Journal of Innovative Learning
Institute for Innovative Learning, Mahidol University
Research Article
2025: Vol. 1 No. 2, pages 42-61

Facilitating Student Learning of Quantum Numbers and Electron Configuration through an Analogical Physical Model Embedded in the 5E Learning Model

Jampel CHODA[a, b], Pirom CHENPRAKHON[b*]
[a]*Chukha Central School, Bhutan*
[b]*Institute for Innovative Learning, Mahidol University, Salaya, Thailand.*
*Corresponding author: Pirom.che@mahidol.ac.th

Received: May 21, 2025; Revised: June 22, 2025; Accepted: June 30, 2025

Abstract: Quantum numbers and electron configuration are important topics for students to learn as they form the basis for learning many advanced chemical concepts. Learning these topics has been found difficult for students as the contents in these topics are abstract. Literature thus far has explored and diagnosed many learning deficiencies related to these two concepts. In this research, an analogical physical model was implemented using 5E learning model to allow students to explore, express, communicate and construct scientific concepts. The research was conducted through a single group pretest-posttest design. The learning unit was implemented with 81 grade 11 students majoring in science in one public school in Bhutan. The data were collected using the Quantum Conceptual Test (QCT), which consisted of two-tier multiple choice items, and open-ended questions to measure students' conceptual understanding and the Attitude Survey Questionnaire (ASQ), which consisted of five-point Likert-type scale items and open-ended questions to investigate student' perceptions towards learning unit. The paired-sample t-test results of QCT showed that students' conceptual understanding of quantum numbers and electron configuration was significantly improved at the 0.05 significant level from the pretest mean score of 12.16 ± 5.29 to the posttest mean score of 23.73 ± 6.16. The qualitative data from the interviews and the reflective journals also showed the effectiveness of the learning unit. The results from ASQ showed that the students' perceptions towards the model-based learning unit were positive, especially on the use of the analogical physical model. Students have appreciated the use of the model as a tool for imagination, visualization and conceptual understating.

Keywords: Higher secondary school, quantum numbers, electron configuration, analogical physical model, 5E learning model

Introduction

Higher secondary students are expected to master fundamental concepts such as quantum numbers, electron configuration, and related principles. These topics form the foundation for understanding more advanced and sophisticated concepts as their education progresses. The importance of these topics can be summarized as follows: First, understanding electron configuration helps predict an element's position in the periodic table, its chemical nature, and its reactivity (Adhikary et al., 2015), with the periodic table widely regarded as the backbone of chemistry (Ali, 2012). Second, quantum numbers specify the probable location of electrons in an atom. This understanding is essential for studying the ground and excited states of the atom, bonding, and the color of compounds (Mabrouk, 2003). Third, quantum numbers and electron configuration describe the behavior and positions of electrons, which is a prerequisite for learning about hybridization and hybrid orbitals (Nakiboglu, 2003). Fourth, these topics are closely associated with various important scientific theories and principles, such as the series of atomic theories, Hund's rule, the Pauli exclusion principle, and the Aufbau principle. These rules are critical for accurately writing electron configurations (Madan & Bisht, 2006). Therefore, the scientific community unanimously agrees that a solid understanding of quantum numbers and electron configuration is fundamental—and, to some extent, prerequisite knowledge—for exploring advanced chemical concepts as students progress in their education.

However, the literature has reported many misconceptions and learning difficulties related to quantum numbers and electron configuration. Students often confuse terms such as shell, orbit, orbital, and energy level (Nakiboglu, 2003; Tsaparlis & Papaphotis, 2002; Taber, 2002a. Taber, 2002b) also noted that students have difficulty forming adequate concepts of orbitals and electronic spin, as well as confusion regarding orbital degeneration and labeling. Additionally, Students often confuse the roles of quantum numbers in describing orbital size, shape, orientation, and spin, leading to misconceptions in visualizing atomic structure and applying electronic configurations. (Zarkadis et al., 2021). Learning these concepts requires engagement with the submicroscopic level of chemistry—an inherently challenging task since these phenomena are unobservable and must be understood through imagination (Laohapornchaiphan & Chenprakhon, 2024). The difficulties with quantum-related concepts can be attributed to two main factors. First, the nature of the concepts themselves: their abstractness, the complexity of the underlying calculations, the specialized language used, and the variety of representations can make these topics seem alien to learners. Second, learning difficulties and misconceptions are often compounded by inappropriate teaching methods and materials (Barke et al., 2009). For example, conventional mathematically oriented teaching has been found inadequate for providing a sufficient qualitative understanding of the underlying principles of quantum mechanics (Dangur et al., 2014; Selçuk & Çalŷskan, 2009).

Therefore, this study was undertaken to address students' conceptual difficulties in learning quantum numbers and electron configuration through the use of an analogical physical model embedded within the 5E instructional approach. The model was designed to make abstract quantum concepts more concrete and accessible, while the 5E framework promoted inquiry-based, student-centered learning. Although both strategies have shown individual promise in science education, their combined application—particularly in the context of abstract topics like quantum numbers and electron configuration—remains underexplored. This integration aimed to enhance students' conceptual understanding by enabling them to visualize atomic structures, engage in active exploration, and construct meaning through structured 5E learning experiences. The study was carried out with Grade 11 science students in a Bhutanese public school, providing a meaningful setting to investigate this approach at the higher secondary level.

Literature Review

In the teaching of quantum numbers and electron configuration, the literature presents a wide range of analogies and mnemonics. School textbooks (Madan & Bisht, 2006), research articles (Garofalo, 1997; Ma, 1996; Fortman, 1993), and academic books (Lovett & Chang, 2005) have presented various analogies to support the teaching of quantum numbers. Similarly, several mnemonic devices have been proposed for teaching electron configuration, including a chunk-based mnemonic scheme (Adhikary et al., 2015), the periodic table as a mnemonic device (Mabrouk, 2003), a mnemonic method for assigning electronic configurations (Iza & Gil, 1995), and a simple mnemonic for electron configuration (Grenda, 1988). The use of analogies and mnemonics has been well recognized in chemistry education, particularly when dealing with abstract and complex

concepts. Effective analogies can clarify students' thinking, address misconceptions, and help visualize abstract ideas (Orgill & Bodner, 2004). Analogies are also considered effective concept-building tools (Harrison & Treagust, 1993). Many researchers advocate for the use of analogies in teaching, as they simplify difficult content by linking it to familiar knowledge (Glynn, 2008; Harrison & Treagust, 2006; Müller & Rau, 2025).
Moreover, inquiry-based use of analogies allows students to explore and articulate their ideas (van Joolingen, 2004).

However, caution is necessary when using analogies instructionally. Sarantopoulos and Tsaparlis (2004) warned that failing to consider the limitations of analogies may result in misconceptions. Harrison and Treagust (2006) and Glynn (2008) described analogies as "a double-edged sword," because while they may facilitate learning, they can also introduce alternative conceptions. For quantum-related topics, researchers have recommended the use of a visual–conceptual approach to broaden students' understanding of key quantum mechanical terms (Dangur et al., 2014). In addition, the use of images, simulations, or concrete models has been suggested to visualize the abstract mathematical structures in quantum mechanics (Greca & Freire, 2014).

