

Researchers have found that computational thinking helps people develop good character traits and improves their learning ability (Tresnawati et al., 2020). Computational thinking skills have been examined in many areas, such as STEM programming, robots, and board games (Leonard et al., 2016; Tekdal, 2021; Wang et al, 2022). Board games have been used to help people learn how to think logically. Board games are a very effective way to help students at all levels of education, from elementary school to college, improve their computational thinking skills (Wangenheim et al., 2019). Chemistry and computational thinking cannot be separated. Chemistry is a natural science that studies matter's nature, structure, composition, reactions, and transformations (Govender, 2022). In the study of chemistry, many aspects require applying computational thinking. Materials for teaching chemistry often cover many ways to think, from learning concepts to thinking about how to think.

The study of atomic structure and the periodic system of elements is essential for understanding chemical concept predicting properties, and organizing chemical knowledge (Chowdhury, 2022). Hence, it needs learning tools that are clear, easy to use, and fun, but pay attention to the chemical ideas that students need to understand. This research aims to develop board games integrated with computational thinking.

2. Research Method

2.1. Development of the Boardgame

Research and Development study aims to create a popular board game (monopoly), which is integrated with computational thinking for high school chemistry class X, with the selected material being atomic structure and periodic system of elements. The goal is to improve student learning outcomes and motivate students to enjoy learning chemistry subjects in class especially at Nurul Fikri Boarding School Bogor by integrating computational thinking skills as an essential part of chemistry learning in the 21st-century.

This study used the Hannafin and Peck development model. The research method proposed by Hannafin & Peck encompasses a thorough need assessment phase to identify specific learning objectives and student needs. Following this, during the design phase, instructional strategies and materials are meticulously crafted to address these identified needs, ensuring alignment with the learning objectives. Subsequently, in the implementation stage, the designed instruction is put into action, fostering an interactive and engaging learning environment tailored to facilitate effective learning outcomes (Tegeh et al., 2014). This model was chosen because it suits the research needs, provides a detailed step-by-step guide, and follows the product to be developed, which includes three steps: Analysis, Design, and Development and implementation.

The chemistry material developed in this board game includes electron configuration and quantum mechanics. Through electron configuration, students can determine the position of elements in the periodic system, including periods and groups. After determining the electron configuration, students will identify the appropriate quantum numbers (principal, magnetic, and azimuth) and the numbers indicating the electron spin direction. In addition to the concepts of electron configuration and quantum mechanics, this board game also introduces students to chemical terminology and provides information about the elements' facts in everyday life. The first step is to analyze needs, including issues in the learning environment, 21st-century skills, materials, learning preferences, and student profiles. The second includes designing the product by creating a storyboard design as a conceptual plan. The third step involves developing the product based on the previous analysis, including creating a prototype that the Expert Review team assesses.

The game includes specific tasks that integrate computational thinking: Pattern Recognition (identifying trends and patterns within the periodic system), Abstraction (simplifying complex chemical concepts to understand underlying principles), Algorithm Design (creating step-by-step methods to solve chemical equations or predict element properties), and Decomposition (arranging four quantum numbers of elements correctly). The product is then implemented on the research subject through one-to-one and small group trials and the last is implemented in an actual situation (field test) that involved 46 senior high school students. Each stage was regularly evaluated by a team of experts (media and material) to identify and correct shortcomings.

2.2. Game Description

We developed learning media in the form of a popular board game known as Monopoly in chemistry learning (see Figure 1). This media is designed to encourage students' CT skills through the game mechanism.

