A Study on Promoting Elementary Students' Construction of Research Questions in Chemistry Science Fairs through Generative AI and Cognitive Apprenticeship-Based Instructional Design

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Abstract

This study explores how elementary school teachers can integrate generative AI with cognitive apprenticeship to guide students in gradually constructing researchable questions during a chemistry science fair project. The participants were four upper-grade elementary students, each provided with a mobile device pre-configured with specific AI prompts. The instructional design comprised three phases: topic generation, question-formulation strategy guidance, and abstract analysis, integrating teacher scaffolding and AI assistance throughout the process. Data sources included students' learning portfolios and their dialogue logs with the AI system. Analysis was conducted using the six dimensions of cognitive apprenticeship. The results indicate that teachers played the roles of cognitive modeling and strategic coaching, while the generative AI served as both a reasoning trigger and a real-time scaffolding tool. This dual-support system facilitated students' transition from vague, ill-defined interests to the formulation of operational research questions with awareness of variable control. The study suggests that teachers can effectively leverage generative AI as a support tool to enhance students' quality of questioning and scientific inquiry thinking throughout the science fair process.

Keywords: Generative AI, cognitive apprenticeship, science fair, research question construction, chemistry inquiry

Introduction

In Taiwan's science fairs, students must meet three fundamental requirements: propose researchable questions, effectively control variables, and design complete and feasible experimental plans. These requirements not only test students' scientific knowledge and skills but also reflect their understanding and application of scientific inquiry methods. Through these requirements, students can experience the scientific research process in practice and cultivate a rigorous scientific attitude.

However, at the elementary school level, students' research questions often tend to be interesting and entertaining but lack operability and verifiability. For example, some questions, while intriguing, cannot be tested through experiments or with controlled conditions. This suggests that younger students, when designing questions, often overlook the feasibility of scientific inquiry and the importance of variable control.

Award-winning science fair projects often share common features: rigorous and thorough research design, creative thinking with a clear problem focus, strong examples of how to ask questions and adjust variables, and effective development of scientific thinking and communication skills throughout the process. These projects stand out not only in results but also in their ability to inspire audiences and other participants, becoming exemplary learning models in science fairs.

To address the gap between students' natural curiosity and the scientific rigor required in research, instructional support frameworks such as the Cognitive Apprenticeship model have been widely advocated (Collins, Brown, & Newman, 2018). This model consists of six important stages: “Modeling”—experts demonstrate and reveal their thought processes; “Coaching”—providing guidance and real-time feedback; “Scaffolding”—offering necessary support and gradually reducing dependence; “Articulation”—guiding learners to articulate their thinking and strategies; “Reflection”—comparing different methods and outcomes to promote improvement; and “Exploration”—encouraging independent application and extended learning. Through this model, teachers can effectively guide students from imitation to independent thinking, ultimately enabling them to engage in self-directed inquiry.

Moreover, students’ ability to improve their questioning skills involves not only external scaffolding but also the development of self-regulation skills, including self-monitoring, self-evaluation, and self-reflection (Zimmerman, 2000). Research also indicates that metacognitive prompts—whether provided by teachers or embedded in learning tools—can enhance both students’ understanding of content and their grasp of the nature of science (Peters & Kitsantas, 2010). These findings suggest that strategically designed teacher and AI supports could foster both cognitive and metacognitive growth in student question-asking.

In the task design of this study, Task 1 was entirely student-directed, with no teacher support and AI serving only as a “Responder”. This stage consisted of four student-led sessions aimed at observing whether students could generate high-quality chemistry research questions when relying solely on AI.

Task 2 included one teacher-led session and four student-directed activities. The teacher selected science fair project summaries that matched students’ abilities and provided AI prompts, with AI serving as a ”Coach” to help students learn how to interact strategically with AI and focus on chemistry research variables.

Task 3 further increased teacher guidance, with a total of seven sessions, including two teacher-led classes. The teacher guided students in analyzing science fair project summaries, provided the summary content and AI prompts, and AI acted as a “Co-constructor” to collaborate with students in generating research questions. This design aimed to observe whether students could demonstrate higher-level question-posing abilities with comprehensive teacher and AI collaborative support.