The present study employed an analogical physical model to teach quantum numbers and electron configuration—topics known for their abstract and conceptual difficulty. The model, originally developed by Choda and Chenprakhon (2015), had not yet been implemented or evaluated for its instructional effectiveness. It was designed in response to earlier recommendations and aimed to explore the potential of analogical physical models in science education. The term analogical physical model is used because the representation shares structural similarities with key aspects of the target concepts. In science education, models play a crucial role in bridging theoretical and observable phenomena (Seok & Jin, 2011). They serve as cognitive and communicative tools (Rodhe, 2012; Beltramini et al., 2006), offer alternative visualizations (Rodhe, 2012), and foster curiosity, motivation, and engagement (Satterthwait, 2010). When used as a teaching strategy, analogical physical models provide both visual and symbolic representations that help make abstract ideas more accessible. Visual features have been shown to enhance conceptual understanding (Rotbain et al., 2006), and object-mediated learning helps students maintain focus during learning tasks (Satterthwait, 2010).

To guide the model's implementation, this study employed the 5E instructional model, which has been widely recognized for promoting student engagement and improving learning outcomes (Joswick & Hulings, 2024; Garcia et al. 2021). Research has emphasized that instructional materials used within the 5E framework should match students' cognitive levels and support meaningful knowledge construction (Tuna & Kacar, 2013). In the context of chemistry education, the 5E instructional model has been found effective in enhancing students' cognitive processes and improving their attitudes toward the subject. (Sotáková & Ganajová, 2023).

Taken together, the literature supports the educational value of both analogical physical models and the 5E learning approach. However, limited research has examined their combined application in teaching highly abstract chemistry topics such as quantum numbers and electron configuration. This gap highlights the need to investigate how an analogical physical model, implemented within a 5E learning model, can support conceptual understanding at the higher secondary level. The present study was designed to address this need.

In this study, it was assumed that integrating the analogical physical model with a well-structured strategy like the 5E learning model would help organize instruction and support the flow of learning activities. Furthermore, using a concrete physical model may enhance the implementation of the 5E instructional approach and lead to improved student outcomes. Thus, the study was designed to address the following research questions:

1) Does the analogical physical model embedded within the 5E learning model enhance students' conceptual understanding of quantum numbers and electron configuration?
2) What are students' perceptions regarding the nature of the topics, the use of the analogical physical model, and the learning activities in teaching quantum numbers and electron configuration?

Methodology

This research followed a quantitative research design, specifically a single-group pretest-posttest design. To enhance the interpretation of the results and provide deeper insights into students' experiences, qualitative data were also collected through interviews. This supplementary qualitative data served to triangulate and support the quantitative findings. The learning unit was divided into two parts: part I was about quantum numbers, and part II was about electron configuration. The learning of quantum numbers concerns about the following four concepts:

1) Understanding of the meaning and role of quantum numbers.
2) Identifying and interpreting the relationship between quantum numbers.
3) Locating electrons with respect to their shell, subshell, and orbitals through quantum numbers.
4) Identifying the capacity of different energy levels and variation of energy in various shells, subshells, and orbitals.

Likewise, there were electron configuration concerns about the following two concepts:

1) Understand the rules and principles for writing electron configuration.
2) Write electron configuration using different notations, identify valance electron, and write valance electron configuration. Both the learning units were employed using an analogical physical model driven by the 5E learning model.

Research participants

This study was conducted with 81 Grade 11 science students (mixed genders) from a public school in Bhutan, aged between 18 and 21 years. All participants were presumed to have similar educational backgrounds, as they were enrolled based on set criteria using ability rankings. Typically, science and mathematics marks from the Grade 10 public examination were considered for enrollment in the science stream. Students in this stream study physics and chemistry as compulsory subjects, with mathematics and biology as optional. A convenience sampling method was used to select participants, as all students in the Grade 11 science stream at the selected public school were available and met the inclusion criteria for the study.

Data collection

The administrative approval was sought from the Mahidol University Central Institutional Review Board (MU-CIRB) prior to the data collection. Similar approval has also been sought from the Ministry of Education, Bhutan, and the school authority as well as the subject teacher of grade XI Science. The consent letter from the participants were produced prior to the data collection. 81 students gave their consent and were included in this study. However, only 79 students completed both the pretest and posttest; data from these 79 students were used in the final analysis.

The participants were oriented with the entire data collection process and their roles, the dates for tests, the implementation of learning units, and the interview before the data collection. The pretest was conducted a day before learning units I and II were implemented. The reflective journal and ASQ were administered right after the implementation of the learning unit II, and the posttest and interview were done in the following days.

Quantum Conceptual Test

The Quantum Conceptual Test consisted of 26 items. Of the 26 items, 14 of them were two-tier multiple-choice items, and the rest were open-ended questions. Every two-tier multiple-choice question had four possible choices of answers and four reasoning statements. Students select an answer from the first tier and the reason from the second tier. There was one keyed (correct) answer and three plausible distractors for both the first and second tiers. All the questions were framed in line with the Bhutanese chemistry curriculum for grade XI and related chemistry books (Madan & Bisht, 2006; Clugston & Flemming, 2000; Suchocki, 2004).

The pilot test for the quantum conceptual test was conducted to find the reliability of the test items with 40 students majoring in science from grade XI. The participants who took part in the pilot test were similar to the current study regarding their educational background and context in which they were exposed to educational experiences, as they followed the same curriculum. The Cronbach's alpha reliability coefficient of two-tier multiple-choice items and open-ended items were found to be 0.80 and 0.71, respectively, indicating both the parts of QCT items were reliable, as the acceptable range for alpha value is 0.7 to 0.9 (Tavakol & Dennick, 2011). 6 experts did the validity; 3 experts were teachers teaching chemistry to higher secondary levels and had teaching experiences of more than 9 years. The other 3 experts were university lecturers with experience in content and research methodology. The average Index of Item-Objective Congruence (IOC) for Quantum Conceptual Test items was 0.96, providing quantitative evidence of the high validity of the tool. The item is considered valid if the IOC is 0.75 and above (Tunner & Carlson, 2003).

Attitude Survey Questionnaire

The Attitude Survey Questionnaire consisted of 16 Likert-type scale items (five-point scale ranging from strongly disagree to strongly agree) and three open-ended questions. The open-ended questions asked what students liked most about the learning activity, what they disliked most, and their suggestions for improvement. The reliability coefficient (Cronbach's alpha) for the overall items was found to be 0.72, indicating acceptable reliability. For validity, the overall Index of Item-Objective Congruence (IOC) was 0.93, indicating high content validity.

Semi-structured interview

The semi-structured interview was conducted to collect supplementary data to support the findings from the Quantum Conceptual Test and the Attitude Survey Questionnaire. The interview questions were organized around four themes: content knowledge, compatibility of using models, implications of the model, and general impressions of the learning unit employed. There were 12 predetermined items aligned with the four identified themes, although additional probing questions were asked as needed during the interview. The total of 6 students, 2 each from low, average and high achievers on the basis of their midterm exam score were selected for the interview. A total of six students were selected for the interview, with two students each representing low, average, and high achievers based on their midterm examination scores. All interviews were audio-recorded, transcribed verbatim, and subsequently analyzed.

Reflective journal

Students were asked to reflect on their overall impressions of the learning unit's implementation and write a short journal entry describing what they had learned, what they felt they needed to learn further, and what improvements could be made to enhance the learning unit in the future. Reflective journals were collected from all 81 participating students and used as a supplementary source to support the findings from the Quantum Conceptual Test and the Attitude Survey Questionnaire.