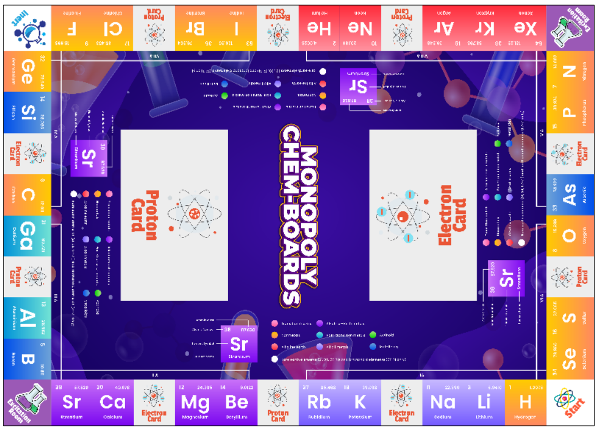

Figure 1. Monopoly Chem Board Design

Monopoly Chem Board is a game designed to improve high school student's understanding of chemistry material in the atomic structure and periodic system of elements. The board area consists of 44 cells, there are quantum number tokens, element cards, proton cards, electron cards, excitation rooms, inert rooms, wiggle room, and verification dictionaries. The rules of the game are stated in the rulebooks and resemble those of Monopoly. The game starts with the player rolling the dice to move the piece according to the number on the dice.

In this board game, proton cards are designed as chance cards. On this card, there are rewards obtained from the game. The proton card is an additional component to make the game more interesting. Figure 2 shows the back side of proton card. On the front of the card there is a reward challenge statement, for example "If you can name all the elements in group IIIA, you will get a special token [Ne] from the Wiggle Room."

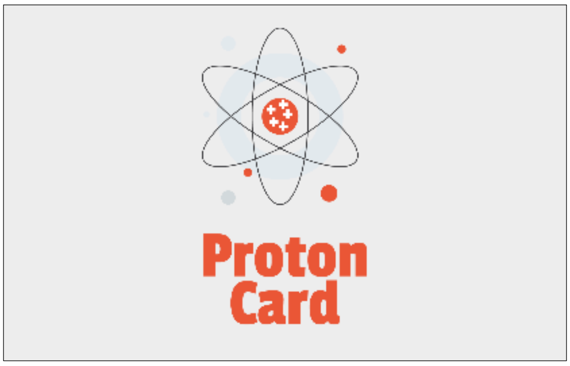

Figure 2. Proton Card (Back Side)

Electron cards are designed as general fund cards. On this card, there are challenges that must be done by the player. This electron card is also an additional component to make the game more interesting and challenging. Figure 3 shows the back side of electron card. On the front of the card there is a punishment challenge statement, for example "You are challenged to name the elements of group IVA. If successful, please take a proton card. Conversely, if it fails, you must give an *spdf* token to the Wiggle Room."

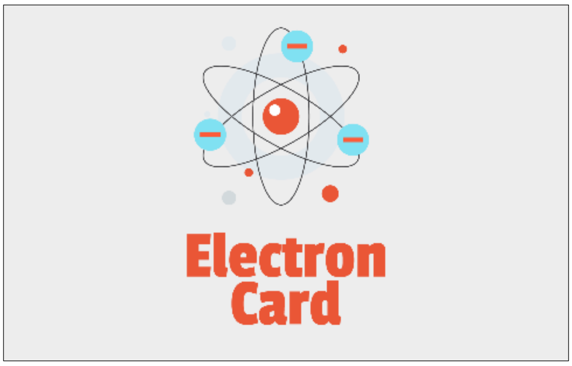

Figure 3. Electron Card (Back Side)

Element claim cards are issued as evidence of ownership for each specific element on the game board, outlining penalties for unauthorized access. A maximum of 30 certificates are produced, aligning with the number of elements present on the board. Furthermore, these certificates provide educational insights into the physical and chemical characteristics of elements, contributing to a deeper understanding of their practical applications in everyday contexts. Figure 4 shows an example of element claim card.