The three core research questions of this study were:

(1) Can students propose high-quality chemistry research questions when using only AI without teacher support?

(2) Does teacher-supported AI interaction help students focus on chemistry research variables?

(3) Can students’ chemistry question-posing abilities be enhanced through the six stages of the Cognitive Apprenticeship model?

Methodology

This study involved four fifth-grade students who demonstrated a high level of interest in science fair topics and had prior experience using generative AI. The research design was divided into three task stages, each focusing on a different chemistry concept. Task 1, titled “Making Bouncy Balls,” explored the principles of polymer elasticity. Task 2, “Natural pH Indicators,” utilized red cabbage and butterfly pea flowers as research materials. Task 3 investigated the relationship between cyanotype printing and pH, specifically examining how acidity affects the color changes in cyanotype images.

In terms of data collection, three main types of data were gathered. First, complete conversation transcripts between the students and the generative AI were collected to analyze the AI’s role and influence in the questioning process. Second, students' worksheets and the research questions they generated in each task were collected to examine the types and levels of questions posed. Third, students' reflective notes after each task were collected to gain insight into their shifts in thinking and learning experiences throughout the process.

For the analytical framework, students' questions were first categorized into five types based on their nature: Factual Questions, Procedural Questions, Reasoning Questions, Explanation Questions, and Hypothetical Questions. Next, according to Bloom's Taxonomy, questions were classified into six cognitive levels: Remember, Understand, Apply, Analyze, Evaluate, and Create. Through this dual classification framework, the study was able to examine students' questioning performance and changes in ability from both the perspective of question type and cognitive level, under varying tasks and instructional support conditions.

Results

Based on the conversation data between students and the generative AI across the three tasks (see Table 1), in Task 1, S1 had the highest number of interactions with the AI (10 times), indicating the greatest reliance on AI when no teacher support was provided. In Task 2, with the teacher providing summaries and prompt phrases, all students significantly increased their interactions with the AI (a total of 79 times), with S2 reaching as many as 44 interactions, reflecting that the support strategy effectively enhanced student–AI communication. By Task 3, although the total number of interactions decreased to 23, the quality of the research questions generated by the students improved noticeably.

In terms of research question quality (see Table 2), in Task 1, none of the students were able to propose acceptable research questions. In Task 2, some students were able to pose 1–2 qualifying research questions. By Task 3, S1, S2, and S3 each proposed four high-quality research questions, and S4 proposed one, indicating that through three consecutive tasks combined with teacher support, students' research question quality improved significantly.

Table 1. Number of Student–AI Interactions Across Three Tasks

Task	S1	S2	S3	S4	Total number
Task1	10	2	2	3	17
Task2	15	44	12	8	79
Task3	4	7	6	6	23

Table 2. Number of High-Quality Research Questions Proposed by Each Student Across Three Tasks

Task	S1	S2	S3	S4
Task1	No good question	No good question	No good question	No good question
Task2	2 good question	1 good question	No good question	1 good question
Task3	4 good question	4 good question	4 good question	1 good question

Using S1 as an example for qualitative analysis, the types of questions posed showed a clear shift over the course of the tasks. In terms of question levels, the proportion of factual questions (Q1) decreased, while the proportions of explanation questions (Q4) and hypothetical questions (Q5) increased (see Figure 1). This indicates a transition from merely seeking factual information to engaging in deeper reasoning and hypothesis construction. According to Bloom’s taxonomy, the proportion of questions at the remembering level (B1) declined, while the proportions at the evaluating (B5) and creating (B6) levels increased (see Figure 2), reflecting a gradual development of S1’s questioning ability toward higher-order thinking.