Data analysis

Analysis of Quantum Conceptual Test

The two-tier multiple-choice items and the open-ended questions were analyzed separately using different criteria and marking schemes; however, their final results were combined to assess the specific learning goals. For analyzing the two-tier multiple-choice items, one mark was awarded only if both the concept and the reasoning parts were answered correctly. No marks were given for partially correct responses. This approach was intended to increase the credibility of the results by minimizing the likelihood of blind guessing.

Previous research has shown that two-tier tests offer advantages over traditional one-tier multiple-choice items by reducing measurement error. In a one-tier test with five answer choices, the probability of guessing the correct answer is 20%. However, in a two-tier format—where an item is considered correct only when both parts are answered correctly—the probability drops to approximately 4% (Tüysüz, 2009). In this study, with four answer choices in each tier, the chance of guessing the correct answer was reduced to just 6.25%.

For the analysis of the open-ended items, responses to each question from both the pretest and posttest were categorized into three groups: correct answers, partially correct answers, and incorrect answers, as shown in Table 1. The criteria for categorizing responses were adapted from previous studies on diagnostic tests (Abraham et al.,1994; Nakiboglu, 2003) and marking criteria from Sarantopoulos and Tsaparlis (2004). Modifications were made as necessary to align with the objectives of the present study.

Table 1. Marking criteria for open-ended questions

Category	Criteria	Marks
Correct answer	Answers contain all components of the validated response.	2 marks
Partial correct answer	Answers contain at least one of the components of the validated response	1 mark
Wrong answer	Irrelevant responses, alternative conception, non-sense responses or not attempted	0 marks

Analysis of Survey Attitude Questionnaire

To determine students' perceptions of the developed learning units, the ratings provided for each Likert-type questionnaire item were analyzed using the mean and standard deviation of both individual items and overall constructs. For negatively worded items, reverse coding was applied using the formula (highest value + lowest value – selected response), i.e., 5 + 1 – selected response, as described in previous research (DeCoster, 2000). This adjustment was made when calculating the mean of the construct. Perceptions were primarily interpreted based on each construct's mean score and standard deviation. However, the means of individual items were also considered in cases where the overall results were ambiguous. The criteria for interpreting the results were adapted from previous research (Pitafi & Farooq, 2012), as shown in Table 2.

Table 2. The Criteria to Infer Students' Perceptions

Scale	Interpretation
Below 3.0	Negative
3.0	Neutral
3.1 to 3.5	Slightly positive
3.6 to 4.5	Moderately positive
4.6 and above	Highly positive

The open-ended questions were analyzed by the 'thematic analysis' method as the approach is flexible, easy to follow, and useful in summarizing the key features (Braun & Clarke, 2006). The themes generated were grouped under three categories: likes, dislikes, and suggestions for improvement. We also calculated the frequency distribution for each theme to provide more insight into our findings.

Semi-structured interview

Data from the semi-structured interviews were analyzed using thematic analysis. The audio recordings were transcribed verbatim, after which the coding process began. Similar codes were grouped together to generate themes. These themes were then described and illustrated with examples from the interview dialogues.

Reflective journal

The purpose of the reflective journal was to allow students to express what they had gained from the learning experience, what they felt they needed to learn further, and what could be done to improve the learning atmosphere. The data were analyzed using thematic analysis. The themes were generated from the student's responses, and the frequency distribution of responses was presented for each theme.

Analogical Physical model

The analogical physical model used in this study was developed in 2015 (Choda & Chenprakhon, 2015) based on the quantum mechanical model of the atom proposed by Erwin Schrödinger in 1926. According to this model, the atom is visualized as a positively charged nucleus surrounded by a standing, stationary electron wave that extends around the nucleus. Schrödinger used advanced quantum mechanics to develop an equation that describes the properties of electrons within an atom. His equation led to the concept that there are specific regions of space around the nucleus where the probability of finding an electron with a given energy is high. These regions are known as atomic orbitals. Similar to Bohr's atomic model, which assigns numbers to electron orbits, the quantum mechanical model assigns four quantum numbers to atomic orbitals. These quantum numbers provide detailed information about the probable location of electrons around the nucleus and describe their behavior. The principal quantum number, angular quantum number, and magnetic quantum number specify the electron's location in terms of shell, subshell, and orbital, respectively. The electron spin quantum number indicates the direction of the electron's spin (Chang, 2007; Madan & Bisht, 2006). Quantum theory defines these quantum numbers as integers that specify the atom's shells, subshells, orbitals, and electron spin. Accordingly, a mapping between scientific concepts (the target) and the developed physical model has been established, as shown in Table 3.

Table 3. The source and analog mapping

Source (target) features	Model (analog) features
Shells (principal quantum numbers, *n*)	Shells (layers of thermocol)
Subshells (angular quantum numbers, ℓ)	Subshells (small sub-layers inside main layers)
Orbitals (magnetic quantum numbers, m_ℓ)	Orbitals (stick inside sub-layers)
Opposite spin of electrons in same orbital (electron spin quantum numbers, m_s)	Different color beads
Electrons	Plastic beads
Energy level	Different height in shells and subshells

The developed physical model shares several key structural features with the target scientific concepts; therefore, it is referred to as an "analogical physical model." As shown in Figure 1 and explained in Table 3, the model visually represents all four quantum numbers.

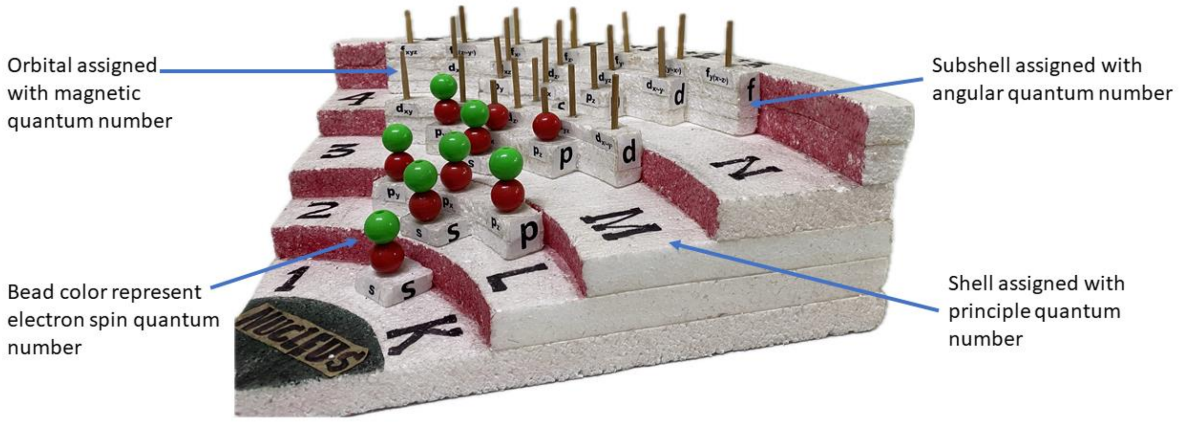

Figure 1. The analogical physical model representing four quantum numbers

Learning Units Implementation

The learning intervention was conducted over two consecutive days and consisted of two sessions, each lasting 120 minutes. The first session focused on quantum numbers, while the second addressed electron configuration. In total, students received 240 minutes of instruction, with each session structured according to the 5E learning model and incorporating the analogical physical model, as detailed in Tables 4 and 5.

Learning Unit I: Quantum Numbers

The learning objectives

- Understand the meaning and role of each quantum number.
- Identify and interpret the relationship between quantum numbers.
- Locate the electrons with respect to their shell, subshell and orbitals through quantum numbers.
- Identifying the capacity of different energy level and variation of energy in various shells, subshells and orbitals.