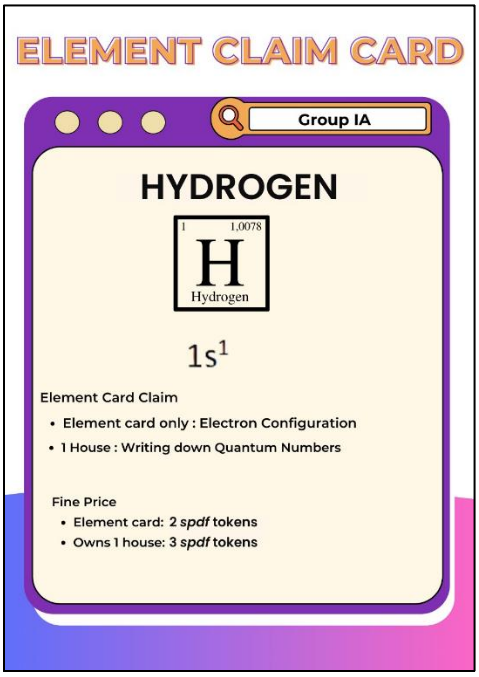

Figure 4. Element Claim Card

Another component in this game is the tokens used as a transaction tool. Each player gets several tokens at the beginning of the game and can get additional tokens as the game progresses. The board game is also completed with a verification dictionary. The verification dictionary consists of atoms, electron configurations and quantum numbers.

The boards and cards are designed based on the suitability of the material and the characteristics of upper-secondary level students. The materials used are study materials that are not easily torn or damaged. Illustrations were created using a Photoshop application and selected from websites that provide easily accessible illustrations and non-commercial and legal use. The terms used are adjusted to the chemistry glossary, especially the keywords of the atomic structure and periodic system of elements.

2.3. Board Games Rule

This game is suitable for high school seniors, and it requires at least three players, with one student acting as the checker (wiggle room). Each person gets ten element tokens: 1s (three tokens), 2s (three tokens), 2p (two tokens), and 3s (two tokens), and the players decide the order of play. Players roll the dice and move forward based on the number they get. They can roll more dice if they get a six on the dice. At the beginning of the game, each person must finish one round of the Monopoly board and cannot claim any element cards. The rules of inactive room, excitation room, and others are used in the first round of the game. Everyone crossing the starting line will get a free element token from the wiggle room.

After the first round, each player can claim an element card by putting their *spdf* tokens in the same order as the electrons in the element card they want to claim. Players who sort their *spdf* tokens correctly will get an element card and an element certificate. If a player enters an element claimed by another player, they must pay a fine written on the certificate. Players can buy an element house by writing down the quantum number of the element and showing it to the element checker. Example: The quantum number of the element Na is n = 1, l = 0, m = 0, and s = 1/2. Purchasing an elemental house can only be done when a player passes through the game board after claiming an elemental card. A player must pay a fee equal to the tokens shown on the elemental certificate if they are trapped in an elemental house that an adversarial player has claimed. Proton cards (prize) and electron cards (challenge) are added to the game board. If players enter the "Inert" box on the elemental board, they cannot play for one round. Players who stop at the Excitation Room box, will not get any fines, prizes or penalties and players can freely continue their game. The game lasts for 7 rounds, and the winner is the player with the most elemental houses at the end of those rounds.

2.4. Feasibility and Effectiveness Assessment

The products from the development results in the form of media board games are given to a team of experts to be reviewed, and the results of the review in the form of suggestions and criticisms are used as evaluations to make improvements so that they can then be tested on students.

An analysis will be carried out based on the instrument provided at the feasibility and effectiveness test stage. The board game is declared feasible or not based on a questionnaire from media and material experts, which will then be calculated using Eq. 1.

$$\bar{x} = \frac{\sum x}{n} \quad (1)$$

$\bar{x}$ = Average score of each aspect or all aspects
$\sum x$ = Number of scores for each aspect or all aspects
n = Number of students or users

3. Result and Discussion

3.1. Board Games Media Assessment

The board games that have been developed are then validated by several expert reviews from lecturers. Validation was carried out to assess the feasibility of the board games designed in terms of media and material as a reference for product development ready for use. This validation was done using an assessment instrument, which was then given an average score. Media validation involves several experts, including board game designers, lecturers, and education practitioners. These experts collectively contributed to the evaluation process, and Table 1 summarizes the outcomes of their assessment of the board games from a media perspective.