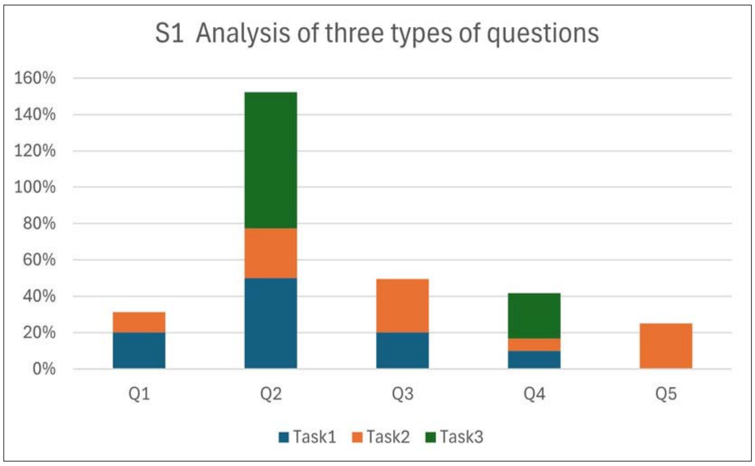

Figure 1. S1 Distribution of Question Types Across Three Tasks

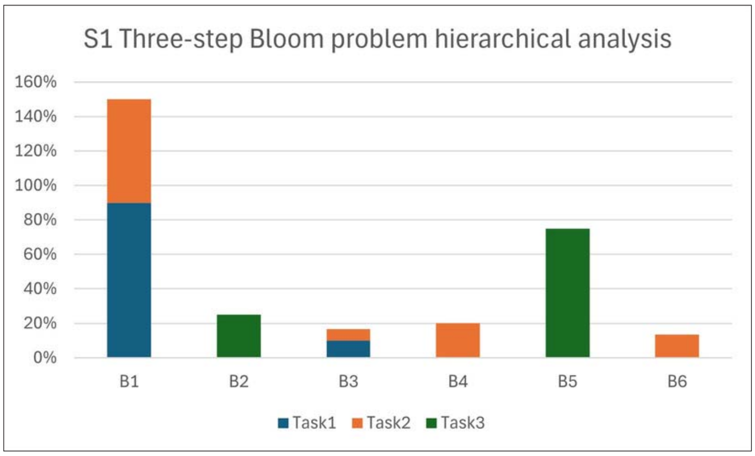

Figure 2. S1 Three-Step Bloom’s Taxonomy Analysis Across Three Tasks

Based on the qualitative analysis of S2, the questions posed showed a clear transformation across the three tasks. In terms of question level distribution, the proportions of factual questions (Q1) and procedural questions (Q2) gradually decreased, while the proportion of hypothetical questions (Q5) increased (see Figure 3),. This indicates that after multiple tasks, S2’s questioning shifted from focusing on basic knowledge and procedural steps to more exploratory and speculative thinking.

From the perspective of Bloom’s taxonomy, the proportion of questions at the remembering level (B1) decreased significantly, indicating a reduced reliance on simple knowledge recall. At the same time, the proportions of questions at the analyzing level (B4) and creating level (B6) increased(see Figure 4), reflecting that S2, through interactions with AI, gradually demonstrated higher-order thinking skills, such as analyzing variable relationships, comparing different possibilities, and creatively generating new ideas or hypotheses. This shift suggests that, with teacher guidance and AI support, the student's questioning ability improved qualitatively from lower-order to higher-order levels.