Table 4. 5E learning model in the learning unit I

5E	Activities
Engagement (20 minutes)	For learning the concept of quantum numbers, students participated in a simple group activity where they were asked to draw the atomic structure they were familiar with. They were provided with a set of guided questions to discuss within their group. These questions were designed to streamline students' thinking and guide them toward the current topic. The purpose of this activity was to check students' prerequisite knowledge of various atomic models, which is important for understanding quantum numbers and electron configurations.
Exploration (50 minutes)	For quantum numbers, students were provided with an analogical physical model and a set of instructions in the form of a worksheet. There were four main concepts to be explored: 1) Familiarize themselves with the model, identify different parts, and understand what each part represents. 2) Understand the meaning of each part represented in the model. 3) Understand the capacities of shells and subshells. 4) Understand the relationship between quantum numbers. Students worked in groups to explore the concepts using the model and worksheet. Teachers acted as facilitators, monitoring students' activities and providing assistance when needed. Students were instructed to complete the worksheet and prepare to explain their answers. They wrote down the answers discovered using the model and occasionally referred to the textbook to ensure the accuracy of their discussions. This phase generated rich student-to-student and student-teacher interaction.
Explanation (20 minutes)	Students discussed the concepts they had explored and prepared explanations. Each group presented their answers to the class, providing justifications, while other groups responded by either supporting or challenging the ideas presented. They were encouraged to use the analogical physical model to demonstrate their understanding and validate their responses. The discussions often revealed conflicting ideas and generated questions that helped clarify the concepts and allowed the teacher to address misconceptions. Students explained the role of quantum numbers, including the concepts of shells, subshells, and orbitals, the relationships among quantum numbers, and how to determine the electrons in an atom using quantum numbers.
Elaboration (20 minutes)	In this phase, the teacher provided a worksheet to help students deepen their understanding of quantum numbers and their applications. Students were guided to find all four quantum numbers for specific electrons. For example, they determined the quantum numbers for the 6th, 10th, and 17th electrons of an element with atomic number 18. Using the analogical physical model with beads, students identified those electrons and then determined the corresponding quantum numbers. Once they completed the worksheet, they were asked to explain and demonstrate how they arrived at their answers.
Evaluation (10 minutes)	Although students' understanding was evaluated informally throughout the lesson, formal assessment occurred during this phase. Final evaluation involved asking students targeted questions and collecting their reflective journals.

Learning Unit II: Electron Configuration

The learning objectives

- Understand the rules and principles for writing electron configuration.
- Write electron configuration using different notations.
- Identify valance electron and write valance electron configuration.

Table 5. 5E learning model in the learning unit II

5E	*Activity*
Engagement (20 minutes)	To introduce electron configuration concepts, students worked in groups to discuss and formulate rules for writing electron configurations. They were asked to explain and demonstrate their rules to the whole class. Each group received two worksheets: Worksheet 1 for writing their rules, and Worksheet 2 for writing the electron configuration of an element randomly selected from a provided list (which included elements from the alkaline and halogen groups). Students were given autonomy to create rules based on their prior knowledge. They were also instructed to write the steps they followed to arrange electrons. After group discussions, each group presented their rules and configurations to the class. Discrepancies that arose during the presentations sparked critical thinking and encouraged deeper exploration of the concepts. This activity also helped the teacher assess students' prior knowledge in order to design subsequent activities that matched their learning needs. However, the activity was not intended to assess the accuracy of their answers but rather to explore their existing understanding and stimulate curiosity. A short class discussion followed the group presentations.
Exploration (50 minutes)	In this phase, students further explored the rules and principles of electron configuration. They read relevant sections of their textbooks to identify key rules, wrote explanations for each, and demonstrated the application of these rules by writing configurations for specific elements. All groups were assigned the same element and asked to fill its orbitals, then compare their work. This created a healthy sense of competition. When one group presented, other groups critiqued their work, prompting the presenting group to justify their choices. This collaborative environment helped students understand how each rule contributes to writing correct electron configurations.
Explanation (20 minutes)	Each group was assigned an element and used beads in the analogical model to arrange electrons accordingly. They discussed their reasoning and presented their configurations to the class. While a group presented, the teacher asked other groups to check whether the configuration followed the rules and to complete a worksheet identifying the rules applied or violated. Students were asked to justify whether the presenting group had followed the rules accurately. This activity helped students internalize the concepts and demonstrate their understanding. The session concluded with a task in which students drew orbital diagrams of the assigned elements. A short clarification session followed to address any remaining misconceptions.
Elaboration (20 minutes)	Elaboration (20 minutes) Each group randomly selected three elements from a box and arranged electrons using the model. They determined the number of electrons and valence electrons, wrote full and valence electron configurations, and drew the orbital diagrams. Additionally, they were instructed to write configurations using both n l x notation and electron-box notation. Students were reminded to determine n, l, and x using the model and to treat each orbital as a "box" for notation purposes. This activity deepened their conceptual understanding of electron configuration.
Evaluation (10 minutes)	Evaluation (10 minutes) Students were evaluated through both formative and summative methods. Teachers asked questions at the end of each activity and collected worksheets and reflective journals from both groups and individual students. Sample questions: Which orbitals should be filled first? What rule or principle tells you this? Is this the correct way to place electrons in atomic orbitals? Why? (The teacher validated students' understanding of the rules by referring to the model.)

Results

One of the aims of this study was to examine the effectiveness of the developed learning units on students' conceptual understanding of quantum numbers and electron configuration. Data collected from the Quantum Concept Test (QCT) were analyzed using a paired-sample t-test, as the Shapiro–Wilk test for normality indicated that the data were normally distributed ($p = 0.32$, $p > 0.05$). The results of the paired-sample t-test, as shown in Table 6, indicated that the difference between the mean pretest and posttest scores was statistically significant at the 0.05 level ($p = 0.000$, $p < 0.05$). The mean score increased from 12.16 ± 5.29 in the pretest to 23.73 ± 6.16 in the posttest, out of a maximum possible score of 38. This finding suggests that the analogical physical model embedded within the

5E learning model was effective in enhancing students' conceptual understanding of quantum numbers and electron configuration.

Table 6. Paired-sample t-test result of students' performance in pretest and posttest.

Test	Total	Total	Mean	SD	t	df	Sig. (2-tailed)
Pretest	79	38	12.16	5.29	22.24*	78	0.00
Posttest	79	38	23.73	6.16			

*Significant with the level of $p < 0.05$

To further investigate the effectiveness of the learning units on specific concepts, the mean pretest and posttest scores for each construct were analyzed. The percentage of mean scores is presented in Table 7. Students demonstrated relatively high prior knowledge in Concept A and Concept D, with mean pretest scores of 47.1% and 40.7%, respectively. Conversely, low prior knowledge was observed for Concept B and Concept C, with mean pretest scores of 17.8% and 14.0%, respectively. However, posttest results showed that Concept A had the highest score (mean = 81.0%), followed by Concept D (mean = 73.4%). The lowest posttest score was recorded for Concept F (mean = 49.8%). When examining the differences between pretest and posttest scores, the greatest gain was observed in Concept B, followed by Concept C. This indicates that the learning units were particularly effective in improving students' understanding of these two concepts. In contrast, Concept F showed the smallest improvement, suggesting that the learning units were least effective for this particular concept.