Table 1 shows that the created board game medium has achieved an average rating of 4.56 on a Likert scale, which is a research tool for assessing the attitudes, opinions, and perceptions of individuals and groups (Sugiyono, 2021). This data from the Likert scale indicates that the board game medium is highly favourable and well-suited for research. The board games media already have complete board game components, are easy to use, the game's rules can be understood well, facilitate students in learning, and have an attractive appearance from the selection of colours, letters, and images. However, several suggestions for improvement include adding time duration information to the game rules, additional information on the target users of board games, and information on the selection of printed materials. Based on this, researchers have implemented enhancements to the provided recommendations.

Table 1. Board Games Media Assessment Results

No	Question	Result Average	Description
1	Board games user-friendly	4.50	Good
2	Board game rules are easy to understand	4.25	Good
3	Board games facilitate students to learn	5.00	Excellent
4	Interesting board games display	5.00	Excellent
5	The words are easy to understand	4.50	Good
6	Each Board Game component's color scheme is appropriate	4.25	Good
7	Matching letter types and sizes on board games is appropriate	4.25	Good
8	Image selection on board game components is suitable	4.50	Good
9	Board game components are complete	5.00	Excellent
10	Strong and durable media	4.25	Good
11	Board games has fulfilled the criteria of learning media.	4.75	Excellent
	Average	4.56	Good

3.2. Board Games Content Assessment

Besides checking the media, experts also evaluated this board game for its chemical content. The experts collectively contributed to the evaluation process, and the following summarizes the outcomes of their assessment of the board games from a content perspective.

Table 2. Board Games Content Assessment Results

No	Question	Result Average	Description
1	The content is related to the skills pupils need to learn	4.30	Good
2	The content can be used a board game	4.30	Good
3	The completeness of the material is in accordance with the level of student development	5.00	Excellent
4	4 Illustrations of the material are relevant to the competencies to be achieved	4.30	Good
5	The content given is based on science facts	4.70	Excellent
6	The material presented is by the latest developments	5.00	Excellent
7	Computational thinking systematically organizes media content	4.70	Excellent
8	Chemical vocabulary and concepts are simple	4.30	Good
9	Makes it easy to read	5.00	Excellent
10	The media has fulfilled the criteria for chemical material	5.00	Excellent
	Average	4.70	Excellent

Table 2 shows that the expert team's average evaluation score for board games is 4.7, signifying its excellence. The selection of chemistry materials was based on considerations of students' learning needs, their profiles, recent developments in the field, and the scientific principles of chemistry. Additionally, the information provided enhances students' understanding of concepts related to atomic structure and the periodic system of elements.

Feedback from the media and material experts guided researchers in improving the developed products. All input and suggestions from the experts were used to further develop into the recommended version. The revisions were mostly on the game rules such as adding time duration and specifying target audiences. For the media aspects, changes were made to the design and color selection of each component of the board game.

3.3. Trial Class

Following the validation by the expert team and product enhancements based on feedback from both media and material experts, a one-on-one testing phase was conducted involving three students in XI grade at Nurul Fikri Boarding School Bogor. This step aimed to evaluate the product's suitability from a user perspective. During this phase, the three students played the board games from start to finish and provided assessments and feedback. The evaluation used instruments with a Likert scale ranging from 1 to 5. The data collected will serve as a reference for refining the final version, making it suitable for research purposes.

The students who were involved in the one-on-one trial gave a positive response. Students provided some input and suggestions regarding some typing errors and difficulties in understanding the rules of the game. After that, a small group trial was conducted to see the feasibility of board games when used in a large number of players and different groups. Through this trial, there were several inputs from students about the duration of the game, the readability of the game rules, ease and effectiveness in playing.

In addition to quantitative data, qualitative data was also obtained through the results of interviews about student testimonials in the "Quantum Chem Board" play trial. Here are some of the input and suggestions submitted by students:

"It's good, but at first I was confused when I first played." (Student 1)

"The game is really good, don't forget to fix the mistakes I made yesterday!!!" (Student 2)

"There are a lot of tokens so it's a bit difficult and requires a process to collect them. Maybe it can be made into a place or something. Grouping them might be easier." (Student 3)