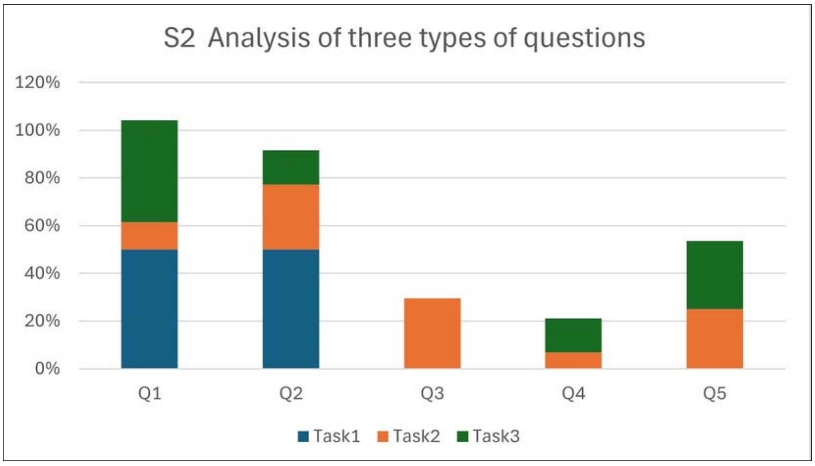

Figure 3. S2 Distribution of Question Types Across Three Tasks

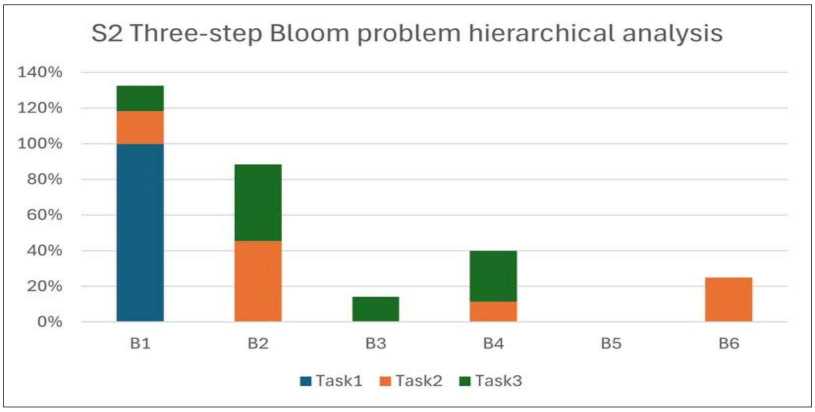

Figure 4. S2 Three-Step Bloom's Taxonomy Analysis Across Three Tasks

From the qualitative analysis of S3, it is evident that the types of questions posed gradually shifted toward higher-level thinking across the three tasks. In terms of question levels, the proportions of factual questions (Q1) and procedural questions (Q2) decreased, while the proportions of reasoning questions (Q3) and explanation questions (Q4) increased(see Figure 5). This indicates that the student gradually reduced questions focused solely on factual information and procedural steps, and began attempting reasoning and explanation.

According to Bloom's taxonomy, the proportion of questions at the remembering level (B1) showed a downward trend, while the proportion at the understanding level (B2) increased significantly(see Figure 6). This reflects that, over the course of the tasks, S3 transitioned from merely recalling facts to better understanding and interpreting scientific concepts. Although there was no clear performance yet in higher-order levels such as analyzing, evaluating, and creating, the cognitive process already showed a progression from lower-order to mid-level thinking.