Table 7. Mean percentage of pretest and posttest scores in each construct

Construct	Pretest (%)	Posttest (%)	Mean Gain (%)
A) Understanding the meaning and the roles of quantum numbers.	47.1%	81.0%	33.9%
B) Understanding the relationship between different quantum numbers.	17.8%	63.8%	46.0%
C) Understanding the use of quantum numbers to locate the electrons.	14.0%	59.5%	45.5%
D) Understanding energy level and the capacity of shells, subshells and orbitals.	40.7%	73.4%	32.7%
E) Understanding the rules and principles of writing electron configuration	30.0%	66.0%	36.0%
F) Competences in writing electron configuration and identify valance electrons	26.3%	49.8%	23.5%

Attitude survey questionnaire results

The survey was conducted to examine students' perceptions in three areas: 1) perceptions of the nature of the topics, 2) perceptions of the overall learning activities, and 3) perceptions of learning with the analogical physical model. Responses to each item on the Likert-type questionnaire were analyzed by calculating the mean scores for the individual items grouped under each predetermined construct. Students' perceptions of each construct were then interpreted from the grand mean of all the items associated with that construct. The criteria for determining the levels of students' overall perceptions were adapted from previous research (Pitafi & Farooq, 2012). The results indicated that students' overall perceptions of the nature of the topics (content) and the learning activities were moderately positive, with mean scores of 4.20 ± 0.54 and 4.47 ± 0.74, respectively (Tables 8–9). Students' perception of the use of the analogical model was found to be highly positive, with a mean score of 4.57 ± 0.70 (Table 10). Detailed accounts of each dimension are presented in the following paragraphs.

Students' perception towards nature of the topics

A summary of students' perceptions toward the nature of the topics is presented in Table 8. The results indicated that quantum numbers and electron configuration were perceived as slightly difficult, with mean scores of 3.46 ± 0.92 and 3.78 ± 0.77, respectively. However, students also felt that these topics were important, with a mean score of 4.77 ± 0.64, and interesting to study, with mean scores of 4.36 ± 0.73 for quantum numbers and 4.47 ± 0.67 for electron configuration. Overall, students' perceptions toward the nature of the topics were moderately positive, with an average mean score of 4.20 ± 0.80.

Table 8. Student's perceptions towards nature of the topics

Items	Mean	SD	Interpretation
Quantum number is an easy topic for me	3.46	0.92	Slightly positive
I found contents related to quantum numbers very interesting.	4.36	0.73	Moderately positive
I feel understanding quantum number is important	4.77	0.64	Highly positive
Electron configuration is an interesting topic	4.47	0.67	Moderately positive
I am confident about quantum numbers and electronic configuration topic	3.78	0.77	Moderately positive
Overall	**4.20**	**0.80**	**Moderately positive**

Students' perception towards the learning activities

The results in Table 9 indicated that students' perceptions of the analogical physical model embedded within the 5E activities were positive. The activities were viewed as useful, enjoyable, and interactive, with mean scores ranging from 4.56 to 4.95 and an overall average of 4.47 ± 0.63. Students showed the highest level of agreement with the statement expressing their desire for teachers to conduct such activities in the future, which received a mean score of 4.95 ± 0.22. The lowest perception was related to time consumption, with a reverse-coded mean score of 3.36 (original score: 2.64 ± 1.18), indicating that students did not strongly feel the activity was time-consuming. Overall, students demonstrated a slightly positive perception of time use and also felt that the activities stimulated their critical thinking about scientific concepts.

Table 9. Students' perceptions towards the learning activity

Items	Mean	SD	Interpretation
I enjoyed doing the activity	4.65	0.57	Highly positive
I was actively engaged throughout the lesson.	4.56	0.59	Moderately positive
I found activity useful	4.83	0.44	Highly positive
I wish teachers to use such activity in their teaching in future	4.95	0.22	Highly positive
Activity encouraged thinking on scientific concepts	4.43	0.82	Moderately positive
Activity was time consuming*	2.64	1.18	Slightly positive
Overall	**4.47**	**0.63**	Moderately positive

*Item that was considered reverse coding for finding overall mean and standard deviation

Students' perception towards the use of the physical model

A summary of the results is presented in Table 10. Students responded positively to the use of the analogical physical model in teaching quantum numbers and electron configuration, with an overall mean score of 4.57 ± 0.70. The mean scores for individual items ranged from 3.38 to 4.75, taking into account the reverse coding of one item. Students showed the highest positive perception for the statement expressing their desire for teachers to use this model in future lessons, with a mean score of 4.75 ± 0.54. The lowest perception was related to the complexity of the model, with a reverse-coded mean score of 3.83 (original score: 2.17 ± 1.16). Students felt that the model enhanced their understanding of the concepts and helped them construct mental images of the atom. The results also indicated that students enjoyed learning with the analogical physical model and that it sparked their curiosity. They strongly disagreed with the notion that the model made the concepts more complex, as shown by a low mean score of 2.17 ± 1.16. On the contrary, they believed the model was beneficial and expressed a strong recommendation for its use in future teaching.

Table 10. Student's perception towards the use of the physical model

Items	Mean	SD	Interpretation
I found the use of models made me understand the topic better.	4.74	0.65	Highly positive
Model helped me to construct mental images of an atom	4.64	0.58	Highly positive
I would suggest teachers to use model-based instruction in teaching this topic	4.75	0.54	Highly positive
The use of models made concept very complex and complicated *	2.17	1.16	Moderately positive
I was very curious when teachers used model	4.54	0.78	Moderately positive
Overall	**4.57**	**0.70**	Highly positive

**Item that was considered reverse coding for finding overall mean and standard deviation*

Discussion

The effectiveness of the developed learning unit on students' conceptual development was inferred from the pretest and posttest results of the Quantum Concept Test (QCT), and further supported by qualitative evidence from interviews and reflective journals. The paired-sample t-test showed a statistically significant difference between the mean pretest and posttest scores at the 0.05 significance level. The total mean score increased from 12.15 ± 5.29 (pretest) to 23.73 ± 6.16 (posttest), indicating that the analogical physical model embedded within the 5E learning model was effective in enhancing students' conceptual understanding of quantum numbers and electron configuration. This finding aligns with previous research by Rodhe (2012), Harris et al. (2009), and Rotbain et al. (2006), who reported that model-based instruction was effective in improving students' conceptual understanding. Evidence from semi-structured interviews and reflective journals further supported this result. Students appeared more confident, and most of the questions related to conceptual content in the interviews were answered convincingly and with clear explanations when needed.

Additionally, approximately 56 out of 81 students mentioned in their reflective journals that they had understood the concepts of quantum numbers. Examples of their reflections include:

> *"I learned many things and now I am almost perfect with the four quantum numbers and how to arrange electrons."*
> *"I learned many new things about quantum numbers, which are in our syllabus but I hadn't clearly understood before. Now, I feel I fully understand and am confident about them."*

Similarly, 54 out of 81 students reported that they had gained a better understanding of the rules and principles related to electron configuration. Some reflections include:

> *"I fully understood quantum numbers, and my doubts were completely cleared. I realized that Hund's rule, the Pauli exclusion principle, and the Aufbau principle are essential when writing electron configurations."*
> *"I learned how to arrange electrons in atoms, understood the rules for doing so, and everything about the atom became much clearer."*
> *"I understood the rules for filling electrons in orbitals in detail."*

The results from multiple data sources—conceptual tests, interviews, and reflective journals—clearly reflect the effectiveness of the analogical physical model in teaching quantum numbers and electron configuration. This conclusion is supported by: (1) the increase in students' mean test scores; (2) their accurate and satisfactory responses during interviews; and (3) their expressions of confidence and positive remarks about learning with the analogical model in their reflective journals. Furthermore, the conceptual test results showed an increase in posttest mean scores across all conceptual areas, as presented in Table 7. The improvement in mean scores ranged from 23.5% to 46% following instruction using the analogical model. The highest conceptual gain was observed in students' understanding of the relationship between different quantum numbers (46.0%), followed by their ability to use quantum numbers to locate electrons (45.5%). The smallest gain (23.5%) was found in students' competence in writing electron configurations and identifying valence electrons.