3.4. Field Test

Following a comprehensive process involving expert evaluation, revision, and individualized trials, board games were tested on 29 high school students in grade X in Nurul Fikri Boarding School Bogor. The results of psychological assessments revealed that the participants in the study had diverse learning styles. According to Wirawan (2022), a significant proportion of students, approximately 45%, exhibit a preference for audio-visual learning. Conversely, the remaining 55% of students demonstrate a kinesthetic learning style. Consequently, game-based learning media emerges as a viable and appropriate instructional tool for accommodating these diverse learning preferences. In this particular scenario, board games align with the attributes and traits commonly exhibited by pupils. In addition to instructing students on atomic structure, these board games facilitate student engagement through gameplay, problem-solving utilizing gaming patterns, strategy development, and identifying essential issues, all while minimizing potential distractions. This aligns with computational thinking, which encompasses defining a problem and devising a solution utilizing principles derived from computer science (Wing, 2008).

Incorporating computational thinking stages into board games has enhanced students' computational thinking skills (Tsarava et al., 2014). Hence, the researcher integrates computational thinking (CT) skills into the game-related tasks and chemical questions posed to students at both the commencement and conclusion of the board games, exemplified by the CT skill assessment framework.

Table 3 presents a research endeavor to evaluate the efficacy of incorporating computational thinking within board games as a teaching approach for atomic structure and the periodic system of elements. A pre-and-post-testing method was implemented to assess this, involving questions aligned with the grid described in the table. The questions were given to students, and then the effectiveness was analyzed.

Table 3. Evaluation of the Effectiveness of Integrating Board Games with Computational Thinking

CT Skill	Description	Activity in Board Games	Question in Chemistry Test
Abstractions	Students can simplify complex problems by eliminating unnecessary variables.	At the beginning of the board game, students decide which element to claim.	Presented with an element symbol, students determine what element it is based on the sign.
Algorithmic Thinking	Students create steps to solve a problem by using the principles of the situation in question.	Given a challenge in the form of a question contained in an electron card.	Students are tasked with determining the atomic number of an element by analyzing the provided information regarding its position within the periodic system of elements.
Pattern Recognition	Students relate to prior knowledge and identify patterns, similarities, and relationships between prior knowledge and what is being learnt now, then conclude.	Collect and sort *spdf* tokens appropriately based on the electron configuration of the element card to be claimed.	Presented an element symbol, students make a modern electron configuration and conclude the period and group of the element.
Decomposition	Students break down the problem into smaller parts.	Students correctly write four quantum numbers from the element cards claimed to get the element house.	Students arrange an element's quantum numbers (main, azimuth, magnetic, and spin quantum numbers).

Based on the pre-test and post-test data obtained, the N-gain score can then be calculated by dividing the difference between post-test and pre-test scores by the difference between the ideal score and the pre-test score. This N-gain score is used to measure effectiveness. Table 4 shows the N-Gain effectiveness categorisation.

Table 4. N-Gain Effectiveness Categorisation

Percentage (%)	Interpretation
< 40	Non-effectice
40 – 55	Less effective
56 – 75	Moderately effective
> 76	Effective

The N-Gain obtained in this research was 0.7. This score shows that Quantum Chem Board is moderately effective in learning chemistry subjects on atomic structure and the periodic system of elements.

In addition to improving N-Gain, these board games also facilitate students to play, solve problems through the introduction of playing patterns, develop strategies and recognize important points and ignore distractors and provide stimulus in growing students' CT skills. This is in accordance with the expected impact of integrating computational thinking in board games. as a thought process that is closely related to the ability to formulate a problem and then find a solution based on computer working principles (Wing, 2008) and Tsarava et al. (2014) about collaborative media games in the form of board games can support learning activities and help children hone CT skills.

4. Conclusion

Board games that incorporate computational thinking are effective in facilitating the learning of atomic structure and the periodic system of elements in senior high school X grade. These games provide students with a stimulating environment to develop and enhance four fundamental computational thinking abilities: abstraction, pattern recognition, algorithmic thinking, and decomposition. However, to improve accessibility in the future, it would be wise to consider creating a digital version, which would provide quicker and more efficient access. Henceforth, this initiative would promote the attainment of quality education in Indonesia by using board games.

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