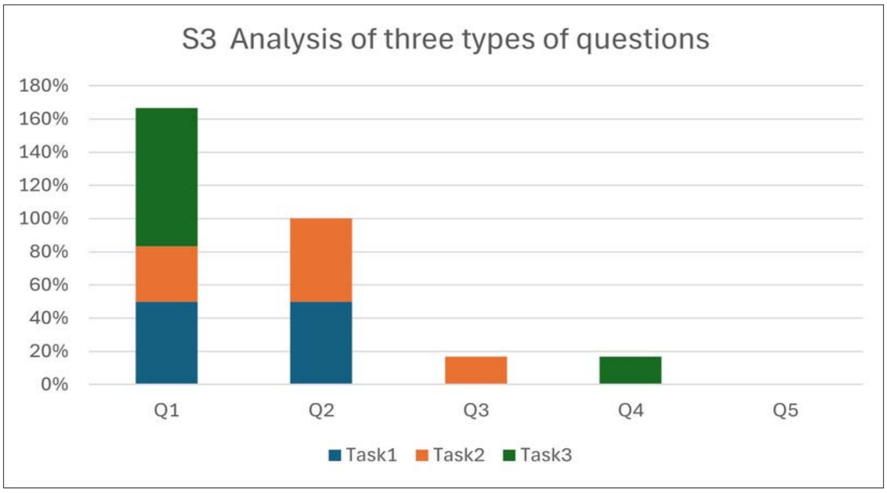

Figure 5. S3 Distribution of Question Types Across Three Tasks

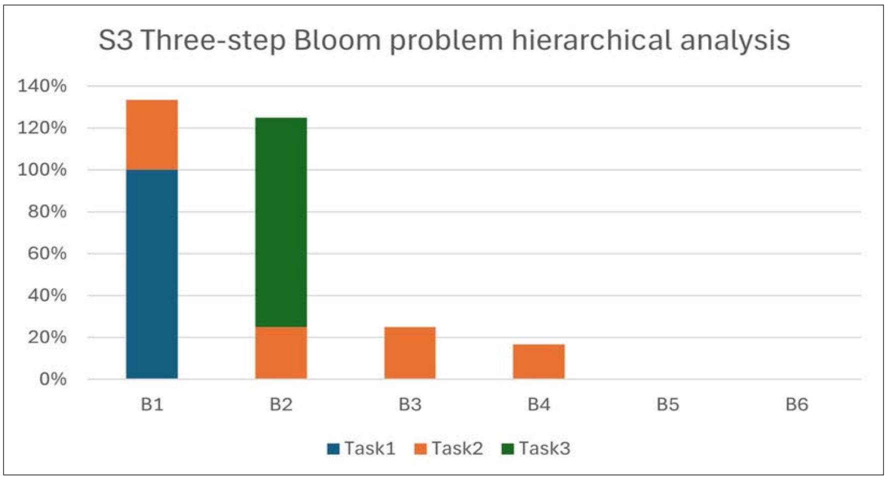

Figure 6. S3 Three-Step Bloom's Taxonomy Analysis Across Three Tasks

From the qualitative analysis of S4, it can be seen that the student's questioning showed a trend of shifting from lower-order to higher-order thinking across the three tasks. In terms of question levels, the proportions of factual questions (Q1) and procedural questions (Q2) gradually decreased, while the proportions of explanation questions (Q4) and hypothetical questions (Q5) increased(see Figure 7). This indicates that S4's questions gradually moved from a focus on factual knowledge and procedural aspects toward more reasoning-based and predictive inquiry.

In terms of Bloom's taxonomy, the proportion of questions at the remembering level (B1) decreased significantly, while the proportions at the evaluating level (B5) and creating level (B6) increased(see Figure 8). This reflects that, during interactions with AI, S4 was increasingly able to engage in critical judgment and creative thinking. Such a shift demonstrates that, in a context where teacher support and AI collaboration are provided, a student's questioning ability can progress from basic knowledge recall to the production of higher-order thinking.