In traditional settings, knowledge is typically transferred through teacher notes and textbooks, with students reproducing this information during exams—a pattern observed in learning quantum concepts as well (Johnston et al., 1998). For instance, students often memorize formulas such as (n−1) to determine possible angular quantum numbers (ℓ) for a given principal quantum number (n), and ($2\ell+1$) to determine the magnetic quantum numbers (m_ℓ). However, this memorization adds cognitive load and does not guarantee conceptual understanding. Students often struggle to grasp what each number actually represents. In contrast, the developed analogical physical model helped students build this understanding more intuitively. By using the model to determine the numbers associated with shells, subshells, and orbitals—corresponding to principal, angular, and magnetic quantum numbers, respectively—students were better able to understand the relationships between quantum numbers and the meanings behind the formulas. Understanding the origin of these formulas supports deeper learning, compared to simply memorizing them. Previous studies (e.g., Rotbain et al., 2006) have shown that active engagement with chemical representations can reduce students' anxiety and improve comprehension of abstract concepts.

This finding aligns with prior research (Rotbain et al. 2006; Micallef & Newton, 2024), who found that concrete models supported students in better visualizing and understanding abstract ideas. It also supports Desmalinda and Padang (2014) findings that model-based instruction fosters creativity and deeper conceptual understanding. Interview data from this study further confirmed the model's value, with students specifically stating that it clarified the four quantum numbers and enhanced their comprehension. For example:

Student A: It [the model] clearly showed us the four quantum numbers and helped us practice the rules for electron configuration.
Student B: This model is perfect for learning about quantum numbers.
Student C: When I learned without the model, I couldn't really figure out the concepts. The model helped me understand better.

Moreover, using the analogical model in an inquiry-based setting allowed students to explore more deeply how formulas are constructed. In terms of locating electrons using quantum numbers, students first learned the designations used for shells, subshells, and orbitals. The model illustrated that shells are labeled K, L, M, etc., corresponding to principal quantum numbers 1, 2, 3, and so on. Similarly, subshells are labeled s, p, d… corresponding to angular quantum numbers 0, 1, 2, and so on. Orbitals such as *s*, p_x, p_y, and p_z represent spatial orientations, which correspond to magnetic quantum numbers (e.g., 0, ±1, ±2).

Once students became familiar with these designations, identifying electron locations became much easier. However, teaching these concepts with models requires thoughtful implementation. Each symbol—such as *s*, *p*, or *d*—not only represents a location but also a shape; p_x, p_y, and p_z further indicate spatial orientation. If these distinctions are not clearly explained, the model may fail to support meaningful learning. As noted by Coll (2006), effective model-based instruction requires students to first become familiar with the model, guided by the teacher.

Interestingly, students also demonstrated awareness of the model's limitations, as shown in the interview responses:

Student A: This model is useful, but if used alongside a slide presentation, it would be much easier to understand.
Student B: More models could be developed to show the orientations as well.

Students appreciated the model's value but also emphasized the need for additional tools to achieve a complete understanding of the concepts.

Students' Perceptions

Students' Perceptions Toward the Nature of the Topics

One of the ongoing challenges in chemistry education is that students often do not favor learning chemistry, as its concepts are frequently perceived as abstract or difficult to understand. Therefore, this study aimed to explore students' perceptions of topics related to quantum numbers and electron configuration. The results indicated that students' perceptions of these topics were moderately positive. Most students agreed that quantum numbers and electron configuration are important, interesting, and somewhat easy to study. However, some students still considered these topics difficult. In their reflective journals, four students explicitly stated that they disliked these topics due to their complexity and difficulty—an observation that aligns with the abstract and mathematically-oriented nature of the subject matter (Dangur et al., 2014; Johnston et al.,1998). As Sirhan (2007) noted, complex or difficult subjects can discourage learners from continuing their studies.

This perception of difficulty was also supported by the conceptual test results, as well as previous literature discussed in earlier sections. Nevertheless, an interesting finding emerged: students still acknowledged the importance of understanding these topics, even if they found them challenging. At the same time, a pattern was observed between students' attitudes toward the topics and their perceived difficulty. In other words, even though students recognized the importance of the topics, they were less likely to enjoy studying them when they perceived the content as too difficult.

Students' Perceptions Toward the Model-Based Learning Activities

This study aimed not only to improve students' conceptual understanding but also to foster motivation through engaging learning experiences. The learning activities were designed using the 5E instructional model and incorporated an analogical physical model. The results of the five-point Likert-type Attitude Survey Questionnaire revealed that students' perceptions of the learning activities were highly positive. Students reported being actively engaged in the lessons, which helped foster critical thinking. They found the activities enjoyable and expressed a desire for more such experiences in the future. This finding was reinforced by qualitative data—about 37 students specifically mentioned in their reflections that they liked the learning activities.

Working in groups, engaging in hands-on tasks, taking responsibility for their own learning, and being exposed to a new instructional approach were among the factors students found appealing. These results are consistent with previous studies indicating that object-mediated learning can motivate students and help maintain their focus (Satterthwait, 2010; Rodhe, 2012). They also align with findings from Duangpummet et al. (2022), which reported that students develop positive attitudes when taught through hands-on and inquiry-based learning approaches.

Interview responses and reflective journals further emphasized that students benefit from having ample time for discussion and activities, and that proper group formation and organization contribute to a more comfortable learning environment. Overall, students' reactions to the learning activities were positive, indicating that the integration of the 5E instructional model with a physical model provided an effective approach for teaching the concepts of quantum numbers and electron configuration.

Perceptions Toward the Use of the Analogical Physical Model

Since the physical model was a crucial component of the learning activities in this developed learning unit, it is important to examine students' perceptions of its use. Results from the Attitude Survey Questionnaire indicated that students' perceptions of using the model to teach the concepts of quantum numbers and electron configuration were highly positive. Although limited literature directly addresses students' perceptions of using models to teach these specific topics, Desmalinda and Padang (2014) found that students exhibited excitement and interest when learning quantum numbers and electron configuration through modeling activities. While direct references are scarce, the broader literature provides ample evidence that analogies and models can effectively engage students and support the understanding of abstract concepts, as discussed further below.

In the current study, students perceived that the model helped them understand the concepts more clearly, sparked curiosity, and aided in forming mental images of atomic structure. Qualitative data from open-ended questions, interviews, and reflective journals provided strong support for students' appreciation of the model's use in teaching. From the open-ended responses, it was found that 45 out of 81 students expressed a liking for the model. They described it as interesting, useful, and—most importantly—effective in enhancing their understanding of the associated concepts.