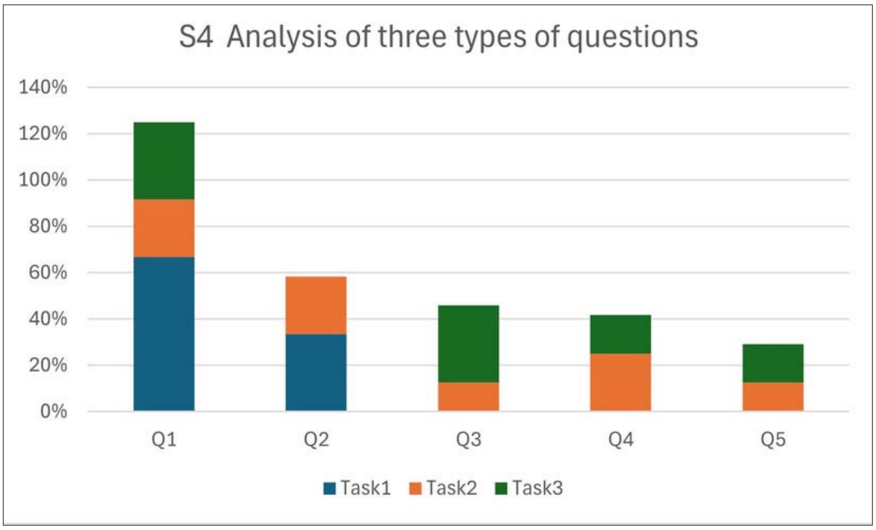

Figure 7. S4 Distribution of Question Types Across Three Tasks

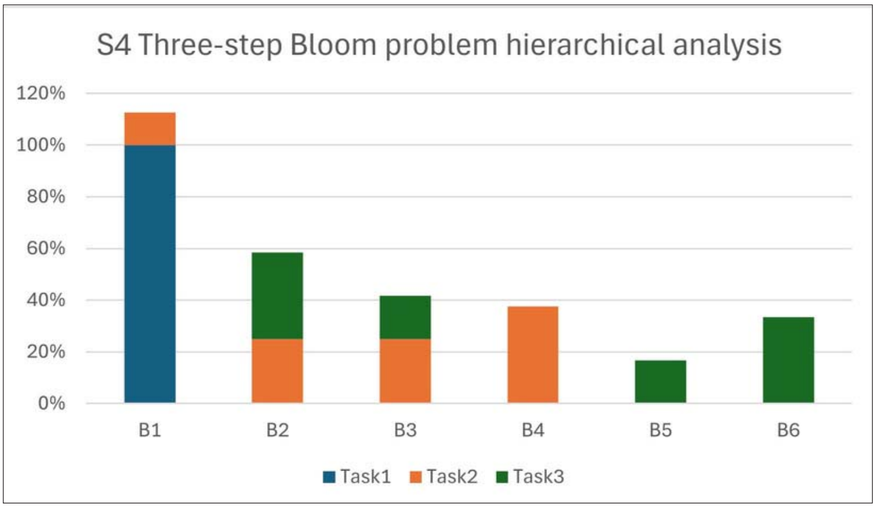

Figure 8. S4 Three-Step Bloom's Taxonomy Analysis Across Three Tasks

For the first research question—"Can students propose high-quality chemistry research questions relying solely on AI?"—in Task 1, students interacted independently with the AI, but most of the questions they posed were simple or vague and failed to focus on scientific variables. For example, S1 stated, "*I didn't know where to start,*" and S3 mentioned, "*The bouncy ball turned into slime.*" These responses indicate that, in the absence of guidance, students had difficulty identifying the key points of inquiry, reflecting that at the "Modeling" stage of the Cognitive Apprenticeship model, they still required more support.

For the second research question—"Does teacher-supported AI help students focus on chemistry variables?"—in Task 2, students were provided with science fair project summaries and key prompts, enabling them to focus their questions on variable control and pose more testable research questions. S4 commented, "*The summary made it easier for me to ask questions,*" while S2 said, "*The answers helped me come up with better questions.*" These findings suggest that, with teacher guidance and AI assistance, students were able to conduct more effective inquiry design. This stage corresponds to the "Coaching" and "Scaffolding" stages of the Cognitive Apprenticeship model.

For the third research question—"Can students' chemistry question-posing skills be enhanced through the six stages of the Cognitive Apprenticeship model?"—in Task 3, students were able to independently use prompts to interact with the AI and demonstrated greater reflection and deeper thinking, generating questions that were more specific and targeted. S3 remarked, "*AI also asked me harder questions,*" and S4 stated, "*It helped me think deeper.*" These statements reflect that students had reached the "Articulation", "Reflection", and "Exploration" stages of the Cognitive Apprenticeship model, showing significant progress in both questioning ability and cognitive level.

Conclusions

The results of this study show that when students engaged in chemistry inquiry without any support, their questions were mostly simple and factual in nature, lacking the characteristics of in-depth investigation and experimental validation. However, when teacher guidance was combined with generative AI support, the quality of students' questions improved significantly—not only becoming more creative, but also meeting the criteria for experimental testability and focusing more precisely on the control and examination of scientific variables. In addition, students' questioning abilities exhibited a gradual progression through the six stages of the Cognitive Apprenticeship model, moving from basic knowledge recall in the early stages to higher-order thinking characterized by critical and creative abilities. These findings indicate that the collaborative support of teachers and AI has a significant effect on fostering students' scientific questioning skills.

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