Interview data revealed that students found the model user-friendly and felt it provided a hands-on, practical experience that fostered active learning and meaningful engagement. Several students even expressed the wish that such models be used in other subjects and that educational organizations take the initiative to supply these models to schools. These findings align with previous studies. For example, Roberts et al. (2005) reported that the engaging and interactive nature of physical models stimulates student interest and enthusiasm. Rodhe (2012) also found that physical models generate interest and offer valuable variation in teaching pedagogy. Similarly, Beltramini et al. (2006) and Satterthwait (2010) reported that models support students in maintaining focus on learning goals and help motivate learners.

However, some limitations were identified by the students. A common concern was that the model seemed fragile and not durable. Students suggested that future versions be constructed using sturdier materials. Some students were also skeptical about the model's ability to represent electron configurations for elements with higher atomic numbers and to depict the orientations of orbitals. This suggests that some students did not fully grasp that a single model cannot represent all aspects of reality. This limitation reflects a core principle of modeling theory: a single model represents only specific aspects of a target concept, and multiple models may be required to fully represent complex phenomena (Oh & Oh, 2011). In response to these limitations, students suggested increasing the number of shells and subshells in the model to allow for discussions of heavier elements. They also recommended using color-coding to represent energy variations across shells and subshells to better illustrate the concept of energy levels.

These suggestions indicate that students not only understood the model well but also recognized its limitations—an essential aspect of model-based instruction. Understanding a model's limitations helps minimize confusion and prevent misconceptions. As Coll (2006) noted, it is important to help students view model limitations as an intrinsic feature of modeling rather than as a flaw or failure. Recognizing these limitations does not diminish the model's value; on the contrary, it helps students use the model more appropriately and effectively in learning.

While a formal statistical correlation was not computed between students' perceptions and their performance gains, the findings suggest a meaningful connection. The overall highly positive perception of the analogical physical model ($M = 4.57$) and learning activities ($M = 4.47$), as reflected in Tables 9 and 10, aligned with a statistically significant increase in conceptual understanding from pretest ($M = 12.16$) to posttest ($M = 23.73$). This suggests that students who found the model engaging and helpful were more likely to be motivated, actively participate, and internalize the content—factors that likely contributed to improved performance. This observation aligns with prior research emphasizing that positive affective engagement enhances cognitive learning outcomes in science education (e.g., Rotbain et al., 2006; Roberts et al., 2005).

Limitation and Recommendations

This study was conducted within the context of the Bhutanese education system and science curriculum; therefore, the findings cannot be generalized to all educational settings. However, given that the participants shared characteristics common to many secondary science students—such as similar curriculum exposure and foundational knowledge—the analogical physical model may hold potential for broader use in comparable classroom settings. Comparative studies across different contexts may be necessary to further evaluate the model's applicability. In addition, the absence of a control group limits the ability to make strong causal claims about the intervention's effectiveness, as improvements could potentially be influenced by external factors. Future studies incorporating control or comparison groups are recommended to strengthen causal inference. The present study employed an analogical physical model in conjunction with the 5E learning model. As a result, the observed effects on students' conceptual understanding were likely due to the combined influence of both instructional strategies. To determine the specific effectiveness of the model alone, further research is recommended.

It is recommended that educators consider integrating analogical physical models into abstract chemistry topics to support visualization and engagement. Curriculum developers may also explore the inclusion of analogical tools aligned with inquiry-based strategies like the 5E model. Future research should examine how this approach performs across diverse educational settings, with varying student abilities, and in comparison, to traditional instructional methods

Acknowledgements

This research was partially supported by a scholarship from the Thailand International Development Cooperation Agency (TICA) awarded to J. Choda. We also gratefully acknowledge research support from Mahidol University provided to P. Chenprakhon.

References

Abraham, M. R., Williamson, V. M., & Westbrook, S. L. (1994). A cross-age study of the understanding of five chemistry concepts. *Journal of Research in Science Teaching, 31*(2), 147–165.

Adhikary, C., Sana, S., & Chattopadhyay, K. N. (2015). Chunking strategy as a tool for teaching electron configuration. *Journal of Chemical Education, 92*(4), 664–667. https://doi.org/10.1021/ed500446t

Ali, T. (2012). A case study of the common difficulties experienced by high school students in chemistry classroom in Gilgit-Baltistan (Pakistan). *SAGE Open, 2*(2). https://doi.org/10.1177/2158244012447299

Barke, H. D., Hazari, A., & Yitbarek, S. (2009). Students' misconceptions and how to overcome them. In *Misconceptions in chemistry: Addressing perceptions in chemical education* (pp. 21–36). Springer.

Beltramini, L. M., Araújo, A. P. U., de Oliveira, T. H. G., dos Santos Abel, L. D., da Silva, A. R., & dos Santos, N. F. (2006). A new three-dimensional educational model kit for building DNA and RNA molecules: Development and evaluation. *Biochemistry and Molecular Biology Education, 34*(3), 187–193.

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology, 3*(2), 77–101. https://doi.org/10.1191/1478088706qp063oa

Chang, R. (2007). *Chemistry* (9th ed., pp. 283–299). McGraw-Hill.

Choda, J., & Chenprakhon, P. (2015). A hands-on physical model for teaching quantum numbers and rules for writing electron configuration. In *Proceedings of the 3rd Global Summit on Education*.

Clugston, M., & Flemming, R. (2000). *Advanced chemistry*. Oxford University Press.

Coll, R. K. (2006). The role of models, mental models and analogies in chemistry teaching. In P. J. Aubusson, A. G. Harrison, & S. M. Ritchie (Eds.), *Metaphor and analogy in science education* (pp. 65–77). Springer. https://doi.org/10.1007/1-4020-3830-5_6

Dangur, V., Avargil, S., Peskin, U., & Dori, Y. J. (2014). Learning quantum chemistry via a visual-conceptual approach: Students' bidirectional textual and visual understanding. *Chemistry Education Research and Practice, 15*(3), 297–310. https://doi.org/10.1039/C4RP00025K

DeCoster, J. (2000). *Scale construction notes*. Department of Psychology, University of Alabama. http://stat-help.com/scale_20100316.pdf

Desmalinda, M. P., & Padang, J. S. (2014). Model three dimensional visualization of quantum atomic physics lesson in class XII science high school. http://www.qitepscience.org/wp-content/uploads/2015/04/12-MODEL-THREE-DIMENSIONAL-VISUALIZATION-OF-QUANTUM-ATOMIC-PHYSICS-LESSON-IN-CLASS-XII-SCIENCE-HIGH-SCHOOL.pdf

Duangpummet, P., Yodyingyong, S., & Chenprakhon, P. (2022). Fruit puzzle: An inquiry-based activity to investigate high school students' understanding of the relationship between the concepts of density and concentration of solution at the submicroscopic level. *Journal of Chemical Education, 99*(12), 4175–4180.

Fortman, J. J. (1993). Pictorial analogies VII: Quantum numbers and orbitals. *Journal of Chemical Education, 70*(8), 649.

Garofalo, A. (1997). Housing electrons: Relating quantum numbers, energy levels, and electron configuration. *Journal of Chemical Education, 74*(6), 709.

Glynn, S. M. (2008). Making science concepts meaningful to students: Teaching with analogies. In D. W. Sunal & E. L. Wright (Eds.), *Four decades of research in science education: From curriculum development to quality improvement* (pp. 113–135). Information Age Publishing.

Garcia I Grau, F., Valls, C., Piqué, N., & Ruiz-Martín, H. (2021). The long-term effects of introducing the 5E model of instruction on students' conceptual learning. International Journal of Science Education, 43(9), 1441-1458.

Greca, I. M., & Freire, O. (2014). Teaching introductory quantum physics and chemistry: Caveats from the history of science and science teaching to the training of modern chemists. *Chemistry Education Research and Practice, 15*(3), 286–296. https://doi.org/10.1039/C4RP00006D

Grenda, S. C. (1988). A simple mnemonic device for electron configuration. *Journal of Chemical Education, 65*(8), 697.

Harris, M. A., Peck, R. F., Colton, S., Morris, J., Neto, E. C., & Kallio, J. (2009). A combination of hand-held models and computer imaging programs helps students answer oral questions about molecular structure and function: A controlled investigation of student learning. *CBE—Life Sciences Education, 8*(1), 29–43.

Harrison, A. G., & Treagust, D. F. (1993). Teaching with analogies: A case study in grade-10 optics. *Journal of Research in Science Teaching, 30*(10), 1291–1307.

Harrison, A. G., & Treagust, D. F. (2006). Teaching and learning with analogies. In P. J. Aubusson, A. G. Harrison, & S. M. Ritchie (Eds.), *Metaphor and analogy in science education* (pp. 11–24). Springer. https://doi.org/10.1007/1-4020-3830-5_2

Iza, N., & Gil, M. (1995). A mnemonic method for assigning the electronic configurations of atoms. *Journal of Chemical Education, 72*(11), 1025.

Johnston, I. D., Crawford, K., & Fletcher, P. R. (1998). Student difficulties in learning quantum mechanics. *International Journal of Science Education, 20*(4), 427–446.

Joswick, C., & Hulings, M. (2024). A systematic review of BSCS 5E instructional model evidence. International Journal of Science and Mathematics Education, 22(1), 167-188

Laohapornchaiphan, J., & Chenprakhon, P. (2024). A review of research on learning activities addressing the submicroscopic level in chemistry. *Journal of Chemical Education, 101*(11), 4552–4565.

Lovett, C., & Chang, R. (2005). *Understanding chemistry* (1st ed.). McGraw-Hill.

Mabrouk, S. T. (2003). The periodic table as a mnemonic device for writing electronic configurations. *Journal of Chemical Education, 80*(8), 894.

Madan, R. D., & Bisht, B. S. (2006). *ISE chemistry book I for class XI* (16th ed.). S. Chand & Company Ltd.

Ma, N. L. (1996). Quantum analogies on campus. *Journal of Chemical Education, 73*(11), 1016.

Micallef, A., & Newton, P. M. (2024). The use of concrete examples enhances the learning of abstract concepts: A replication study. *Teaching of Psychology, 51*(1), 22–29.

Müller, C. H., & Rau, M. A. (2025). Instructional analogies dominate, domain-inherent metaphors are overlooked: A systematic review of metaphorical mappings in chemistry education. *Journal of Chemical Education*.

Nakiboglu, C. (2003). Instructional misconceptions of Turkish prospective chemistry teachers about atomic orbitals and hybridization. *Chemistry Education Research and Practice, 4*(2), 171–188.

Oh, P. S., & Oh, S. J. (2011). What teachers of science need to know about models: An overview. *International Journal of Science Education, 33*(8), 1109–1130. https://doi.org/10.1080/09500693.2010.502191

Orgill, M., & Bodner, G. (2004). What research tells us about using analogies to teach chemistry. *Chemistry Education Research and Practice, 5*(1), 15–32.

Pitafi, A. I., & Farooq, M. (2012). Measurement of scientific attitude of secondary school students in Pakistan. *Academic Research International, 2*(2). http://www.savap.org.pk/journals/ARInt./Vol.2(2)/2012(2.2-43).pdf

Roberts, J. R., Hagedorn, E., Dillenburg, P., Patrick, M., & Herman, T. (2005). Physical models enhance molecular three-dimensional literacy in an introductory biochemistry course. *Biochemistry and Molecular Biology Education, 33*(2), 105–110.

Rodhe, A. (2012). Physical models for classroom teaching in hydrology. *Hydrology and Earth System Sciences, 16*(9), 3075–3082. https://doi.org/10.5194/hess-16-3075-2012

Rotbain, Y., Marbach-Ad, G., & Stavy, R. (2006). Effect of bead and illustration models on high school students' achievement in molecular genetics. *Journal of Research in Science Teaching, 43*(5), 500–529. https://doi.org/10.1002/tea.20144

Sarantopoulos, P., & Tsaparlis, G. (2004). Analogies in chemistry teaching as a means of attainment of cognitive and affective objectives: A longitudinal study in a naturalistic setting, using analogies with a strong social content. *Chemistry Education Research and Practice*, *5*(1), 33–50.

Satterthwait, D. (2010). Why are 'hands-on' science activities so effective for student learning? *Teaching Science, 56*(2), 7–10.

Selçuk, G. S., & Çalỳskan, S. (2009). Student understanding of some quantum physical concepts. *Latin-American Journal of Physics Education, 3*(2), 2.

Seok, P., & Jin, S. (2011). What teachers of science need to know about models. *International Journal of Science Education, 33*(8), 1109–1130. https://doi.org/10.1080/09500693.2010.502191

Sirhan, G. (2007). Learning difficulties in chemistry: An overview. *Journal of Turkish Science Education, 4*(2), 2–20.

Sotáková, I., & Ganajová, M. (2023). The effect of the 5E instructional model on students' cognitive processes and their attitudes towards chemistry as a subject. *Eurasia Journal of Mathematics, science and technology education*, 19(9), em2317.

Suchocki, J. (2004). *Conceptual chemistry: Understanding our world of atoms and molecules* (2nd ed.). Von Hoffmann Press.

Taber, K. S. (2002a). Compounding quanta: Probing the frontiers of student understanding of molecular orbitals. *Chemistry Education Research and Practice, 3*(2), 159–173.

Taber, K. S. (2002b). Conceptualizing quanta: Illuminating the ground state of student understanding of atomic orbitals. *Chemistry Education Research and Practice, 3*(2), 145–158.

Tavakol, M., & Dennick, R. (2011). Making sense of Cronbach's alpha. *International Journal of Medical Education, 2*, 53–55. https://doi.org/10.5116/ijme.4dfb.8dfd

Tsaparlis, G., & Papaphotis, G. (2002). Quantum-chemical concepts: Are they suitable for secondary students? *Chemistry Education Research and Practice*, *3*(2), 129–144.

Tuna, A., & Kacar, A. (2013). The effect of 5E learning cycle model in teaching trigonometry on students' academic achievement and the permanence of their knowledge. *International Journal on New Trends in Education and Their Implications, 4*(1), 73–87.

Tunner, R. C., & Carlson, L. (2003). Indexes of item-objective congruence for multidimensional items. *International Journal of Testing, 3*(2), 163–171.

Tüysüz, C. (2009). Development of two-tier diagnostic instrument and assess students' understanding in chemistry. *Scientific Research and Essay, 4*(6), 626–631.

Van Joolingen, W. (2004). Roles of modeling in inquiry learning. In *Proceedings of the IEEE International Conference on Advanced Learning Technologies* (pp. 1096–1097). IEEE Computer Society. http://www.computer.org/csdl/proceedings/icalt/2004/2181/00/21811096.pdf

Zarkadis, N., Papageorgiou, G., & Markos, A. (2021). Understanding quantum numbers: Students' verbal descriptions and pictorial representations of the atomic structure. *International Journal of Science Education, 43*(13), 2250–2269.